

Program and Abstract Book

Berlin 2 - 4 July 2015





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Thursday 2 nd July	Friday 3 rd July	Saturday 4 th July
9:00–11:00 Pre-Workshop Clinical Course	8:00–9:40 Session 3 Spinal Loads: In vivo Measurements	8:30–10:10 Session 7 Spine Biomechanics: Computational Models
	9:40–10:10 Coffee Break	10:10–10:40 Coffee Break
	10:10–12:00 Session 4 Spine Biomechanics: Loading-Deformation	10:40–11:30 Session 8 Spine Biomechanics: Implants
11:00–13:00 Registration		11:30–12:30 Round Table
13:00–13:20 Welcome	12:00–13:30 Lunch Break	12:30–14:00 Lunch Break
13:20–15:15 Session 1 Intervertebral Discs	13:30–15:10 Session 5 Spinal Posture: Deformation	14:15 Transfer to ZOB 15:00 Bus departure to Prague
15:15–15:45 Coffee Break	15:10–15:40 Coffee Break	
15:45–17:25 Session 2 Motion Segment: Load Sharing and Failure	15:40–17:45 Session 6 Spinal Stability: Perturbations	
18:00 Happy Hour	19:00 Dinner	



Venue

Julius Wolff Institute Charité - Campus Virchow Klinikum Institutsgebäude Süd Föhrer Straße 15, 13353 Berlin

Date 2-4 July 2015

Organizers



Hendrik Schmidt Julius Wolff Institute – Charité Berlin, Germany



Saeed A. Shirazi-Adl École Polytechnique Montréal, Canada



Coordinator Friedmar Graicher





Secretary Barbara Schiller

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Welcome Note of the Congress Chairs

Dear colleagues and friends,

We are pleased to welcome you to the 1st international workshop on **Spine Loading and Deformation: From Loading to Recovery** will be held in the beautiful city of Berlin from 2-4 July 2015.

Mechanical loading and deformation in human spine during diurnal activities are recognized to play a major role in the etiology of back disorders and pain. A comprehensive knowledge of these loads/deformations is a basic prerequisite for effective risk prevention and assessment in workplace, sports and rehabilitation, proper management of various disorders, and realistic preclinical testing of spinal implants.

However despite considerable advancement and numerous investigations, many crucial issues remain yet unresolved. In vivo, in vitro and computational model studies are all necessary for tangible progress in this field.

This workshop on spinal loads/deformations aims to bring researchers active in this field together in order to share and discuss their recent works on related areas and explore the potentials of their findings. The research topics cover trunk loads and motions (imaging, sensors and video camera) measurements/predictions during sports, occupational tasks, seated vibration, etc. with focus on the lumbar and thoracic spines.

We cordially welcome you all to the workshop on **Spine Loading and Defor**mation: From Loading to Recovery and wish you an enriching scientific meeting and a pleasant stay in Berlin.

Yours, Hendrik Schmidt Saeed A. Shirazi-Adl

Scientific Program · Thursday, July 2nd

09:00-11:00 Pre-Workshop: Clinical Course

Organizers: Michael Putzier, Matthias Pumberger

Location: Outpatient Clinic, Center for Musculoskeletal Surgery, Charité -Universitätsmedizin Berlin, Campus Mitte, Luisenstraße 13-16, 10117 Berlin

With this course, we invite interested workshop participants to an unique opportunity of research-clinician cross-walk. On the basis of individual clinical cases, the current concepts in spine surgery will be discussed. We provide clinical cases to demonstrate how the biomechanical assessment of musculoskeletal pain / disorders complaints can be used to better manage or treat our patients. Due to logistics constraints, enrollment is limited on the basis of first come first served.

11:00-13:00	Registration / Coffee / Snack
13:00-13:10 Lecture Hall	Welcome and Workshop Opening Remarks Hendrik Schmidt, Saeed A. Shirazi-Adl
13:10-13:15 Lecture Hall	Greetings and Opening from the Dean Axel Pries, Dean, Charité Universitätsmedizin Berlin
13:15-13:20 Lecture Hall	Welcome from the Julius Wolff Institute Georg Duda, Director, Julius Wolff Institute
13:20-15:15 Lecture Hall	Session 1: Intervertebral Discs Moderators: Saeed A. Shirazi-Adl, Pieter-Paul A. Vergroesen
13:20	Dynamic Response of Intervertebral Discs under Loading and Unloading Cycles: On the Role of Fluid Flow Hendrik Schmidt (Berlin, Germany)
13:45	The Poro-Elastic Behaviour of the Intervertebral Disc: a new Perspective on Diurnal Fluid Flow Pieter-Paul A. Vergroesen (Amsterdam, The Netherlands)
14:10	Quantitative T2 Relaxation Time Predict Biomechanical Properties of Porcine Intervertebral Disc Jaw-Lin Wang (Taipei, Taiwan)
14:35	Intradiscal Pressure Measurements: An Error-Free Technique? Maxim Bashkuev (Berlin, Germany)

14:50	Biology and Mechanics: Basic Science on Disc Cell Mechanobiolog – the Benefits of Macrobiomechanics, Challenges and Open Questions Cornelia Neidlinger-Wilke (Ulm, Germany)		
15:15-15:45	Coffee Break		
15:45-17:25 Lecture Hall	Session 2: Spinal Motion Segment: Load Sharing and Failure Moderators: Michael Adams, Judith Meakin		
15:45	Variations in Spinal Load-Sharing, and its Clinical Significance Michael Adams (Bristol, U.K.)		
16:10	On the Load-Sharing Along the Ligamentous Lumbosacral Spine: Finite Element Modeling and Static-Equilibrium Approach Marwan El-Rich (Alberta, Canada)		
16:35	A New Dynamic Disc Loading Simulator Allows Physiological Loading with High Frequency to Provoke Disc Damage and Herniations Hans-Joachim Wilke (Ulm, Germany)		
17:00	Seeking for a Description of Spinal Fatigue Loading Gerd Huber (Hamburg, Germany)		
18:00	Happy Hour Beer, pretzel and live jazz music		

Scientific Program $\,\cdot\,$ Friday, July 3^{rd}

08:00-9:40 Lecture Hall	Session 3: Spinal Loads: In vivo Measurements Moderators: Navid Arjmand, Marcel Dreischarf			
08:00	Leaning with the Free Hand on the Knee Reduces Back Load During One-Handed Lifting Idsart Kingma (Amsterdam, The Netherlands)			
08:25	Loads on a Vertebral Body Replacement during Different Lifting Tasks Antonius Rohlmann (Berlin, Germany)			
08:50	Age Related Changes in Mechanical Demands Imposed on the Lower Back by Manual Material Handling Tasks Babak Bazrgari (Lexington, USA)			
09:15	Estimating 3D Ground Reaction Forces and L5/S1 Moments During Trunk Bending Using an Inertial/Magnetic Sensor Suit Gert Faber (Amsterdam, The Netherlands)			
9:40-10:10	Coffee Break			
10:10-12:00 Lecture Hall	Session 4: Spinal Biomechanics: Loading-Deformation Moderators: Idsart Kingma, Babak Bazrgari			
10:10-12:00 Lecture Hall 10:10	Session 4: Spinal Biomechanics: Loading-Deformation Moderators: Idsart Kingma, Babak Bazrgari Basic Biomechanics of the Spine - What have we Learned in the Past 25 Years? Thomas Oxland (Vancouver, Canada)			
10:10-12:00 Lecture Hall 10:10 10:45	Session 4: Spinal Biomechanics: Loading-Deformation Moderators: Idsart Kingma, Babak Bazrgari Basic Biomechanics of the Spine - What have we Learned in the Past 25 Years? Thomas Oxland (Vancouver, Canada) Estimation of Loads on Human Lumbar Spine - A Critical Review of Past In Vivo and Computational Model Studies Marcel Dreischarf (Berlin, Germany), Navid Arjmand (Teheran, Iran)			
10:10-12:00 Lecture Hall 10:10 10:45 11:10	Session 4: Spinal Biomechanics: Loading-Deformation Moderators: Idsart Kingma, Babak Bazrgari Basic Biomechanics of the Spine - What have we Learned in the Past 25 Years? Thomas Oxland (Vancouver, Canada) Estimation of Loads on Human Lumbar Spine - A Critical Review of Past In Vivo and Computational Model Studies Marcel Dreischarf (Berlin, Germany), Navid Arjmand (Teheran, Iran) Image Driven Subject-Specific Finite Element Models of Spinal Bio- mechanics Judith Meakin (Exeter, UK)			

