

VIRTUAL SYMPOSIUM

Using Motion Analysis Techniques and Musculoskeletal Modeling of the Spine to Better Understand Spinal Disorders and Evaluate Treatment Effects

Program and Abstract Book

May 12, 2021 – 9:00 am – 12:30 pm EDT (1:00 pm – 4:30 pm GMT)



Center for Advanced
Orthopaedic Studies



Human Musculoskeletal
Biomechanics Lab
(HMBL)



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USING MOTION ANALYSIS TECHNIQUES AND MUSCULOSKELETAL MODELING OF THE SPINE TO BETTER UNDERSTAND SPINAL DISORDERS AND EVALUATE TREATMENT EFFECTS

May 12, 2021 – 9:00 am – 12:30 pm EDT (1:00 pm – 4:30 pm GMT)

PROGRAM

(Chair: Stefan Schmid)

Time	Title	Presenter
Session 1 – Development and Evaluation of Motion Analysis Techniques for the Spine		
(Chair: Babak Bazrgari)		
9:00-9:05 am	Welcome remarks	Stefan Schmid
9:10-9:18 am	A reference database of standardised continuous lumbar intervertebral motion analysis for conducting patient-specific comparisons	Alan Breen
9:20-9:28 am	Subject-specific spino-pelvic models reliably measure spinal kinematics during forward bending in adult spinal deformity	Thomas Overbergh
9:30-9:38 am	Spinal palpation error and its impact on skin marker-based spinal alignment measurement in adult spinal deformity	Pieter Severijns
9:40-9:55 am	Q&A and discussion	All
Session 2 – Evaluating the Effects of Spinal Disorders on Motion and Loading		
(Chair: Lennart Scheys)		
10:00-10:08 am	Walking biomechanics and lumbar spine loading in patients with symptomatic lumbar spinal stenosis	Seyed Javad Mousavi
10:10-10:18 am	Walking alterations in adult spinal deformity depend on the type of deformity	Karl Semaan
10:20-10:28 am	Association Between Gait Alterations and Quality of Life in Patients with Adult Spinal Deformities	Abir Massaad
10:30-10:38 am	Alteration of the sitting and standing movement in adult spinal deformity	Eddy Saad
10:40-10:48 am	Assessment of dynamic sagittal balance during walking in patients with adult spinal deformity	Guillaume Rebeyrat
10:50-11:05 am	Q&A and discussion	All
Session 3 – Clinical Applications and Interventions		
(Chair: Dennis Anderson)		
11:10-11:18 am	Patient specific variations in local strain patterns on the surface of a trussed titanium interbody cage	Arjan Loenen
11:20-11:28 am	Acute effects of a single bout of a game-based real-time biofeedback training on 3d trunk movement in patients with chronic non-specific low back pain	Juliane Mueller
11:30-11:38 am	Accounting for biomechanical measures does not enhance the prediction of curve progression in adolescent idiopathic scoliosis	Tito Bassani
11:40-11:48 am	Framingham cohort adjacent segment biomechanics following T10-pelvis spinal fusion: a computational study	Christian Rodriguez
11:50-11:58 am	Biomechanical evaluation of the effect of minimally invasive spine surgery compared with traditional approaches in activities-of-daily-living	John Rasmussen
12:00-12:25 pm	Q&A and discussion	All
12:25-12:30 pm	Final remarks and closing	Stefan Schmid

SESSION 1

Development and Evaluation of Motion Analysis Techniques for the Spine

Chair: Babak Bazrgari

A reference database of standardised continuous lumbar intervertebral motion analysis for conducting patient-specific comparisons

Alexander Breen¹, Alan Breen^{1,2}

¹Centre for Biomechanics Research, AECC University College, Bournemouth, UK ²Faculty of Science and Technology, Bournemouth University, Bournemouth, UK

Introduction

To understand spinal disorders in terms of their biomechanical effects on symptoms and evaluate treatment effects, variables must be repeatable over an acceptable follow-up period in a symptomatically stable population. In previous work using quantitative fluoroscopy (QF), where both the motion task (lumbar flexion) and the analysis were highly standardised, some intervertebral motion sharing characteristics in the lumbar spine were found to be significantly different in NSLBP patients than asymptomatic controls. Control measurements were also stable over 6 weeks, making measures suitable for use in outcome and prognostic studies. Previous studies have measured the outward and return paths of lumbar flexion separately to assess dynamic loading models during bending and lifting. Against such normative data, individual patient studies using the same protocols can be compared. The aim of this study was to establish a database of reference values for key dynamic lumbar motion variables during controlled outward and return bending using standardised QF recording and analysis protocols. These could serve as reference information for both the construction of mathematical models and for comparison with patient-specific kinematics.

Materials and Methods

Low dose continuous fluoroscopic image sequences, recorded at 15 fps, were acquired from 131 asymptomatic participants during active, weight-bearing lumbar flexion and return motion. This used a bending protocol guided by an upright motion frame. This standardised the bending range and velocity and minimized accessory movements. Continuous intervertebral rotations in the sagittal plane were extracted for each level (L2-S1) in each frame and transformed into contributions proportional to the total L2-S1 angle. Mean and \pm 95% confidence intervals across all participants were calculated for each 1% increment of L2-S1 motion. Data were separated to distinguish the flexion and return-to-neutral portions of the bending task. Statistically significant differences between each level's contribution to motion were detected by the absence of overlap in the \pm CI95 bands and checked using statistical parametric mapping.