13:30-15:10 Lecture Hall	Session 5: Spinal Posture: Deformation Moderators: Thomas Oxland, Hendrik Schmidt				
13:30	Surgeons and Scientists: Importance of Spinal Alignment on Surgical Strategy: An Orthopedic Perspective Matthias Pumberger (Berlin, Germany)				
13:55	The Effect of Age and Gender on Lumbar Lordosis, Pelvic Orientation and the Lumbopelvic Rhythm in the Sagittal Plane in 309 Asympto- matic Subjects without Low Back Pain Esther Pries (Berlin, Germany)				
14:20	Sagittal Range of Motion of the Thoracic Spine Using Inertial Sensors Navid Arjmand (Teheran, Iran)				
14:45	Age and Gender Differences in Intrinsic Trunk Stiffness Babak Bazrgari (Lexington, USA)				
15:10-15:40	Coffee Break				
15:40-17:45	Session 6: Spinal Stability: Perturbations				
Lecture Hall	Moderators: Gert Faber, Adamantios Arampatzis				
15:40	Surgeons and Scientists: Movement Disorders: A Challenge for the Spinal Biomechanics Peter Vajkoczy (Berlin, Germany)				
16:05	Stumbling Reactions during Perturbed Walking: Neuromuscular Activity and 3-D Kinematics of the Trunk – A Pilot Study Juliane Mueller (Potsdam, Germany)				
16:30	Effects of a Functional Perturbation Based Intervention on Muscle Strength and Neuromuscular Control of Spine Stability Adamantios Arampatzis (Berlin, Germany)				
16:55	Effects of Sensorimotor and Strength Training to Enhance Core Stability: A Randomized Controlled Trial Steffen Mueller (Potsdam, Germany)				
17:20	Paraspinal Muscle Forces, Spinal Loads, and Locus of Pres- sure Center in Healthy and Low Back Pain Subjects Seated on a Wobbling Chair Ali Shahvarpour (Montreal, Canada)				

19:00 Departure of the Bus to the Restaurant.

19:30 Social Event: Dinner



Scientific Program $\,\cdot\,$ Saturday, July 4th

08:30-10:30 Lecture Hall	Session 7: Spine Biomechanics: Computational Models Moderators: Mohamad Parnianpour, Thomas Zander				
08:30	Muscular Activity Reduces Peak Loads on Intervertebral Discs Syn Schmitt (Stuttgart, Germany)				
08:55	Prediction of the Spine Loading in Scoliotic Subjects by Semi- Automated 3D Reconstruction of Biplanar Radiographic Images Fabio Galbusera (Milano, Italy)				
09:20	Identification of Muscle Synergies in Performing Static Task: A Com- putational Study Investigating the Effects of Cost Function and Alter- native Methods of Input Data Arrangment Mohamad Parnianpour (Tehran, Iran)				
09:45	Thoracolumbar Spine Model with Articulated Ribcage For the Prediction of Dynamic Spinal Loading Dominika Ignasiak (Zurich, Switzerland)				
10:10-10:40	Coffee Break				
10:40-11:30 Lecture Hall	Session 8: Spine Biomechanics: Implants Moderators: Antonius Rohlmann, Marwan El-Rich				
10:40	Sensitivity of Lumbar Spine Loading on Anatomical Parameters Sebastian Dendorfer (Regensburg, Germany)				
11:05	Industry and Scientists: Biomechanical Challenges for Spinal Implant Development Christoph Schilling (Tuttlingen, Germany)				
11:30-12:30	Round Table Closing Discussions & Remarks Moderators: Saeed A. Shirazi-Adl, Idsart Kingma, Hendrik Schmidt Critical assessment of existing approaches, emerging methodologies, future directions,				
12:30-14:00	Lunch Break				
14:15 15:00	Transfer to the bus terminal ZOB Bus departure to Prague				

Abstracts

Session 1: Intervertebral Discs

Dynamic Response of Intervertebral Discs under Loading and Unloading Cycles: On the Role of Fluid Flow

<u>Schmidt H</u>^a, Schilling C^b, Bashkuev M^a, Shirazi-Adl A^c, Dreischarf M^a ^a Julius Wolff Institute, Charité - Universitätsmedizin Berlin, Berlin, Germany ^b Aesculap AG, Research & Development, Tuttlingen, Germany ^c École Polytechnique, Montréal, Canada

The primary function of the intervertebral disc is mechanical; it supports and transmits loads from one level to another while providing the spinal compliance required to perform various tasks. Over the course of daily activities, the disc fluid content continuously varies depending on loading (arising from the upper body weight, external loads, inertia and muscle activation), posture and the internal osmotic pressure (affected by the disc composition). Fluid flow within the disc is governed by this balance, causing fluctuations in the disc hydration and hence disc height. The time dependent mechanical behavior of the intervertebral disc has extensively been investigated by in vitro studies. Nevertheless, it remains yet unclear if conditions in in vitro studies properly emulate those in vivo. In view of long recovery periods in vitro, several studies have raised concerns on the fluid flow through the endplates that might be hampered by clogged blood vessels post mortem thus impeding diffusion in vitro. Studies on ovine, porcine, caprine and rat discs show that under constant compression, the disc height and nucleus pressure decrease due to fluid exudation. The recovery upon unloading is however very slow in time indicating an insufficient fluid inflow.

This paper aims to review and discuss the findings of reported studies as well as our ongoing in vitro investigations on the fluid flow mechanisms in intervertebral discs with special focus on creep and recovery in static and dynamic compression. Results of finite element model studies will also be presented and discussed in order to help identify the underlying mechanisms observed in vitro.

The Poro-Elastic Behaviour of the Intervertebral Disc: a new Perspective on Diurnal Fluid Flow

<u>Vergroesen PPA</u>^{a,b}, van der Veen AJ^b, Emanuel KS^{a,b}, van Dieën JH^b, Smit TH^{a,b} ^a Department of Orthopaedic Surgery, VU University Medical Center, Amsterdam, The Netherlands

^b MOVE Research Institute Amsterdam, Amsterdam, The Netherlands

Daytime spinal loading is twice as long as night time rest, but diurnal disc height changes due to fluid flow are balanced. A direction-dependent permeability of the endplates, favouring inflow over outflow, has been proposed to explain this: however, fluid also flows through the annulus fibrosus. This study investigates the poro-elastic behaviour of entire intervertebral discs in the context of diurnal fluid flow. Caprine discs were preloaded in saline for 24 hours under different levels of static load. Under sustained load, we modulated the disc's swelling pressure by replacing saline for demi-water and back again to saline, both for 24h intervals. We measured the disc height creep and used stretched exponential models to determine the respective time constants. Reduction of culture medium osmolality induced an increase in disc height, and the subsequent restoration induced a decrease in disc height (Fig. 1). Creep varied with the mechanical load applied. No direction-dependent resistance to fluid flow was observed. In addition, time constants for mechanical preloading were much shorter than for osmotic loading, suggesting that outflow is faster than inflow. However, a time constant does not describe the actual rate of fluid flow; close to equilibrium fluid flow is slower than far from equilibrium. As time constants for mechanical loading are shorter and daytime loading twice as long, the system is closer to the loading equilibrium than to the unloading equilibrium. Therefore, paradoxically, fluid inflow is faster during the night than fluid outflow during the day (Fig. 2).



Quantitative T2 Relaxation Time Predict Biomechanical Properties of Porcine Intervertebral Disc

Lin LY, <u>Wang JL</u>

Institute of Biomedical Engineering, National Taiwan University, Taipei, Taiwan

The disc is an anisotropic biphasic organ. The time-dependent behavior may result from interactions between the solid and fluid phase of tissue. The T2 mapping techniques can provide information about the interaction of water and the collagen networks, hence may be an indicator for the biomechanical properties of disc. The purpose of this study is to find the correlation of T2 relaxation time in respect to the rheological and viscoelastic properties of disc.

55 healthy porcine thoracic discs were imaged using a 3T MRI scanner. The T2 relaxation time of NP and AF were acquired. After MRI scanning, discs were dissected for mechanical tests. To find the rheological properties of discs, the creep tests were performed (1 hour 0.8 MPa) and the linear biphasic model was used to find the aggregate modulus and hydraulic permeability. The Dynamic Mechanical Analysis tests were conducted to find the viscoelastic properties. The discs were applied with 0.1~0.8 MPa compressive stress at frequencies from 0.03 to 10Hz. The phase angle of discs was acquired after the test. Pearson correlation was performed to correlate between T2 and disc biomechanical properties. A p-value less than 0.05 was considered to be significant.

Significant correlations were found between the disc permeability and T2 value of NP, but not in AF. No significant correlations were found between the aggregate modulus and T2 values of both NP and AF. The phase angle significantly correlates with the T2 values of AF, particularly at 0.03, 0.1, and 0.3 Hz.

Acknowledgement: NSC-103-2221-E-002-060-MY3

Intradiscal Pressure Measurements: an Error-Free Technique?

<u>Bashkuev M</u>^a, Vergroesen PPA^b, Dreischarf M^a, Schilling C^c, van der Veen AJ^b, Schmidt H^a, Kingma I^d

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^d Faculty of Human Movement Sci., MOVE Research Inst. Amsterdam, VU University Amsterdam

As the most direct way to evaluate spinal loads, intradiscal pressure (IDP) measurements are employed in numerous in vivo and in vitro investigations. Various sensors differing in size and measurement principles are currently available, but no data exists regarding inter-sensor reliability in assessing the IDP. Moreover, despite discs of various species used in animal studies can strongly vary in size and mechanics, the possible impact of sensor insertion on the IDP has never been investigated before. This short communication aims to address the mentioned questions.

Synchronized signals of two differently sized pressure transducers (diameters: 1.33 and 0.36 mm, Fig. 1) during in vitro measurements in two species (bovine and caprine), as well as their influence on the measured pressure were compared. First, the discs were subjected to three cycles of 30 minutes loading and unloading and the pressure was measured by two sensors simultaneously to assess the inter-sensor reliability. In the second test, the effect of the transducer size was evaluated by alternatingly inserting one transducer into the disc while recording the resulting pressure change with the second one.

While the sensors yielded similar responses to loading and unloading (ICC: consistency: 0.968-0.999; absolute agreement: 0.755-0.993) when used simultaneously, the size of the sensor was found to influence the measured pressure during the insertion tests. The magnitude of the effect differs between species (p = 0.001), with pressure increasing drastically, by 76-177%, when inserting the larger sensor in caprine specimens.

Results suggest that IDP measurements require special attention to the



choice of a proper sensor, in particular for species with a small disc size.

Figure 1: The sensors used in measurements are a strain gauge based needle mounted transducer (top) and a miniature fiber optic pressure sensor based on the Fabry-Pérot principle (bottom).

Basic Science on Disc Cell Mechanobiology - the Benefits of Macrobiomechanics, Challenges and Open Questions

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For understanding disc-degeneration associated back pain and for the development of suitable biological treatment strategies, it is important to know how mechanical influences regulate cellular responses and influence disc physiology and pathology. Intervertebral discs (IVDs) act as the joints of the spine, providing it with mobility and flexibility, and allowing it to bend and twist under the variety of high loads acting on the spine. The structure and biochemical composition of intact discs are perfectly adapted to fulfill these multiple functions. However, disc structure changes over the whole human lifetime. During ageing, discs degenerate progressively and disc structure undergoes changes that impair its biomechanical function; these degenerative alterations are associated with back pain.

The disc matrix is constantly made and turned over by a small population of resident cells which respond to the changing mechanical stimuli arising from applied loads. As the extracellular matrix mediates the mechanical stimuli to the cells, the stimuli to the cells and their responses depend on the state of disc maturity and health. Disc mechanobiology investigates these interactions between mechanical stimuli, state of the matrix and biologic processes at the cellular, tissue, organ and organism level. Its aim is to study the impact of mechanical influences on disc physiology and pathology. In particular, this research aims to improve understanding of degenerative pathways and possibly to contribute to developing improved strategies for treatment of disc degeneration.

This review summarizes the most important literature findings on disc biomechanics from experimental studies and some findings from computational modeling. It reviews disc mechanobiology studies in animal models, organ culture and cell culture experiments. Findings from these studies have increased knowledge of how mechanical loads influences disc matrix turnover. However transfer of results to the physiological situation in human discs is limited by age and species differences in animal studies, while experimental design in cell and tissue culture models tends simplify loading regimes and does not recreate the physicochemical environment seen in vivo. This review also stresses that disc degeneration is a multi-factorial problem where mechanical influences are only one of the factors involved; many other intrinsic and extrinsic influences such as matrix composition, ageing, genetic inheritance, and nutrient supply interact with altered loading conditions. To understand the cellular mechanisms underlying these complex interactions it is important to go beyond current molecular biology studies and elucidate the cellular signaling pathways involved in the sensing of mechanical loads by the cells and in conversion of these external signals into cellular responses. Such studies will aid in uncovering molecular pathways of degeneration and in understanding the complex interactions between loads and biochemical stresses.

In summary, disc mechanobiology is a multidisciplinary research field that needs the input from biomechanics and FEM studies as well as histology, molecular biology, biochemistry and medicine. Integration of different experimental approaches will provide data that increase understanding of disc physiology and pathology and which may contribute to the development of new therapeutic targets and improved strategies for treatment of disc degeneration.



Form and Function Measurement of the Back

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Session 2: Motion Segment: Load Sharing and Failure

Variations in Spinal Load-Sharing, and its Clinical Significance

<u>Adams MA</u>, Dolan P

University of Bristol, Bristol, UK

It is the concentration of mechanical loading that leads to tissue failure and back pain, rather than its overall magnitude. We consider how the distribution of compressive loading on the lumbar spine can be influenced by several factors.

Compressive loading on the spine is normally resisted by the vertebral bodies and intervertebral discs, with the fluid-like properties of a healthy disc ensuring an even distribution of compressive stress on disc and vertebral body alike. However, if an intervertebral disc is narrowed (by ageing, herniation, or endplate fracture) then more than half of the compressive force can be transferred to the neural arch, and concentrations of compressive stress arise in the annulus fibrous, particularly the posterior annulus. Effects are sensitive to posture. These changes in load-sharing can explain a great deal of spinal pathology, including osteoarthritic changes in the apophyseal joints, delamination and collapse of the annulus fibrosus, and anterior collapse of the vertebral body.

Time-dependent 'creep' can play a major role in these processes. Disc creep (which occurs by reversible fluid-flow) reduces disc height by 10-20% during each day, altering load-sharing as indicated above. Bone creep (which may not be reversible) is much slower, but is measureable in cadaveric experiments if bone mineral density is low. Bone creep appears to play a major role in vertebral deformity and in spondylolisthesis in elderly people. Preliminary data suggests that cement augmentation of vertebrae (as used clinically) can restore compressive load-sharing towards normality, and may be particularly effective in reducing bone creep.

On the Load-Sharing Along the Ligamentous Lumbosacral Spine: Finite Element Modeling and Static-Equilibrium Approach

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A harmonic synergy between the load-bearing and stabilizing components of the spine is necessary to maintain its normal function. Dysfunction of any spinal component results in system perturbation which may lead to immediate compensation or long-term adaptation of the other components. Previous studies on spinal load-sharing used simplified geometry (e.g. sagittally symmetric spine) which neglects the coupling movement effects or applied superposition by removing the spinal components one by one which neglects their interaction while carrying load.

To investigate the load-sharing along the ligamentous lumbosacral spine under flexion/extension moment coupled with follower compressive load.

A 3D nonlinear detailed finite element model with realistic geometry and developed at tissue level [1] was used. It was subjected to compressive follower load combined with 7.5Nm flexion/extension. Magnitude of the follower load increased from 400N at L1 to 575N at L5 which corresponds to the compression forces produced in the lumbar discs due to an upper body weight of ~40kg [2]. At the deformed configuration, a section was created at each segment level and a free body diagram of the upper vertebra was drawn. The internal forces and moments in the disc were calculated using the equilibrium equations which included the applied load and the forces in the ligaments and facet joints provided by the FE analysis. Load-sharing was expressed as percentage of load carried by spinal components (Fig. 1).

The load-sharing varied along the spine. When the spine is subjected to applied load, the resulting forces and moments are mainly resisted by the discs and ligaments particularly the capsular ligament respectively.



Fig.1 Spinal Load-Sharing under Follower Load Combined with Flexion/Extension

The facet joints contribute in resisting extension particularly at levels L4-S1. The effects of spine geometry variations on spinal load-sharing will be studied in the future using the proposed approach.