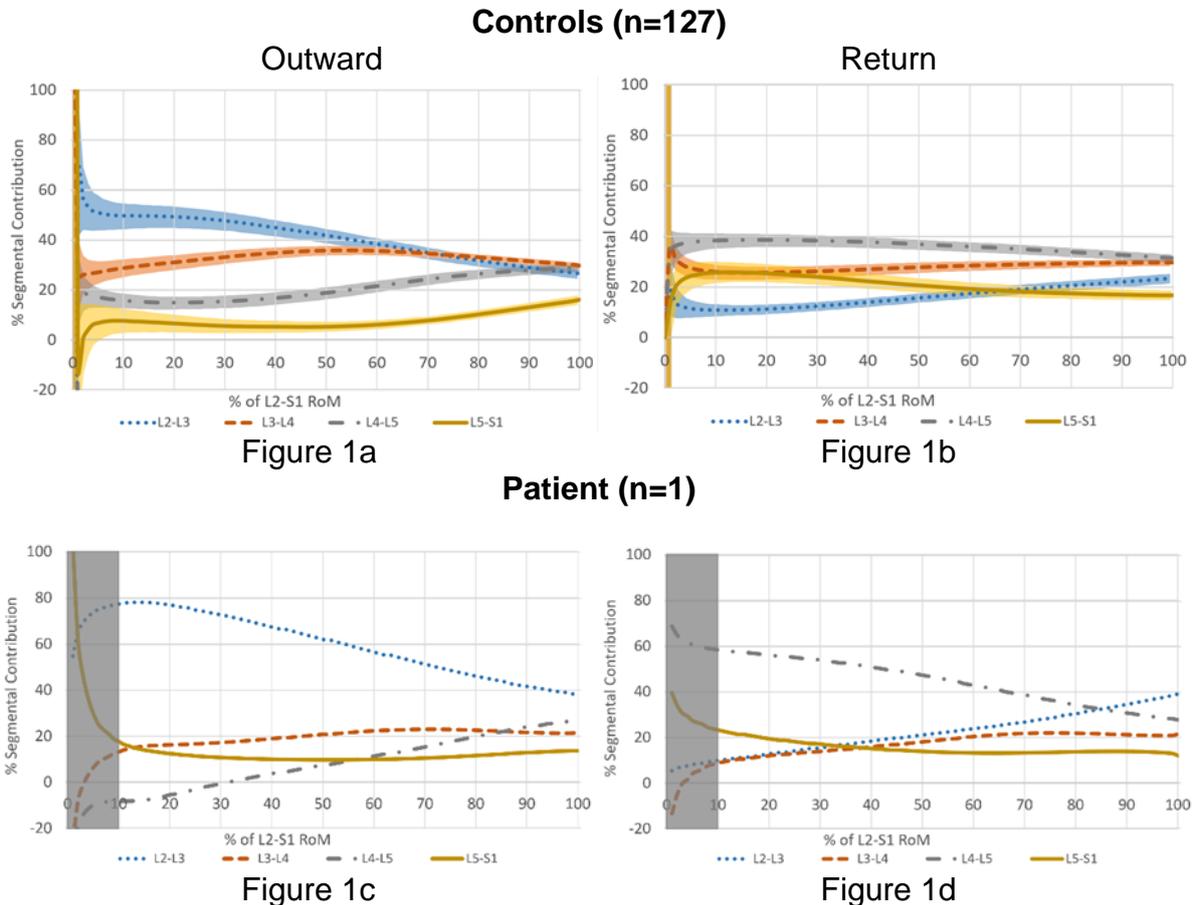
Results and discussions

Full data sets were extracted from 127 participants, (48.8% female, mean age 38.6 years, range: 21-70). The proportion of the motion performed by each level at full flexion was similar to previous studies. However, there were significant differences in the contributions to bending during motion, both between and within levels, which change as participants progress through the tasks (Figs 1a and b). Each intervertebral level also had its own characteristic motion signature, with significant differences ($p < 0.05$) between each level's contribution. These were sustained throughout the motion.

In the individual back pain patient example (Fig 1c), L2-3 initially accepted a higher proportion of the outward motion than that of the controls (Fig 1a), and considerably less at L4-5, although both showed return to near-normal sharing levels by completion of the bend. On the return motion (Fig

1d), it is L4-5 that initially accepts a higher proportion in this patient, and L3-4 considerably less, although by the time the upright position has been reached, all but L4-5's share of the motion resemble the normative values (Fig 1b).

Figure 1. Proportional contributions to motion from L2-S1 with 95% CIs in 127 healthy controls in a) flexion, b) return and comparison with a patient with chronic, non-specific low back pain c) and d).



Conclusions

In the controls, despite differences in gender, BMI, age, anatomy, co-ordination and strength, all levels exhibited consistent motion contributions. This was attributed to the use of the guided motion apparatus (Fig 1), making the database also suitable for comparison with both cross-sectional and longitudinal data from individuals and with groups of patients with low back pain in research and clinical studies. The patient (Fig 1c), exhibits much more initial flexion at L3-4 than the controls during forward bending, while L4-5's motion is initially paradoxical. On return, L4-5 initially accepts much more of the motion and L2-3 much less (Fig 1d). These differences are likely to be related to a combination of loading, motor control and tissue material characteristics. They may also be suitable for modelling dynamic segmental loading in clinical and occupational settings.

Subject-specific spino-pelvic models reliably measure spinal kinematics during forward bending in adult spinal deformity

Thomas Overbergh^{1*}, Pieter Severijns¹, Erica Beaucage-Gauvreau¹, Thijs Ackermans¹, Lieven Moke^{1,3}, Ilse Jonkers², Lennart Scheys^{1,3}

¹Institute for Orthopaedic Research and Training (IORT), Department of Development and Regeneration, Faculty of Medicine, KU Leuven, Leuven, Belgium

²Human Movement Biomechanics Research Group, Department of Movement Sciences, KU Leuven, Belgium

³Division of Orthopaedics, University Hospitals Leuven, Leuven, Belgium

Introduction: Aiming to complement today's mostly static insights of the adult spinal deformity (ASD) pathology and thereby improve the often poor outcome of surgical treatment, image-based subject-specific models and simulations are recently being introduced. Although the accuracy of manually creating subject-specific models from medical images, and associated marker-driven kinematic analyses have already been quantified (Overbergh et al., 2020), the reliability thereof has not yet been investigated. The aim of this work was to evaluate the reliability of using subject-specific spino-pelvic models to determine ASD spine kinematics in terms of (1) the overall test-retest repeatability, (2) the inter-operator agreement of the subject-specific modeling method and (3) the sensitivity of the intervertebral joint kinematics thereof.

Materials and Methods: To evaluate the overall repeatability, five ASD subjects and one control subject participated in a test-retest study with a two-week interval. At both time instances subject-specific spino-pelvic models were created by a single operator and then used to simulate the forward trunk flexion motion recorded in the motion laboratory. The kinematic reliability was expressed as intraclass correlation coefficients (ICC's) of the range of motion (ROM) of six conventional spino-pelvic parameters (lumbar lordosis (LL), thoracic kyphosis (TK), sagittal vertical axis (SVA), pelvic tilt (PT), T1 and T9 spino-pelvic inclination (T1-SPI, T9-SPI)). Next, to evaluate inter-operator agreement, three trained operators each created a model for three ASD subjects (Figure 1) which were then used to simulate the same forward trunk flexion motion. As before, ICC's of ROM of spino-pelvic parameters were used to evaluate inter-operator agreement. Lastly, to representatively evaluate the uncertainty and sensitivity of the intervertebral joint kinematics to operator variability, a Monte-Carlo probabilistic simulation produced a large amount of representative model variations, for three ASD subjects, based on the experimentally estimated operator-variability of the different operator-dependent parameters in the models.