Naserkhaki S, et al. "How Does Lumbosacral Spine Geometry Affect Spinal Load-Sharing? Finite Element Analysis Using Personalized Geometries" 7th World Congress of Biomechanics, Boston, July 6-11, 2014.
El-Rich M, et al. "Muscle Activity, Internal Loads, and Stability of the Human Spine in Standing Postures: Combined Model and in Vivo Studies" 2004, Spine, 29(23) pp. 2633-2642.

A New Dynamic Disc Loading Simulator Allows Physiological Loading with High Frequency to Provoke Disc Damage and Herniations

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^d SpineServ GmbH & Co. KG, Ulm, Germany

The cause of disc herniation in not well understood yet. It is assumed that heavy lifting and extreme postures can cause small injuries starting in the inner annulus. Such injuries are accumulated over years until its structure is weakened and finally a single loading event leads to a sudden failure of the last few intact lamellae. However, failure may also start from the outside close to the endplate working its way into the disc until nucleus material can be extruded through this channel. The goal of this study is to provoke such disc failure due to repetitive loading to elucidate the mechanism of disc failure.

Six sheep segments (L3-4, L5-6) were loaded under various combined loading conditions (5-18° flexion-extension, 3-12° lateral bending, 0-10° axial rotation, 500-800 N axial compression, up to 1200 loading cycles, 1 Hz) in a newly developed dynamic six-degree-of-freedom disc loading simulator. Before and after testing the discs were examined in a ultra highfield μ MRI (11.7 Tesla). A three dimensional reconstruction was performed to visualize the internal disc lesions.

Typical failure patterns and herniations could be provoked with complex asymmetrical loading protocols. Lateral reversed loading protocol lead to similar mirror-inverted lesions.

A delamination could be detected between the nucleus and posterior annulus on the ipsi-lateral side of rotation and ruptures on the anterior-lateral side. These rupture resulted in something similar to a protrusion on the contra-lateral side of rotation.

These preliminary tests showed that it is possible to create artificial lesions in the disc with complex loading protocols. The aim of further tests is to better understand the mechanisms by which disc failure occurs at the microstructural level under different loading conditions. Visualization with μ MRI at different time

points is a promising method to investigate the gradual development of such lesions, which may finally lead to disc failure.

Figure 1: Dynamic six-degrees of freedom disc loading simulator and threedimensional reconstruction of provoked internal disc lesions.



Seeking for a Description of Spinal Fatigue Loading

Huber G^a, Nagel K^a, Skrzypiec D^b, Klein A^c, Püschel K^c, Morlock MM^a

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^c Dept. of Legal Medicine, University Medical Centre Hamburg-Eppendorf, Hamburg, Germany

Wöhler, Weibull and Palmgren-Miner equations are powerful tools to predict fatigue behaviour of technical systems. For the skeletal system similar knowledge is hardly available – neither for materials nor for functional units. Improvements in finite elements modelling increase the demand for such knowledge, if predictions about the health risk of whole body vibrations or about the potential success of implants will be done.

In vitro data might fill this gap, but the parameters are difficult to harvest, since specimens' characteristics differ largely. This study is aiming to provide descriptions of fatigue behaviour of functional spinal units.

Functional spinal units (T10/T11 to L4/L5) were exhibited to high numbers of compression fatigue cycles (n=41, mean age 49yrs) and pooled with those sustained moderate numbers of loading cycles1 (n=70, mean age 52yrs). A variety of combinations of the two determining aspects were considered: I) Specimen specific strength expressed by size and age, II) Type of loading expressed by the relation between its two peek values and its absolute value.

Product of specimen characteristic: 'age/area', loading characteristics: '(1-Fmin/Fmax)' and the applied loading: 'Fmean' enables a basic linear (logarithmic space) description of the variation (Fig. 1, R²=0.25).

Combinations of specimenspecific and load-specific parameters help to match the experimental findings – even though the variation remains high. In conjunction with numerical modelling, the derived curves might provide a step to enable the appraisal of occupational diseases and



Fig. 1: Cycles to failure of the pooled spinal specimens in relation to specimens' and loading type characteristics (unfilled markers represent specimens that did not fail within the applied fatigue loading).

in the following could help to determine the duty cycles for new implants.

Acknowledgment: Funded by FIOSH, Germany, F2059/F2069

[1] Brinckmann, P. et al.: Fatigue fracture of human lumbar vertebrae. Clin Biomech, 3(S1) 1988

Session 3: Spinal Loads: In vivo Measurements

Leaning with the Free Hand on the Knee Reduces Back Load During One-Handed Lifting

Kingma I, Faber GS, van Dieën JH

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When picking objects from the floor, Low Back Pain patients often tend to support the upper body by leaning with one hand on a knee. While this strategy may reduce back load, this has not yet been assessed, probably due to the difficulty of measuring the forces between hand and knee.

Ten healthy male subjects lifted a pencil and a crate from the floor, with four lifting techniques (free, squat, stoop and a Weight Lifters Technique (WLT)), each of which performed with and without leaning with one hand on the knee. A six Degrees of Freedom force transducer, with a comfortable surface to support the hand on, was mounted just above the subjects' knees. Hand forces, ground reaction forces, full body kinematics, and trunk EMG were measured during lifting. Using inverse dynamics and taking the forces between hand and knee into account, we calculated 3D L5S1 joint moments, and subsequently estimated spine forces using an EMG-assisted trunk model.

For lifting a pencil, average peak compression forces decreased with hand support, with effects ranging from 5% for stoop lifting to 27% for the WLT. For lifting a crate, peak compression forces decreased with 19% (stoop lifting) to 26% (free lifting) when compared to two-handed lifting. When compared to one-handed lifting without support, lifting the crate with hand support resulted in average reductions of 0% (stoop lifting) to 17% (WLT). It is concluded that leaning with a hand on the knee can lead to substantial reductions of low back loading during lifting.

Loads on a Vertebral Body Replacement during Different Lifting Tasks

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Repeated lifting of weights has been identified as a reason for low back pain. It is still a matter of debate whether squat lifting leads to lower spinal loads than stoop lifting. Therefore, this study aims to quantify in vivo the loads on a vertebral body replacement (VBR) during lifting using both lifting techniques. The effect of the distance between the weights and feet on the VBR loads was also determined. Moreover, the implant loads were compared for lifting a weight laterally and in front of the body.

Telemeterized VBR were implanted in five patients. The implant loads were measured during lifting weights between 4 and 10.8 kg. Lifting was performed with both hands using the squat and stoop lifting technique and the corresponding trunk and thigh inclinations were measured. The distance of the lifted weight from the shoe tips was also varied between 10 and 30 cm. A weight of 10 kg was additionally lifted laterally with the right hand.

The measured trunk and thigh inclinations were significantly different for squat and stoop lifting. However, similar maximum implant loads were measured when weights were lifted in both techniques. The maximum implant loads increased with increasing distance of the lifted weight. Lifting a weight laterally caused lower implant forces than lifting it with both hands in front of the body.

The current biomechanical study does not provide evidence for advocating the squat lifting technique. The anterior-posterior position of the carried weight relative to the spine strongly affects the spinal load.

Age Related Changes in Mechanical Demands Imposed on the Lower Back by Manual Material Handling Tasks

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Aging is becoming an increasingly important risk factors for low back pain (LBP) due largely to the growing population of older workers. The objective of this study was to investigate the differences in lower back loading when persons of different age complete the same manual material handling (MMH) task.

Sixty gender-balanced participants, aged 20 - 70 years, completed two MMH tasks involving lowering a 5 kg load from upright standing posture to both their knee height (Task-1) and a fixed height of 50 cm (Task-2), and then lifting back to the upright posture. Kinematics and kinetics data were respectively collected using accelerometers and a force platform. Mechanical demands of the MMH task on the lower back (i.e., net external moment and reaction forces) were estimated using measured kinematics and kinetics along with an inverse dynamic procedure involving a rigid multi-segment model of the lower extremities and pelvis.

The maximum net external moment and reaction forces along (axial) and perpendicular (shear) to the spine, as well as corresponding flexion angles of the thorax and pelvis, are summarized in Tables 1 and 2. Older individuals completed Task-1/Task-2 with similar/lower net moments, lower/lower axial forces, and higher/higher shearing forces imposed on the lower back. Increased lumbar shear forces were likely due to larger flexion of pelvis and lower flexion of the lumbar spine older participants and may result in a higher risk of LBP.

Age	Moment	Axial force	Shearing force	Pelvis rotation	Thorax rotation
range	(N.m)	(N)	(N)	(degree)	(degree)
22-28	96	500	183	22	82
32-38	105	500	184	22	86
42-48	86	493	232	28	87
52-58	82	466	270	33	83
62-68	90	455	314	38	93

Table 1: Measured kinematics and estimated loads in the lower back for Task-1

Table 2: Measured kinematics and estimated loads in the lower back for Task-2

Age	Moment	Axial force	Shearing force	Pelvis rotation	Thorax rotation
range	(N.m)	(N)	(N)	(degree)	(degree)
22-28	120	503	200	24	82
32-38	122	501	187	21	83
42-48	108	498	239	28	84
52-58	101	490	240	29	79
62-68	108	486	265	31	76

Estimating 3D Ground Reaction Forces and L5/S1 Moments During Trunk Bending Using an Inertial/Magnetic Sensor Suit

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This study evaluated the performance of a wearable inertial/magnetic motion capture (IMC) system (Xsens) in the estimation of 3D ground reaction forces (GRF) and L5/S1 moments during trunk bending tasks.

Ten healthy male subjects performed three tasks, 1) symmetric forward trunk bending, 2) 45° asymmetric trunk bending and 3) fast forward trunk bending. Using the ambulatory IMC system, GRF were estimated based on the full-body kinematics (using Newton's second law: F=m·a), and L5/S1 moments were estimated based on the upper-body kinematics using a top-down inverse dynamics analysis. As a gold standard reference, GRFs were measured with Kistler force plates (FPs), and L5/S1 moments were calculated using a bottom-up inverse dynamics model based on FP data and lower-body kinematics measured with an optical motion capture system (Optotrak).

Averaged over subjects, GRF RMS errors remained below 10 N (±1.5% of Body weight) for the normal symmetric and asymmetric trunk bending and below 20 N during fast trunk bending. L5/S1 moment RMS errors remained below 10 Nm for all tasks (±8% of the peak extension moment). This is an encouraging result considering that these L5/S1 moment errors are in the range of the accuracy of the gold standard inverse dynamics methods. Only for the lateral flexion component errors were somewhat larger. It is concluded that, provided absent or known hand forces, IMC based estimation of L5/S1 moments is a promising method with potential application for back load monitoring at the workplace.



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¹ Boyle C. Cheng, PhD, Biomechanical Pullout Strength and Histology of Plasmapore^{xpe} Coated Implants: Ovine Multi Time Point Survival Study, Aesculap ART129 12/13



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Session 4: Spinal Biomechanics: Loading-Deformation

Basic Biomechanics of the Spine -What have we Learned in the Past 25 Years?

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The 2nd edition of White & Panjabi's textbook, Clinical Biomechanics of the Spine, was published in 1990. The third edition is in the final stages of preparation. Obviously, there has been considerable research on the biomechanics of the spine over these past 25 years. The focus of this presentation will be to review what we have learned in regards to the 'basic fundamentals' of spine biomechanics - which is addressed in Chapter One of the book. We will consider the fundamentals of the whole spine, the functional spinal unit, and the individual components of the spine (e.g. vertebra, intervertebral disc, ligaments, spinal cord etc). In these broad categories, we will revisit our understanding in 1990 and review the main highlights of new knowledge gained through 25 years of research. We will also note areas where our understanding is lacking and thereby identify promising topics for future research. In this presentation, as in the White & Panjabi textbook, our emphasis will be on experimental research using human material, either in vivo or in vitro. The insights gained from mathematical models and animal experimentation are included where relevant. With this presentation, we hope to celebrate the substantial gains that have been made in the field over these past 25 years and also identify the work that remains to be done.

Estimation of Loads on Human Lumbar Spine

A Critical Review of Past In Vivo and Computational Model Studies

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Excessive loads on human lumbar spine during diurnal activities are recognized to play a major role in the etiology of back disorders and pain. A comprehensive knowledge of these loads is a prerequisite for proper management of various spinal disorders, effective risk prevention and assessment in workplace activities, sports and rehabilitation, realistic testing of spinal implants as well as adequate loading in in vitro studies. During the last five decades, researchers have used a variety of in vivo techniques to estimate spinal loads by measuring changes in the body height, the intradiscal pressure or forces and moments transmitted via instrumented implants. In addition, computational models have been employed as powerful means to directly compute spinal loading under various static and dynamic activities.

This paper aims to systematically review, compare and critically evaluate the existing literature on in vivo measurement and computational model studies of lumbar spinal loads. Towards this goal, the paper reviews in separate sections models dealing with static postures (standing, sitting, lying), slow dynamic activities (walking, stair climbing, lifting) as well as fast dynamic activities (lifting, sudden perturbations vibrations and impact). The findings are beneficial in many areas in work place design and ergonomics, biomechanics, and clinical environments.

Image Driven Subject-Specific Finite Element Models of Spinal Biomechanics

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Finite element (FE) modelling is an established technique for investigating spinal biomechanics. Using image data to produce FE models with subject-specific geometry and displacement boundary conditions may extend their use to the assessment of individuals. The aim of this work was to evaluate the feasibility of this approach and explore the how it could be developed into a practical method.

Lumbar spine magnetic resonance images from nine individuals in the supine, standing and sitting postures were obtained. 2D FE models of the vertebral bodies and discs were created from the supine data. Vertebral bodies were modelled as rigid bodies and two material models for the discs were assessed (elastic and poroelastic). The relative translation and rotation of the vertebral bodies as the individual moved to standing or sitting was determined and applied to the model. The resulting stresses and bulging of the L4/L5 disc were determined.

The models predicted that sitting tended to generate higher stresses and bigger bulges than standing with variation between individuals; this is consistent with measurements reported in the literature. The results from the two material models were in broad agreement with each other although the 2D poroelastic model predicted larger disc bulges than would be expected in vivo.

This study demonstrates the feasibility of using image data to drive subject-specific FE models of the lumbar spine. Further development of the technique has the potential to yield a method that may generate new insights into spinal biomechanics for a range of applications.

Effects of External Load Magnitude, Elevation, and Orientation on Trunk Response

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It is important to evaluate the trunk musculoskeletal response under a wide range of manual material handling tasks as the external load elevation, orientation, and magnitude alter. In earlier studies (El Ouaaid et al, 2014a, b), we investigated the trunk active and passive response under limited load orientations and elevations that generated identical flexion moments at the L5-S1. In this work, however, we aim to compute trunk muscle forces, stability and spinal loads under 3 fixed levels of external forces each applied at 3 elevations and 13 orientations.

Methods: Under an identical upright standing posture and total body weight (68.3 kg)/height (181 cm) (El Ouaaid et al, 2014a, b), the trunk muscle response is computed using a validated kinematics-driven model (El Ouaaid et al, 2014b) as the external loads of 80, 120, and 160 N are applied symmetrically via both hands. Each loads is held at 20, 40, and 60 cm heights above the L5-S1 oriented upward (-90°), inclined upward (-75, -60, -45, -30, -15°), horizontal (0°), inclined downward (15, 30, 45, 60, 75°) and finally downward in gravity direction (90°). In addition, in all analyses, an antagonist moment of 10 Nm is applied in order to generate abdominal or extensor antagonist coactivity depending on the load orientation. Abdominal, local lumbar, and global extensor muscle forces as well as spinal compression/shear forces at the L5-S1 and L4-L5 lumbar levels are estimated. Finally, the trunk stability margin is evaluated.

Results and Discussion: Changes in the external load elevation and orientation substantially influence forces in all muscle groups. Overall, forces in local lumbar muscles reach their maximum under horizontally oriented loads whereas the global extensor muscles as well as external moment at the L5-S1 peak under loads inclined downward. The spinal compression and shear forces also reach their maximum under gravity-directed inclined loads and decrease as the external load turns direction upward reaching their minimum under upward loads. The trunk stability also increases as the external load turns upward.

Acknowledgement: this work is supported by The IRSST (Quebec) and NSERC (Canada).

Session 5: Spinal Posture: Deformation

Importance of Spinal Alignment on Surgical Strategy: An Orthopedic Perspective

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In 1741 Mr. Andry de Bois-Regard coined the term orthopedics and portrayed a currently relevant discussion on global balance and alignment (Fig. 1). Over the past decades, by evolving surgical techniques and spinal fusion strategies, the outcome of spine surgery has improved dramatically. The correction of overall coronal and/or sagittal plane decompensation is identified as one of the main predictors of successful spinal surgical outcome. In daily clinical practice, assessment of spinal alignment is performed by measuring pelvic tilt, sacral slope, pelvic incidence and sagittal vertical axis. In current literature standard values for all parameters and formulas of correction have been established to define surgical strategies.