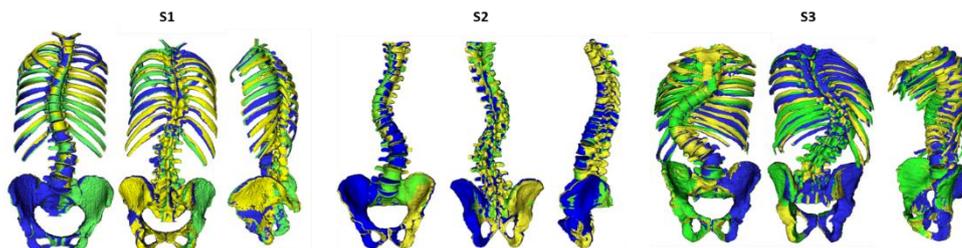


Figure 1: Illustration of the alignment reconstruction for the three subjects (S1, S2 and S3) by the three operators: O1 (green), O2 (yellow) and O3 (blue).

Results and discussions: An excellent test-retest reliability was obtained for the ROM of lumbar lordosis (ICC=0.86), sagittal vertical axis (ICC=0.91), pelvic tilt (ICC=0.80) and T1-and T9-spino-pelvic inclination (ICC= 0.91 and 0.91). The thoracic kyphosis ROM had a poor (ICC= 0.12) ICC. The ICC's of all spino-pelvic

parameters in the operator-agreement test were excellent (>0.87) and even higher than in the test-retest reliability. Lastly, the Monte-Carlo uncertainty analysis indicated mean 90% confidence intervals between 1.04° - 1.75° on the intervertebral joint estimations of the three subjects, and revealed the definition of the intervertebral joints as the most sensitive operator-dependent model parameters. The box and whisker plots show a higher variability at the lumbar and low-thoracolumbar region compared to the upper thoracic region (Figure 2).

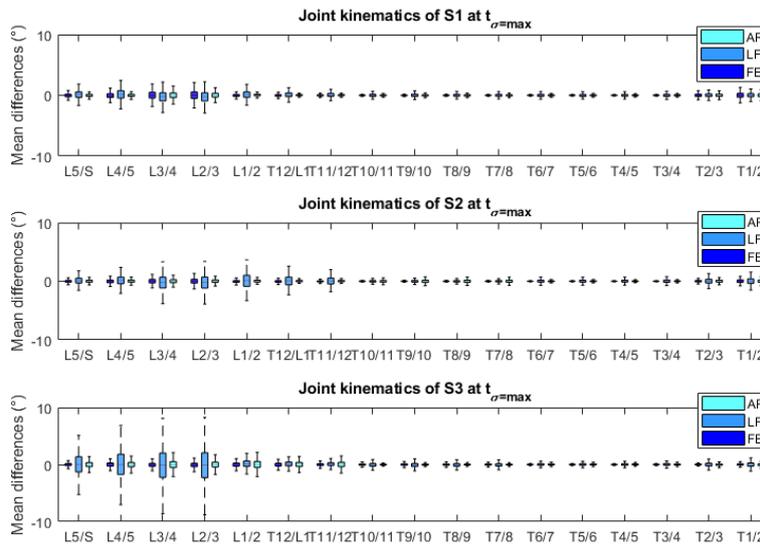


Figure 2: Box and whisker plot of the joint values at the time instance of the largest variation ($t_{\sigma=\max}$) of each DOF, relative to the baseline model's joint angles, for each subject. The upper and lower edges of the box are the 75th and 25th percentiles, the horizontal bar in the box is the median (50th percentile) and the upper and lower bars are maximum and minimum values. AR: axial rotation; LF: lateroflexion; FE: flexion-extension.

Conclusions: Our systematic inter-operator approaches identified a limited impact of operator-induced variability on kinematic simulations of spine flexion in an ASD population. This excellent inter-operator agreement, compared to the lower test-retest reliability, for the same motion, however, importantly indicates that the dominant portion of overall test-retest variability is limitedly originating from aspects of the modeling, but rather from intra-subject differences over the two-week time interval. Improved standardization of the maximal forward trunk flexion together with multiple acquisitions averaged per session, may improve the test-retest reliability. In conclusion, although the current modeling method is dependent on manual inputs of the operators, causing additional variability in the simulation output, its isolated effect on the kinematics was very limited, indicating the modeling method to be highly reliable for kinematic analysis of spinal motion.

Acknowledgment: This study was funded by KU Leuven C2 funds, Medtronic and a strategic basic research PhD grant (SB/1S56017N) of the Research Foundation – Flanders (FWO).

References:

Overbergh, T., Severijns, P., Beaucage-Gauvreau, E., Jonkers, I., Moke, L., Scheyts, L., 2020. Development and validation of a modeling workflow for the generation of image-based, subject-specific thoracolumbar models of spinal deformity. *J. Biomech.* 110, 109946.

Spinal palpation error and its impact on skin marker-based spinal alignment measurement in adult spinal deformity

Pieter Severijns^{1,2,†}, Thomas Overbergh^{1,†}, Stefan Schmid⁴, Lieven Moke^{1,3}, Lennart Scheys^{1,3}

¹Institute for Orthopaedic Research and Training (IORT), Department of Development and Regeneration, Faculty of Medicine, KU Leuven, Leuven, Belgium

²Department of Rehabilitation Sciences, KU Leuven, Leuven, Belgium

³Division of Orthopaedics, University Hospitals Leuven, Leuven, Belgium

⁴Spinal Movement Biomechanics Group, Division of Physiotherapy, Department of Health Professions, Bern University of Applied Sciences, Bern, Switzerland

†These authors have contributed equally to this work and share first authorship

Introduction: Spinal alignment measurement in spinal deformity research has recently shifted from using mainly two-dimensional static radiography towards skin marker-based motion capture approaches, allowing three-dimensional (3D) assessments during dynamic conditions. The validity and accuracy of such skin marker-based methods is highly depending on correct marker placement. In this study we quantified, for the first time, the 3D spinal palpation error in adult spinal deformity (ASD) and compared it to the error in healthy spines. Secondly, the impact of incorrect marker placement on the accuracy of marker-based spinal alignment measurement was investigated.

Materials and Methods: 3D, mediolateral and inferosuperior palpation errors for thoracolumbar and lumbar vertebral levels were measured on biplanar images by extracting 3D positions of skin-mounted markers and their corresponding anatomical landmarks in 20 ASD and 10 healthy control subjects. Relationships were investigated between palpation error and radiographic spinal alignment (lordosis and scoliosis), as well as body morphology (BMI and soft tissue (ST) thickness). Marker-based spinal alignment was measured using a previously validated method, in which a polynomial is fit through the marker positions of a motion trial and which allows for radiograph-based marker position correction. To assess the impact of palpation error on spinal alignment measurement, the agreement was investigated between lordosis and scoliosis measured by a polynomial fit through, respectively, (1) the uncorrected marker positions, (2) the palpation error-corrected (optimal) marker positions and (3) the anatomically-corrected marker positions (towards the vertebral body), and their radiographic equivalents expressed as Cobb angles (ground truth), using Spearman correlations and root mean square errors (RMSE).