However, a possible bias can be introduced by numerous factors. All standard values are measured on conventional plain radiographs, thereby prone to bias, with influencing factors including the radiologist, the measuring surgeon as well as the patient. Furthermore, neither spino-pelvic compensatory effects, nor biomechani-

cal relevant structures such as ligaments, tendons or muscles are considered. Therefore, even in cases of thoroughly planned deformity correction surgery, the positive predictive value of surgical outcome varies significantly.

The solution to overcome the current clinical limitations requires a deeper understanding of the biomechanical aspects of the spine. Novel tools allowing an individualized functional assessment of the spine are warranted to illustrate its unique biomechanical characteristics.

Figure 1: Mr. Andry's first described an approach for the treatment of spinal scoliosis. The deformity correction should be achieved by external splinting. Frontispiece of Nicolas Andry de Bois-Regard, Orthopédie, 1741.



The Effect of Age and Gender on Lumbar Lordosis, Sacrum Orientation and the Lumbopelvic Rhythm in the Sagittal Plane in 309 Asymptomatic Subjects without Low Back Pain

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Frequent upper body bending is associated with low back pain (LBP). The complex flexion movement, combining lumbar and pelvic motion, is known as the "lumbopelvic rhythm" and can be quantified by means of the L/P ratio (lumbar range of flexion (ROF) divided by pelvic ROF). This parameter might be helpful to differentiate between asymptomatic subjects and LBP patients, however, the influence of the factors age and gender is in detail unknown.

In the present study, the Epionics SPINE system, containing strain-gauge technology and acceleration sensors, was used to assess lumbar angle and sacrum orientation during upright standing and during upper body flexion in 309 asymptomatic subjects (age: 20-75 yrs; σ : 134, Q: 175). The effect of the factors age and gender on lumbar lordosis, sacrum orientation and subsequently the lumbopelvic rhythm was investigated.

Aging significantly reduced the lumbar lordosis $(8.1^\circ; >50 \text{ yrs compared to } 20-35 \text{ yrs})$ as well as the sacrum orientation (6.6°) during standing. With aging the lumbar ROF decreased by 7.5°, while the pelvic ROF compensated this effect and increased by 7.0°. The L/P ratio decreased from 0.80 to 0.65 during aging; however, this decrease was only significant in men. Gender influenced sacrum orientation in standing and in flexion as well as the L/P ratio during the middle and late phase of flexion.

In this study, the influence of age and gender on lordosis, pelvis and the lumbopelvic rhythm could be clearly demonstrated. These findings are of great importance for individual prevention of LBP and lay the baseline to differentiate symptomatic from asymptomatic subjects, age- and gender-matched.

Sagittal Range of Motion of the Thoracic Spine Using Inertial Sensors

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Evaluation of the range of motion (ROM) of the thoracic spine in the sagittal plane is valuable in many areas such as the patient discrimination for diagnostic purposes and the biomechanical modelling for spinal load predictions. Previous cadaveric, medical imaging, and skin-marker video motion analysis studies have reported quite different sagittal ROMs varying from ~4 to 32°. The present study aims to measure sagittal ROM of the thoracic spine using inertial tracking devices as source-less (no cameras or transmitters required), low-cost, light, and portable tools for the measurement of human movements in workplaces and clinical centers.

Eleven young healthy males with no recent back or shoulder complications volunteered for the study (22.6 years (SD 0.9), 74.3 kg (SD 13.4), and 177.7 cm (SD 9.9)). The sensors were securely attached to the spinous processes at the T1, T5, T12, and S1 levels using double-sided tapes to prevent movements of the sensors with respect to the underlying skin. Participants were requested to flex forward to their maximum voluntary rotation and subsequently return to their initial neutral standing posture with no constraints on the pelvis, their feet shoulder width apart, and their knees extended.

The means of peak voluntary flexion rotations at the T1-T5, T5-T12, and T1-T12 were 7.5° (SD 3.6), 13.2° (SD 6.4), and 20.7° (SD 7.4), respectively. In addition, means of peak voluntary flexion rotations at the T1 (total trunk rotation), S1 (total pelvis rotation), and T12-S1 (total lumbar rotation) were 117.4° (SD 17.3), 47.5° (SD 4.4), and 52.0° (SD 8.3), respectively. Paired t-test analysis indicated significantly larger contribution from the lower thoracic vertebrae (T5-T12) to the total trunk rotation when compared to the upper ones (T1-T5) (p<0.001). The measured forward flexion ROM of the thoracic spine (20.7°) in this study is larger than that measured in vitro in cadaveric studies (4-12°) but smaller than that reported in vivo in supine position using CT imaging (31.7°).

Age and Gender Differences in Intrinsic Trunk Stiffness

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Aging is an important risk factor for low back pain (LBP). Given the role of lower back biomechanics in the development of LBP, it is important to characterize agerelated changes in active and passive aspects of lower back biomechanics. Here, 60 participants in five age groups between 20 and 70 years completed two data collection sessions involving several experiments related to lower back biomechanics. Age-related differences in intrinsic trunk stiffness were investigated using a systems identification approach involving a sudden perturbation paradigm along with a lumped-parameter model of the lower back. Sudden perturbation tests included a pseudo-random sequence of anterior-posterior position perturbations (±5mm) that were completed with two levels of active extension pre-load (i.e., 20% and 30% of maximum voluntary extension effort-MVE). The driving force throughout the perturbations was measured using a load cell and resulting kinematics were measured using two laser displacement sensors. Preliminary analyses revealed no differences in intrinsic trunk stiffness of individuals between 20% and 30% MVE pre-loads. Hence, mean stiffness across both effort levels was used for subsequent analyses. Intrinsic stiffness generally increased with age and was larger among males vs. females. An exception to this general trend was the intrinsic stiffness of females > 62 years old, and that was lower than among females 42 - 58 years old.

An increase in trunk intrinsic stiffness with age suggests that the higher incidence of LBP among older individuals may not be largely related to spinal instability.







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Adult Movement Disorders pose a Distinct Neuromuscular Challenge to Spinal Biomechanics leading to Complex Spine Deformities

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Movement Disorders are among the most prevalent neurodegenerative disorders among adults. The most prominent disease states are Parkinson disease (PD) and Dystonia. PD for example affects over 1 million people in the US. It is estimated that the lifetime risk of developing PD is 1.5%. With the aging of the population, the prevalence of movement disorders will likely continue to grow.

Movement disorders are slowly progressive neurodegenerative disorders with limited therapeutic possibilities. Among those, the most established ones are pharmacological neurotransmitter replacement therapy and deep brain stimulation (DBS). Among the cardinal motor signs of movement disorders are increased, asymmetric muscle tone, rigidity and gait disorder/postural instability.

Due to these neuromuscular pathological hallmarks, patients with movement disorders pose significant biomechanical challenges to the spine. This is often aggravated by the fact that these patients tend to develop marked osteoporosis with impaired bone quality, postural instability, depression, cognitive impairment, and a tendency to fall due to instability and equilibrium difficulties. Thus, patients with movement disorders may present with postural or fixed deformities. For example, a recent estimate of the prevalence of deformities in PD was 33.5%. Spinal malalignment might occur both in the sagittal and coronal plane and risk factors for developing deformities include age, female sex, movement disorder severity, and back pain.

On the other hand, these patients also pose a significant challenge to the spine surgeon due to the refractory neuromuscular and biomechanical stress on the spine. Thus, problems in spine surgery for patients with movement disorders include high complication and re-operation rates (70-100%), secondary instability at index or adjacent level (recurrent kyphosis), and hardware failure. General recommendations encompass restrictive indications, avoidance of destabilizing maneuvers, such as decompression alone, and the best benefit/risk ratio for decompression and short instrumentation for compensated deformities. However, for severe decompensated deformities that necessitate correction, long instrumentation in order to correct deformitiy and spino-pelvic alignment are unavoidable.

In summary, the growing number of patients with movement disorders will pose a significant challenge and dilemma to modern spine surgery. A better understanding of the link between neuromuscular pathology and spinal biomechanics might help to improve surgical results for these patients.

Stumbling Reactions during Perturbed Walking:

Neuromuscular Activity and 3-D Kinematics of the Trunk – A Pilot Study

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Involvement of reflex activity of lower leg muscles in the compensation of falls is well investigated. A displacement of the trunk as a compensation strategy is unclear. Therefore, purpose of the study was the analysis of the kinematics and muscle activity of the trunk during perturbed walking.

10 physically active subjects (5male/5female; 29±3yrs; 179±11cm; 74±14kg) walked (velocity: 1m/s) on a split-belt treadmill while randomly 5 right-sided perturbations (treadmill belt decelerating, 40m/s2, 50ms duration; 200ms after heel contact) were applied. Trunk muscle activity was assessed with a 12-lead-EMG (6 back/ 6 abdominal muscles; 4000Hz). Trunk kinematics were measured with a 3D-motion analysis system (8 cameras; 200Hz) using a trunk model consisting of 12 markers (3 segments: upper thoracic area, lower thoracic area, lumbar area). EMG-RMS [%] (0-200ms after perturbation) was analyzed normalized to RMS of normal walking. Total range of motion (ROM;[°]) for anterior flexion, lateral flexion and rotation of each segment were calculated. Individual differences of ROM were built for walking and stumbling.

Stumbling leads to an increase of ROM for all segments and planes between 1.1 ± 0.2 -fold (OTS in R) to 2.6 ± 1.3 -fold (UTS in LF) compared to normal walking. EMG activity of the trunk is increased during stumbling (abdominal: $665\pm283\%$; back: $501\pm215\%$).

Artificial stumbling leads to a measurable effect on the trunk quantifiable with a displacement of trunk kinematics and increase in EMG activity (polysynaptic reflex activity) compared to normal walking. Higher abdominal muscle activity and ROM of lateral flexion may indicate a specific (muscular) compensation pattern of the stumbling.

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Effects of a Functional Perturbation based Intervention on Muscle Strength and Neuromuscular Control of Spine Stability

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Non-specific low back pain (NS-LBP) is an important worldwide problem that greatly reduces the quality of life of the affected patients. LBP is associated with a decrease in muscle size and strength as well as in the neuromuscular control of spine stability (Beneck et al, 2012; Graham et al., 2014). Therefore our purpose in the current study was to investigate the effects of a novel core rehabilitation intervention based on functional perturbation training on muscle strength and neuromuscular control of spine stability in NS-LBP patients.

Fifty-nine NS-LPB patients participated in the study. They were randomly divided into two experimental (EG) and one control group (KG). EG1 (n=20) performed core perturbation training using a customized apparatus and exercise under unstable conditions. EG2 (n=19) performed a traditional muscle strength exercised program for the trunk muscles. The exercise volume was equal in both interventions (14 weeks, two times per week, 1.5 h per session). In the pre-post measurements we examined the neuromuscular control of spine stability investigating the trunk stiffness after quick release experiments and the local dynamic stability (LDS) using the largest Lyapunov exponents (LLE). Trunk muscle strength was investigated using several maximal isometric and isokinetic contractions.

Trunk muscle strength increased in both EG to a similar extent (~17%), whereas only EG1 showed a significant increase in trunk stiffness (~16%). The LLE did not change in both EG, indicating a no training-induced alteration in LDS of the spine. The CG did not show any differences between pre- and post-measurements.

The novel intervention based on functional perturbation training resulted in an improvement of the neuromuscular control of spine stability in NS-LBP patients without any deficits regarding muscle strength increases compared to traditional resistance training. Therefore, we can argue that a noise-induced neuromuscular training may provide a therapeutic benefit to NS-LBP patients.

References: Beneck et al., Arch Phys Med Rehabil, 93:300-306, 2012. Graham et al., J Biomech, 47:1459-1464, 2014.

Effects of Sensorimotor and Strength Training to Enhance Core Stability: a Randomized Controlled Trial

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Core stability is considered essential to counteract overloading and injury risk. Moreover, maximum strength and loading capacity are regarded as important factors in achieving stability and performance of the trunk during physical activity.

Therefore, the purpose was to evaluate the effect of a sensorimotor and strength training on maximum trunk strength and resistivity to sudden trunk loading.

43 subjects (23f/20m, 29.2 \pm 9.8yrs, 71.7k \pm 13.6kg, 174.0 \pm 10.1cm, Training: 6.2 \pm 6.2h/week) were randomized into sensorimotor (SMT; n=11), strength training (ST; n=16) and control group (CG; n=16). Intervention was 3 times per week for 6 weeks. At baseline (M1) and after six weeks (M2) maximum strength in trunk rotation (ROM: 60°) and flexion/extension (ROM: 55°) was tested on an isokinetic dynamometer in isometric (PTiso), concentric (30°/s; PTcon) and eccentric (30°/s; PTecc) mode. Furthermore, sudden trunk loading was assessed by eccentric (30°/s) mode with additional customized dynamometer induced perturbation (PTecc+pert). Peak torque [Nm] was calculated. Data is presented with mean \pm SD and intervention effects were analyzed by two-way ANOVA (α =0.05).

Training interventions showed no difference for maximum strength in isokinetic trunk rotation or flexion/extension (PTiso, PTcon, PTecc; p>0.05). Load resistivity in trunk perturbation tests showed higher peak torque after SMT (M1/2 rotation: 157±56/176±47Nm, extension: 328±112/352±130Nm, flexion: 114±50/142±50Nm) and ST (M1/2 extension: 360±115/395±116Nm, flexion: 145±57/162±56Nm) compared to CG (p<0.05).

The used sensorimotor and strength training seems valid to improve core stability. The effect size should be seen in the context of already well trained adults.

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Paraspinal Muscle Forces, Spinal Loads, and Locus of Pressure Center in Healthy and Low Back Pain Subjects Seated on a Wobbling Chair

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Stability control on a wobble chair has been the subject of many investigations both to assess the functional response of trunk paraspinal muscles and to identify neuromuscular mechanisms involved during stability control tasks. In this study, muscle active/passive forces, spinal loads, and center of pressure (CoP) positions at the base were computed based on identical measurements performed on both healthy and low back pain subjects.

Seventeen subjects with clinical low back pain (nine men and eight women) and nineteen healthy controls (nine men and ten women) aged between 18 and 65 participated in the in vivo experimental part of this study. The subjects seated on a wobbling chair with feet resting and thighs and legs attached on a wobble chair. A ball and socket joint along with 4 spring supports allowed some forward-backward and lateral movements, while limiting axial rotations of the chair. Two task difficulties were tested by altering the distance of the springs (height: 4.5- cm; stiffness: 8467 N/m) from its pivot. Subjects were instructed to keep the hands on the chest during 60 seconds of each trial. Marker clusters and Optotrak camera system were used to record the chair, pelvis and trunk kinematics in all planes. A force-plate under the chair recorded the CoP. The recorded rotations were then prescribed into an iterative nonlinear transient finite element kinematics-driven trunk model (Shahvarpour et al, 2015) and muscle forces, spinal loads, and CoP positions were computed for a number of healthy and low-back pain subjects. Models were personalized with the recorded kinematics and body weight of each subject. The seated posture was simulated by additional flattening of the lumbar lordosis, especially at the distal L4-S1 levels.

The results for a subject (healthy male; easier task) revealed that the largest compression load (at the L5-S1) varied with time from 568 N to 1153 N. The average of A-P and M-L shear loads at the L5-S1 was, respectively, 264 N and 21 N. Due to the spatial kinematics involved, both extensor and abdominal muscles showed concurrent activities (albeit at rather small levels) that maintained the subject overall stability. Active (stationary and reflexive) muscle forces had larger contribution in trunk stability with respect to passive tissues, as the spine deformation was relatively small. Results are expected to delineate the neuromuscular strategies in such unstable conditions in both healthy versus low back pain subjects.