Results and discussions: The results of this study showed that, although overall accuracy of spinal level identification was similar across groups, mediolateral palpation was less accurate in the ASD group (ASD_{mean}: 6.8mm; Control_{mean}: 2.5mm; p=0.002). Significant correlations with palpation error indicated that determining factors for marker misplacement were spinal malalignment, in particular scoliotic deformity ($r_s=0.77$; $p<0.001$), in the ASD group and body morphology (i.e. increased BMI ($r_s=0.78$; $p=0.008$) and ST thickness ($r_s=0.66$; $p=0.038$)) in healthy spines. Improved spinal alignment measurements after palpation error correction, shows the need for radiograph-based marker position correction methods, and therefore, should be considered when interpreting spinal kinematics.



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Conclusions: Palpation error is increased in adult deformed spines and relates to the severity of the deformity. Its impact on the accuracy of marker-based spinal alignment measurement, indicated the need for radiograph-based marker position correction.

Acknowledgment: This study was funded by KU Leuven C2 funds, Medtronic and a strategic basic research PhD grant (SB/1S56017N) of the Research Foundation – Flanders (FWO). The authors like to thank Kristel Van de Loock and Rowie De Buysscher for their participation in data management and Michiel Brandt for his contribution to the data processing.

References: /

SESSION 2

Evaluating the Effects of Spinal Disorders on Motion and Loading

Chair: Lennart Scheys

Walking biomechanics and spine loading in patients with symptomatic lumbar spinal stenosis

Seyed Javad Mousavi^{1,2}, Andrew C. Lynch¹, Katelyn A. Burkhart^{1,2}, Brett T. Allaire¹, Mohammad Ali Sanjari³, Andrew P. White², Dennis E. Anderson^{1,2}

¹Center for Advanced Orthopaedic Studies, Beth Israel Deaconess Medical Center, Boston, MA, United States

²Department of Orthopaedic Surgery, Harvard Medical School, Boston, MA, United States

³School of Rehabilitation Sciences, Iran University of Medical Sciences, Tehran, Iran

Introduction: Symptomatic lumbar spinal stenosis (SLSS) is a leading cause of pain and mobility limitation in older adults. It is one of the most frequent indications for spinal surgery in patients over 65 years old. Neurogenic claudication – pain, numbness, and weakness in the legs and rapid fatigability while standing or walking- is the hallmark clinical manifestation of SLSS. Limited tolerance for standing and walking is characteristic of SLSS. It is widely believed that patients with SLSS adopt compensatory postures (forward flexed or hunched postures) that improve tolerance for walking, by relieving pressure on the nerves. Despite the association between lumbar spinal stenosis symptoms and trunk posture and walking, biomechanical assessment of gait and posture is broadly lacking in these patients. The purpose of this study was to evaluate trunk posture, particularly lumbar spine and pelvis angles, and lumbar spine compressive loads in standing and walking, and to determine the effect of pain and neurogenic claudication symptoms, in patients with symptomatic lumbar spinal stenosis. We hypothesized that patients would display increased trunk flexion posture and spine loading during walking and in the presence of claudication symptoms.

Materials and Methods: Seven participants with symptomatic lumbar spinal stenosis, aged 44 to 82, underwent a 3D opto-electronic motion analysis during standing and walking trials in pain free and symptomatic states. Passive reflective marker clusters (4 markers each) were attached to subjects at T1, L1, and S2 levels of the spine, with additional reflective markers at other spinal levels, as well as the head, pelvis, and extremities. Whole body motion data was collected during the following tasks in a consecutive order: 1) static upright standing posture (rested or pain free), 2) walking at a self-selected pace without symptoms present (rested) (three trials), 3) walking after onset of symptoms (symptomatic) (three trials), 4) static upright standing posture (symptomatic). To produce the symptomatic state, participants performed a standard walking capacity test, walking over ground or on a motorized treadmill at a self-selected pace until reporting the onset of claudication symptoms, up to a maximum of 30 minutes. Time to onset of symptoms and distance walked were recorded.

Results and discussions: Mean (SD) of the lumbar spine flexion, forward pelvic tilt (pelvic flexion), and spine flexion + pelvic tilt angles were -0.7° (6.9°), 5.9° (8.9°), and 5.1° (4.9°) respectively in asymptomatic walking; and -0.7° (6.8°), 9.6° (9.6°), and 8.8° (7.0°) respectively in symptomatic walking. Pelvic tilt and spine flexion + pelvic tilt were larger during walking than asymptomatic standing ($p < 0.05$), and additionally increased with symptoms ($p < 0.05$). Spine flexion was not different in walking than in standing, however, and did not increase with symptoms ($p > 0.05$). Pelvic tilt in symptomatic walking was larger than pelvic tilt in both asymptomatic standing and asymptomatic walking ($p < 0.05$). Spine flexion + pelvic tilt was larger during asymptomatic walking than asymptomatic standing ($p < 0.05$) and additionally increased during symptomatic walking ($p < 0.05$). In symptomatic standing, lumbar spine flexion, pelvic tilt, and spine flexion + pelvic tilt angles were -0.6° (1.6°), 0.9° (0.9°), and 0.3° (1.4°) respectively, with a small but significant increase in pelvic tilt versus asymptomatic standing ($p = 0.038$). Lumbar loading averaged 512 (170) N in asymptomatic standing, and was increased by an average of 22% during asymptomatic walking. Loading in

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symptomatic standing was not larger than asymptomatic standing, while loading during symptomatic walking was possibly increased by an average of 4% over asymptomatic walking ($p = 0.066$).

Our results indicate a forward shift of the entire trunk during both asymptomatic and symptomatic walking in patients with SLSS, supporting our overall hypothesis. This was primarily due to increased pelvic tilt, and not flexion of the spine. Moreover, pelvic tilt was larger during symptomatic walking than asymptomatic walking, and may be slightly increased during symptomatic standing. Interestingly, while most patients increased pelvic tilt, the effects on spine flexion were variable and on average suggested extension rather than flexion. In fact, the two patients with the largest amounts of pelvic tilt during walking also displayed the largest amount of spinal extension, perhaps suggesting a compensatory action to maintain overall balance.

Conclusions: The lack of increased spinal flexion seen here is not consistent with the commonly held assumption that patients with symptomatic lumbar spinal stenosis adopt flexed spine postures to increase spinal canal diameter and decompress the nerves, thereby relieving or delaying symptoms. Estimates of spine loading suggest a possible increase in spinal compressive loading in the symptomatic state, but the magnitude of any such change was not likely to be consequential. Additional study of walking and spine biomechanics in this population is needed to better understand this issue.