Session 7: Spine Biomechanics: Computational Models

Muscular Activity Reduces Peak Loads on Intervertebral Discs

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For calculating internal, spinal loads the crucial force-bearing structures and mechanical plus physiological boundary conditions must be validly modelled. In this study, we predict the transmission of mechanical excitations to seated humans with a musculoskeletal rigid body computer model (mass: 68 kg) including two legs, the pelvis, a detailed lumbar spine, and the remaining upper body. The five lumbar vertebrae plus intervertebral discs (IVDs), 58 spinal ligaments, 260 active muscletendon units (MTUs), and force contacts at the backside, the buttocks, and the feet are implemented. Whole body movements were synthesised by setting modelbased stimulation input to all MTUs and applying either sinusoidal oscillations (1 -20 Hz, 5 mm amplitude) or impacts (20 ms, 4 ... 16 g amplitude) to the seat. We considered two submaximal muscular stimulation levels (0.01 and 0.10; maximum: 1.0). Compressive forces in the L4/5 IVD during steady-state sitting are approximately 15% higher for the 0.10 stimulation level as compared to the 0.01level (570 N). As an example, however, in 15 Hz vibrations, the peak compressive force is reduced by approximately 15% for the 0.10-level as compared to the 0.01level (1100 N). During impact excitations, the load reduction by increasing muscle activity is even higher (25% decrease for the 0.10-level). We have thus shown, that humans can diminish externally induced peak loads on the internal structures by tuning the muscular activity, for example, by co-activation. This may therefore be a strategy to reduce the damage done to IVDs.

Prediction of the Spine Loading in Scoliotic Subjects by Semi-Automated 3D Reconstruction of Biplanar Radiographic Images

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Computational mechanical modeling of the human spine can provide useful information to better understand spine loads in specific postures and to assist clinicians in planning the best strategy for managing spinal deformities, e.g. in case of scoliosis. The present study proposes a semi-automatic software approach to predict the intervertebral disc loads.

A 3D subject-specific spine mechanical model was reconstructed from radiographic digitized images in the frontal and sagittal planes simultaneously acquired with the EOS Imaging System (EOS Imaging, France). Five adolescent subjects with mild scoliosis (Cobb angles <24°) were evaluated in standing position. For each vertebra a set of landmarks were manually identified on radiographic images via an in-house dedicated software. Coordinates of landmarks were processed allowing calculating geometrical parameters of vertebral configuration in 3D space: i) placement; ii) dimensions; iii) rotation around coronal, sagittal and axial axes. Spherical joints were set between vertebral pairs simulating intervertebral discs. Thoracic joints were kept unable to move in order to model the high stiffness of trunk, whereas lumbar joints were not constrained. Body weight distribution, muscles forces and muscle insertion points on vertebrae were placed according to physiologicallyanatomically appropriate values. Inverse static analysis, able calculating joints reactions in maintaining assigned spine configuration, was performed with Any-Body software (AnyBody Technology, Denmark). Joint reaction forces were computed to quantify load forces acting on intervertebral discs, i.e. axial compression, frontal and lateral shear forces. Although preliminary, results were found comparable with values known from literature revealing the proposed approach as appropriate in describing subject-specific intervertebral disc loads.

Identification of Muscle Synergies in Performing Static Task: A Computational Study Investigating the Effects of Cost Function and Alternative Methods of Input Data Arrangement

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A hallmark of more advanced models is their higher details of trunk muscles represented by larger number of muscles. The question is whether we control these muscles individually as independent agents or we control groups of them called "synergy". To address this, we solved a biomechanical model of spine with 18 trunk muscles that satisfied equilibrium conditions at L4-L5, with different cost functions such as minimum cubed muscle activation, minimum squared activation, and minimum of maximum activation subjected to physiological constraints on allowable muscle activation.

The solutions of 24 tasks sampled in the sagittal-coronal moment space were arranged in a data matrix and the synergies were computed by using non-negative matrix factorization (NNMF) algorithms. Variance accounted for was used to evaluate the number of synergies that emerged by the analysis which were used to reconstruct the original muscle activations.

The VAF reached 97.56% for four synergies and inclusion of additional synergies caused only incremental increase in VAF for minimum cubed activation. The inclusion of torque data in the data matrix aligned the torques generated by each synergy along the four cardinal directions in the moment space (i.e. right and left lateral bending and flexion/extension moments). The synergies were different by choosing alternative cost functions as expected. In addition, synergies were quite different when absolute muscle forces were used versus relative muscle activation in generating the data matrices. The following computational methods show that the synergies can reduce the complexity of load distributions and allow reduced dimensional space to evaluate patient and normal performances in clinical settings.

Thoracolumbar Spine Model with Articulated Ribcage for the Prediction of Dynamic Spinal Loading

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Musculoskeletal modeling is a commonly used method for spinal loading estimation. A better understanding of the thoracic spine kinetics could provide an invaluable insight into the pathobiomechanics of spinal disorders, such as hyperkyphosis, scoliosis, vertebral fractures, or upper back pain. Current models of the thoracic region are not designed for segmental load estimation, or do not include the ribcage, despite its potentially important role in load transmission.

We have developed a numerical musculoskeletal model of the thoracolumbar spine with articulated ribcage, modeled as a system of individual bony segments, elastic elements and thoracic muscles, based on a previously established lumbar spine model and data available from the literature. The inverse dynamics simulations of the model allow for the prediction of spinal loading as well as costal joints kinetics and kinematics.

The predicted thoracic compressive forces correlated well (R2=0.88) with reported intradiscal pressure measurements, providing a first validation of the model. The inclusion of the ribcage did not affect segmental force predictions when the thoracic spine did not perform motion. During thoracic motion tasks, the ribcage had an important influence on the predicted compressive forces and muscle activation patterns. The compressive forces were reduced by up to 32%, or distributed more evenly between thoracic vertebrae, when compared to the predictions of the mod-

el without ribcage, for mild thoracic flexion and hyperextension tasks, respectively.

The developed musculoskeletal model provides a tool for addressing a number of research questions focused on dynamic thoracic spine loading or load sharing between vertebral column and ribcage.



Figure 1 Simulated dynamic tasks of (A) 10° thoracic flexion and (B) 10° thoracic hyperextension and (C-D) corresponding compressive forces (normalized to the loading at upright posture) predicted by a simple thoracolumbar model (Ti) and a thoracolumbar model containing ribcage structures (RC).



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Session 8: Spine Biomechanics: Implants

Sensitivity of Lumbar Spine Loading on Anatomical Parameters

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Musculoskeletal simulations of lumbar spine loading rely on a geometrical representation of the anatomy. However, the influence of geometrical variations is often not considered. This study evaluates the influence of variations in lumbar spine geometrical parameters on lumbar spine loading utilizing five parametrized musculoskeletal lumbar spine models (MM) for four different postures.

The models are based on a custom made MM developed in the AnyBody Modeling System (ABT, DK) and are morphed to the individual geometry of the patients. Integral motion between thorax and pelvis has been prescribed and force dependent joint kinematics [LI] were used to derive the individual position of the vertebral bodies. The models were validated against literature data. Following this, the influence of the dimensions of vertebral body, disc, and posterior parts of the vertebrae as well as the curvature of the lumbar spine were studied (Fig 1). Additionally, simulations with combinations of selected parameters were conducted. In total 3700 models were studied. Changes in L4/L5 resultant joint force were used as outcome variable.

Variations of the vertebral body height, disc height, transverse process width and the curvature of the lumbar spine showed the highest influence on lumbar loading.

The results of the study indicate that measuring vertebral body and disc height, transverse process width and curvature of the lumbar spine would be most important to customize MM.



Figure 1: Studied geometrical parameters and body positions.

Biomechanical Challenges for Spinal Implant Development

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This short communication is intended to highlight the biomechanical challenges for implant development from an industrial perspective.

Hardware related failure of spinal surgical procedures is a common reported clinical phenomenon. The state of the art implants found in clinical practice are more or less developed based on empirical findings. Hence clinical problems such as screw / rod fracture, screw loosening, loss of correction or adjacent segment disease could be related to an insufficient, non-comprehensive understanding of the spinal environment regarding acting loads, deformation in combination with resulting posture under daily life activities.

Besides the number of clinical studies with a high level of evidence for several types of spinal instrumentation are also very rare in terms of having a differentiated picture on the correlation of pathological situation, used instrumentation and patient outcome.

For surgical procedures with novel implant types, e.g. motion preservation implants, dynamic pedicle screw systems, pedicle screw anchorage in osteoporotic bone or regenerative treatments it is extremely demanding to predict the clinical performance with the current biomechanical knowledge. Simulations, in vitro test methods, or animal models for in vivo investigations are lacking taking into account the very complex human spinal environment on different scales (from cellular to whole body level).

Indeed in some areas there is a deep and valuable knowledge available. However this has to be linked together and sharpened in terms of working in accessible research clusters on outcome driven, unsolved problems, ideally realizing a closed loop from research to clinical application.

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On the campus the first 59 minutes are free and every hour afterwards costs 2 €. Disabled parking is available on the campus on Mittelallee.



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