Acknowledgment: This work was funded by grants from the NRSA Institutional Research Training Grants (T32AR55885) and the Department of Orthopaedic Surgery at Beth Israel Deaconess Medical Center. The authors would like to acknowledge M. Mehdi Alemi for contributions to data collection.

Walking alterations in adult spinal deformity depend on the type of deformity

Karl Semaan (1), Eddy Saad (1), Rami Rachkidi (1), Georges Kawkabani (1), Abir Massaad (1), Renée Maria Saliby (1), Mario Mekhael (1), Krystel Abi Karam (1), Marc Fakhoury (1), Elena Jaber (1), Ismat Ghanem (1), Gaby Kreichati (1), Wafa Skalli (2), Virginie Lafage (3), Ayman Assi (1,2)

(1) Laboratory of Biomechanics and Medical Imaging, Faculty of Medicine, Saint-Joseph University, Beirut, Lebanon

(2) Institut de Biomécanique Humaine Georges Charpak, Arts et Métiers ParisTech, Paris, France

(3) Spine division, Hospital for Special Surgery, New York, USA

Introduction: Adults with spinal deformity (ASD) are known to have spinal malalignment affecting their quality of life and walking kinematics. Radiological criteria for ASD classification are based on spinal malalignment either in the frontal (Cobb $>20^\circ$) and/or sagittal plane (TK $>60^\circ$, SVA >50 mm, PT $>25^\circ$). However, it is still unknown which spinal deformity component affects the gait pattern. We hypothesized that gait alterations in ASD would differ according to the type of spinal deformity. The aim was to evaluate kinematic alterations during walking in ASD with different types of spinal deformity.

Materials and Methods: This is a cross-sectional study that included 82 primary ASD (51 \pm 20y, 61F), age and sex-matched to 43 controls. All subjects underwent 3D gait analysis with subsequent calculation of the 3D lower limb, trunk and segmental spine kinematics as well as the gait deviation index (GDI: scored between 0 and 100 and decreases with severity). ASD were classified into 3 groups: 36 with sagittal malalignment (ASD-Sag: PT $>25^\circ$ and/or SVA >50 mm), 25 with only frontal malalignment (ASD-Front: Cobb $>20^\circ$) and 21 with only hyperkyphosis (ASD-HyperK: TK $>60^\circ$). Walking kinematics were compared between groups.

Results and discussions: ASD-Sag and ASD-HyperK had a decreased ROM pelvic obliquity (6 $^\circ$ vs 11 $^\circ$) and rotation (10 $^\circ$ vs 12 $^\circ$), and a decreased ROM of knee flexion/extension (54 $^\circ$ vs 61 $^\circ$) when compared to controls. However, only ASD-Sag showed a decreased ROM hip flexion/extension (38 $^\circ$ vs 45 $^\circ$) and lack of knee flexion in swing (54 $^\circ$ vs 62 $^\circ$). Furthermore, only ASD-Sag exhibited a decreased walking speed (0.8 vs 1.2m/s), cadence (98 vs 117step/min), step length (0.47m vs 0.64m) and GDI (80 vs 96, all $p<0.05$). GDI, knee flexion/extension and walking speed were determined by SVA and PT (adj-R 2 :0.28 to 0.55, fig.1).

Conclusions: Sagittal spinal malalignment seems to be the main driver of gait alterations in ASD. In fact, patients with higher SVA or PT tended to walk slower, with shorter steps in order to maintain stability, with a limited flexibility in the pelvis, hips and knees. These same changes were found to a lesser extent in ASD with only hyperkyphosis but not in those with only frontal malalignment. The patterns of walking alterations shown in this study highlight the importance of differentiating between ASD patients depending on the type of deformity.

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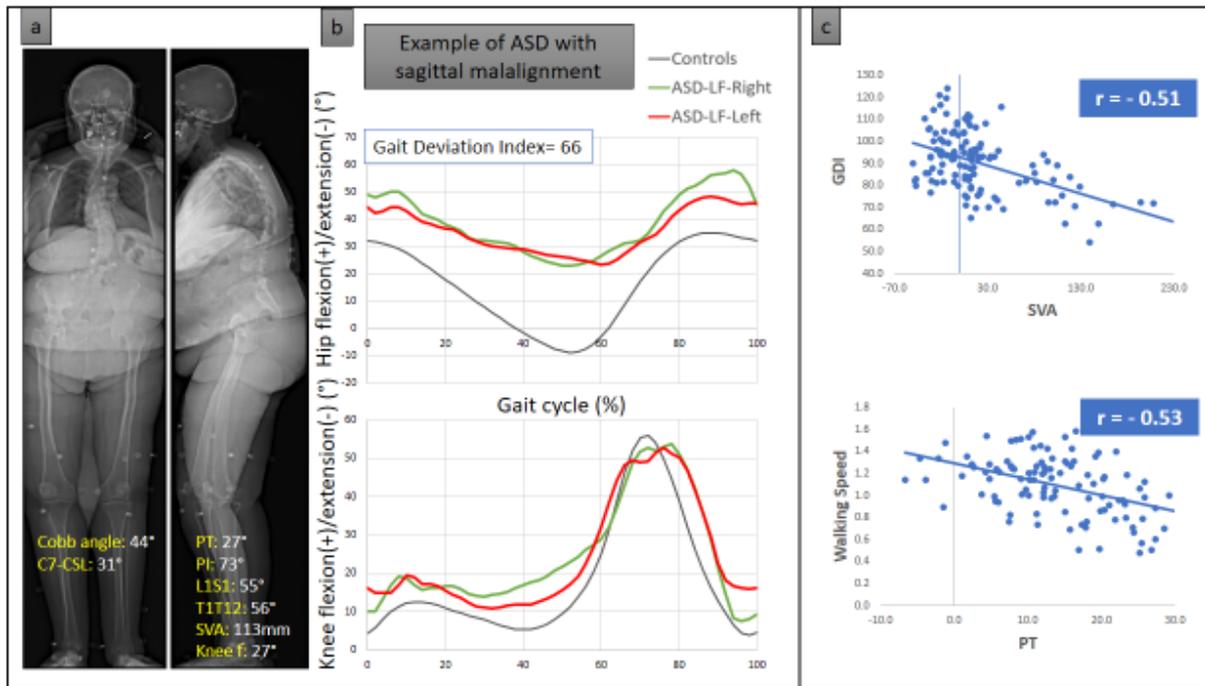


Fig.1- Altered kinematics in ASD (a) with sagittal malalignment during walking (b) and correlations with radiographic parameters (c).

Association Between Gait Alterations and Quality of Life in Patients with Adult Spinal Deformities

Renée Maria Saliby (1), Georges Kawkabani (1), Mario Mekhael (1), Abir Massaad (1), Eddy Saad (1), Rami Rachkidi (1), Ismat Ghanem (1), Khalil Kharrat (1), Gaby Kreichati (1), Virginie Lafage (2), Renaud Lafage (2), Wafa Skalli (3), Ayman Assi (1,3)

- (1) Laboratory of Biomechanics and Medical Imaging, Faculty of Medicine, Saint-Joseph University, Beirut, Lebanon
- (2) Spine division, Hospital for Special Surgery, New York, USA
- (3) Institut de Biomécanique Humaine Georges Charpak, Arts et Métiers ParisTech, Paris, France

Introduction: While numerous studies demonstrated the association between sagittal malalignment and quality of life, daily life activities consist of successive dynamic processes. Little is known about the potential association between gait alteration and patients reported outcomes in ASD.

Materials and Methods: ASD patients underwent a 3D gait analysis with reflective markers covering the trunk, pelvis, and lower limbs. Classic radiographic parameters in 2D and 3D were obtained from full-body images, and quality of life from SF-36, ODI, and VA scores. Determinants of clinical outcomes were investigated by multilinear and hierarchical regressions while controlling for demographics and static alignment.

Results and discussions: The 52 patients recruited (43yo,77%F) presented mild spinal deformity ($PI=53\pm 12^\circ$, $PT=19\pm 13^\circ$, $PI=2\pm 22^\circ$, $SVA=34\pm 60\text{mm}$) and moderate disability ($ODI=26$, $PCS=45$, $VAS=4.4$). While sagittal alignment correlated with HRQL, the strongest correlations were observed for walking speed and hip kinematics (figure 1). The multi-linear regressions predicting PCS and ODI revealed a stronger R^2 for gait parameters (resp 0.55 and 0.6) than radiographic parameters (resp 0.50 and 0.43). When controlling for age, weight, height, SVA and PI-LL, independent determinants of the quality of life scores were: mean hip internal/external rotation and pelvic ROM for PCS ($R^2 = 0.738$), and step length and mean hip abduction/adduction for ODI ($R^2= 0.735$).

Conclusions: This study demonstrated that while radiographic sagittal parameters and gait parameters are individually associated to patient reported outcomes, the combination of both static and dynamic analysis demonstrated a stronger association with HRQL compared to individual concept. These results emphasize the importance of functional evaluation, here illustrated by gait analysis, in ASD care. Improving radiographic and gait parameters simultaneously appears to be a promising way to enhance patients' quality of life.

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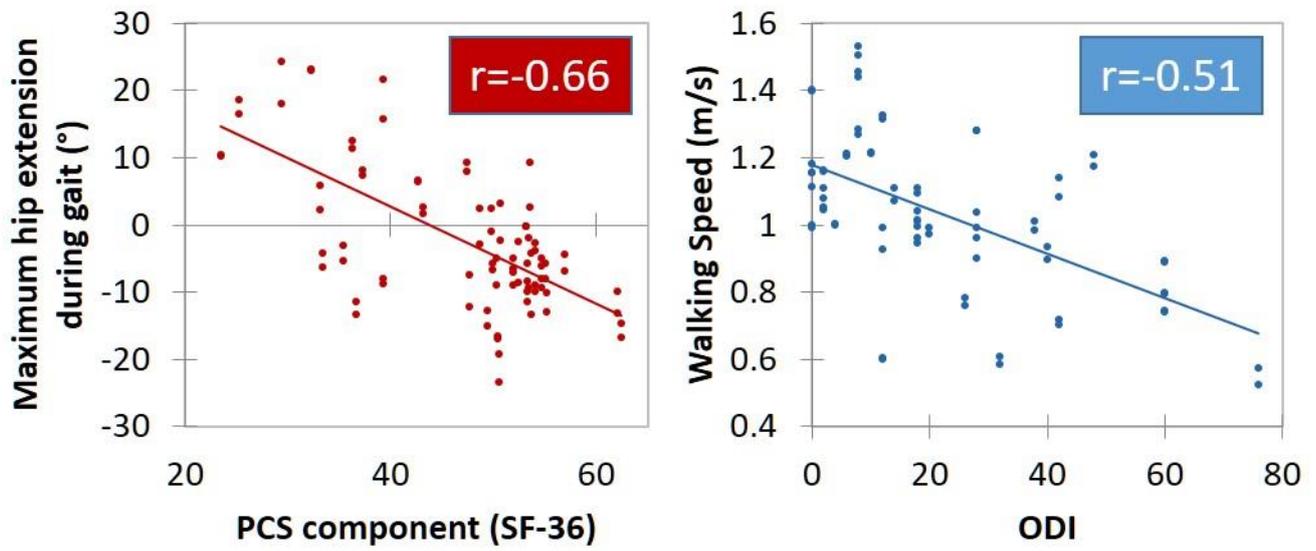


Figure 1- Correlation between HRQL scores and gait parameters

Alteration of the sitting and standing movement in adult spinal deformity

Eddy Saad (1), Karl Semaan (1), Georges Kawkabani (1), Abir Massaad (1), Renée Maria Saliby (1), Mario Mekhael (1), Marc Fakhoury (1), Krystal Abi Karam (1), Elena Jaber (1), Ismat Ghanem (1), Rami Rachkidi (1), Virginie Lafage (2), Wafa Skalli (3), Ayman Assi (1,3)

(1) Laboratory of Biomechanics and Medical Imaging, Faculty of Medicine, Saint-Joseph University, Beirut, Lebanon

(2) Spine division, Hospital for Special Surgery, New York, USA

(3) Institut de Biomécanique Humaine Georges Charpak, Arts et Métiers ParisTech, Paris, France

Introduction: Adults with spinal deformity (ASD) are known to have spinal malalignment affecting their quality of life (QoL) and daily life activities. While walking kinematics were shown to be altered in ASD, other functional activities are yet to be evaluated such as sitting and standing which is essential for patients' autonomy and quality of life perception. The aim of this study was to evaluate sitting and standing kinematics in ASD with different types of spinal deformity and their relationship with their QoL scores.

Materials and Methods: In this cross-sectional study, 60 ASD (52±20 years, 78%F) age and sex matched to 27 controls, underwent 3D motion analysis of the sitting and standing movement. All subjects filled the following QoL questionnaires: Short Form survey SF36 including the physical (PCS) and mental (MCS) components, Oswestry Disability Index (ODI) and Visual Analog Scale (VAS) for pain. ASD were further divided into ASD-Front (N=21, with only frontal malalignment: Cobb>20°), ASD-HyperK (N=16, with only hyperkyphosis TK>60°) and ASD-Sag (N=23, with PT>25° and/or SVA>5cm). The range of motion (ROM) and mean values of lower limbs, thorax, head and spinal segments were calculated on the kinematic waveforms during the sitting and standing movement. Kinematics were compared between the groups and correlations to QoL scores were computed.

Results and discussions: During the sit to stand and stand to sit movements, the ASD-Sag group had larger thorax flexion compared to controls (30 vs 17°). They had decreased lumbar flexion ROM (10 vs 14°), increased thorax flexion ROM (46 vs 36°) especially in the upper segment (C7T2-T2T10: 40 vs 13°) as well as an increased head flexion/extension ROM (27 vs 17°, all p<0.001). ASD-HyperK had similar but less pronounced results, while ASD-front were comparable to controls. Thorax flexion was positively correlated to VAS and ODI (both r=0.4) and negatively correlated to PCS (r=-0.4, all p<0.001). Upper cervico-thoracic sagittal ROM was negatively correlated to PCS (r=-0.4, p=0.01, figure 1).

Conclusions: ASD subjects with sagittal malalignment maintained a flexed trunk attitude during the sit to stand and stand to sit movements with a decreased lumbar ROM, compensating with a larger upper cervico-thoracic and head ROM. These kinematic alterations were correlated with the decreased QoL scores seen in these patients. These changes were found to a lesser extent in ASD with only hyperkyphosis but not in those with only frontal malalignment. This study showed that the sitting and standing movement is altered in ASD and is correlated to their quality of life deterioration, especially in those with sagittal malalignment, showing the importance of differentiation between ASD patients depending on the type of deformity.

USING MOTION ANALYSIS TECHNIQUES AND MUSCULOSKELETAL MODELING OF THE SPINE TO BETTER UNDERSTAND SPINAL DISORDERS AND EVALUATE TREATMENT EFFECTS

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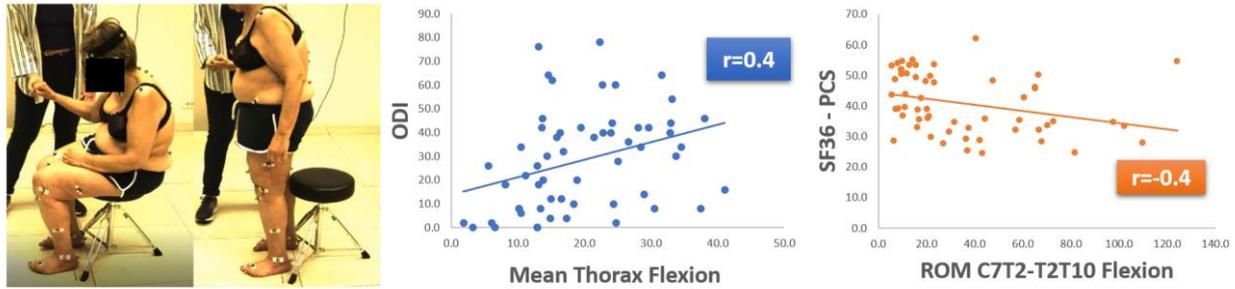


Figure 1- Correlation of the kinematics during the sit to stand movement to the quality of life scores.

Assessment of dynamic sagittal balance during walking in patients with adult spinal deformity

Guillaume Rebeyrat (1), Wafa Skalli (1), Abir Massaad (2), Hélène Pillet (1), Karl Semaan (2), Eddy Saad (2), Joe Mehanna (2), Ismat Ghanem (2), Rami Rachkidi (2), Ayman Assi (1,2)

- (1) Institut de Biomécanique Humaine Georges Charpak, Arts et Métiers ParisTech, Paris, France
(2) Laboratory of Biomechanics and Medical Imaging, Faculty of Medicine, Saint-Joseph University, Beirut, Lebanon

Introduction: Patients with adult spinal deformity (ASD) are known to have an altered quality of life (QoL) with restrictions in their daily life activities. Postural malalignment, such as increased SVA and PT, were shown to be strongly related to the deterioration of QoL in these patients. More recently, the radiographic angle between the odontoid to hip axis with the vertical (ODHA) has shown to be a reliable parameter to evaluate patient's sagittal balance. While postural malalignment is usually assessed on static radiographs, its evaluation during daily life activities, such as walking, can be beneficial in suggesting a functional evaluation for these patients that reflects their QoL concerns. The aim was to assess postural malalignment in ASD during walking by evaluating dynamic sagittal balance.

Materials and Methods: 47 ASD (49±22 years, 34F) and 46 controls (32±11 years, 20F) filled HRQoL questionnaires (SF36, ODI) and underwent gait analysis with calculation of joint range of motion (ROM). Subjects then underwent full-body biplanar Xrays in standing position, with the reflective gait markers still in place. Spinopelvic and postural parameters were calculated from 3D skeletal reconstructions, including radiographic ODHA (rODHA: (+) when the head is shifted forward), rSVA and rPT. Then, 3D bones were registered on each frame of gait in order to calculate the dynamic ODHA (dODHA), dSVA and dPT. Patients with high dODHA, dSVA and dPT (>2SD in controls) were classified as ASD with severe dynamic balance alterations (ASD-DBA), otherwise as ASD-nonDBA. Between group comparisons were investigated. The relationship between dynamic balance alterations and the radiographic parameters as well as the HRQoL outcomes and gait kinematics were explored.

Results and discussions: 12/47 patients were classified as ASD-DBA having an average dODHA during walking of 12.6° (ASD-nonDBA: 3.3°, controls: 2.5°), dSVA of 150mm (ASD-nonDBA: 47, controls: 41mm) and dPT of 26° (ASD-nonDBA: 16°, controls: 13°; all $p < 0.001$). On static radiographs, patients in the ASD-DBA group showed more severe postural & spinopelvic malalignment than ASD-nonDBA patients: rODHA= 3.8° vs -1.7°, rSVA=71 vs 1mm, knee flexion=12 vs 2.5°, rPT=21 vs 16°, LL=41 vs 59°. They also showed more altered HRQoL outcomes: PCS-SF36=33.5 vs 44.5, ODI=42 vs 20 (all $p < 0.001$). The ASD-DBA group had an overall abnormal walking compared to both ASD-nonDBA & controls: they walked with a reduced flexion/extension ROM at the hip (36° vs 43°) and knee (47° vs 60°), had a lower gait speed (0.8 vs 1.2m/s) and shorter step lengths (0.4 vs 0.7m, all $p < 0.001$). Dynamic postural alterations were correlated to QoL scores: dODHA & dPT to ODI ($r=0.50$ & 0.31 resp.), dSVA to PCS-SF36 ($r=-0.54$). The dynamic ODHA was positively correlated to rSVA (0.60), radiographic knee flexion (0.46), rPT (0.23), and negatively correlated to LL (-0.24). Moreover, the multivariate analysis showed that dSVA & dPT were determined (adj-R2=0.75 & 0.85 resp.) by static radiological SVA & PT (resp.), PI-LL mismatch and knee flexion/extension ROM (figure 1).

Conclusions: In normal physiological setting, the task of walking seems to move the head forward relatively to the pelvis by few degrees compared to the static position (from -1.8 to 2.5°). ASD patients with

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severe postural and spinopelvic alterations seem to have an unbalanced alignment of the head above the pelvis in standing position (3.8°) that is exaggerated during walking (up to 12.6°). Similarly, an increased dynamic SVA & PT were seen in these patients. Interestingly, these dynamic postural alterations correlate with the deterioration of QoL in these patients. Although these dynamic alterations are related to the static ones, the PI-LL mismatch and the reduced mobility of the knee seem to be associated with this aggravation. Surgical restoration of the spinal alignment and rehabilitation of the knee mobility may improve walking abilities in these patients and enhance their QoL. Postural alignment parameters such as SVA, PT and ODHA calculated on radiographs and during walking are a promising tool to assess static and dynamic balance in ASD.

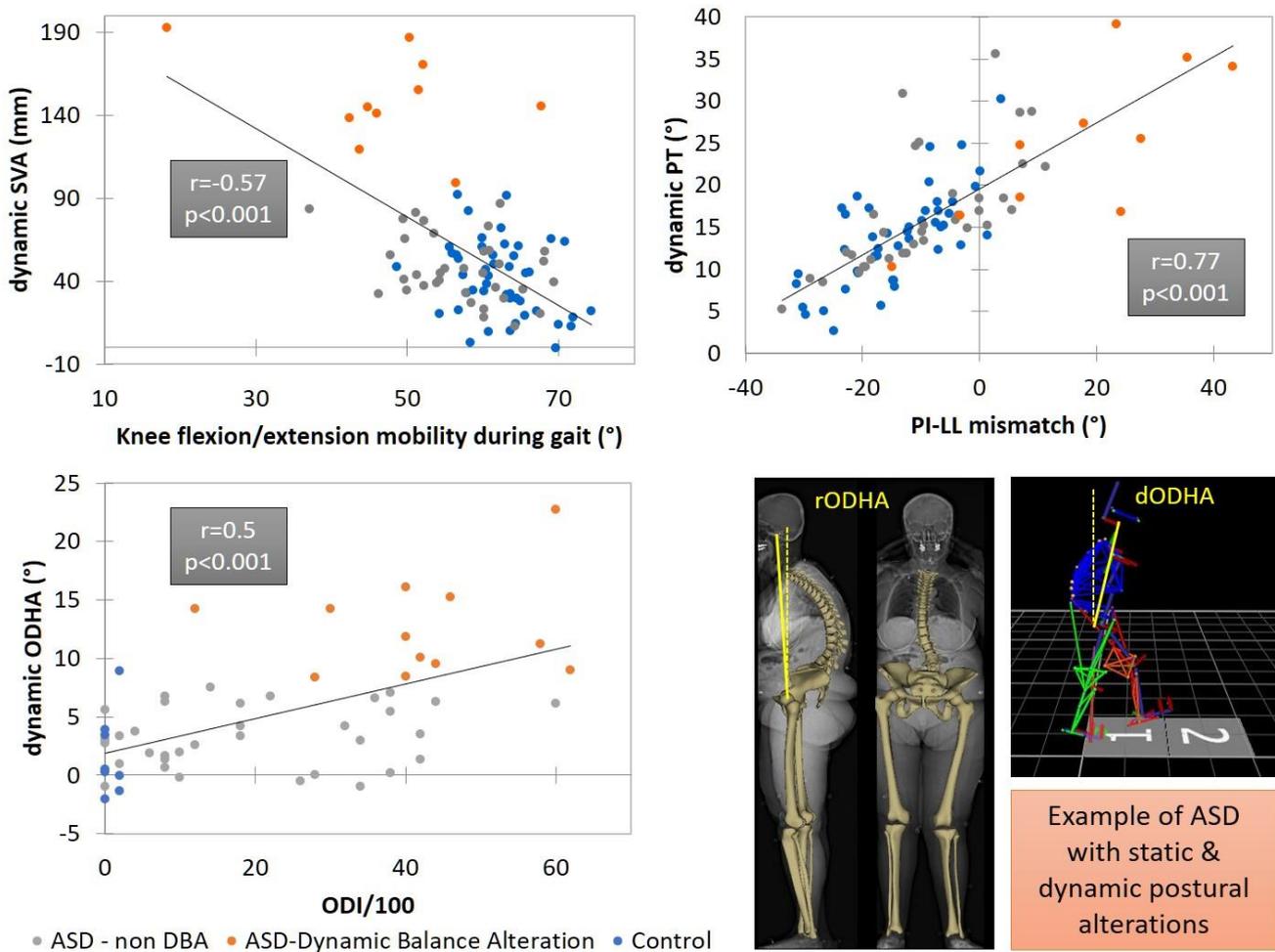


Figure 1- Correlations between dynamic postural alterations (dODHA, dSVA & dPT) with QoL scores, radiographic parameters, and gait kinematics.

SESSION 3

Clinical Applications and Interventions

Chair: Dennis Anderson

Patient Specific Variations in Local Strain Patterns on the Surface of a Trussed Titanium Interbody Cage

Arjan C.Y. Loenen, MSc^{1,2}, Claus Schaffrath, MD, MSc³, Jacobus J. Arts, PhD^{1,2}, and Bert van Rietbergen, PhD^{1,2}

1. *Laboratory for Experimental Orthopaedics, Department of Orthopaedic Surgery, CAPHRI, Maastricht University Medical Center, Maastricht, the Netherlands*
2. *Orthopaedic Biomechanics, Department of Biomedical Engineering, Eindhoven University of Technology, Eindhoven, the Netherlands*
3. *4WEB EU, Assendelft, the Netherlands*

Introduction: Although commonly used lumbar interbody fusion cages have a high success rate, several problems can occur, among which cage migration, cage subsidence and pseudarthrosis. The introduction of metal additive manufacturing techniques has enabled the production of a new generation of highly porous trussed titanium lumbar interbody fusion cages. Such cages can increase resistance to subsidence and enable bone ingrowth throughout the full implant. Furthermore, these implants can be designed such that the *in vivo* local strains at the truss surfaces are in a range that may promote an osteogenic response. The actual *in vivo* strains, however, depend on many factors, including the cage design, size and placement and patient-specific factors such as bone density and the loads applied. Finite element (FE) modeling can be used to investigate the effects of such factors on cage strain levels, but in most studies so far these were performed for idealized loading conditions or using a single patient model, which limits the generalizability of the results. The objective of this research is to determine patient specific variations in local strain patterns on the surface of a trussed titanium interbody fusion cage under physiological loading conditions using FE models of a small population of patients eligible for a spinal fusion operation.

Materials and Methods: Four patient specific finite element models of the total lumbar spine (L1-S1) were derived from a previously established database consisting of patients suffering from lower back pain.^{1,2} The original models consisted of poro-elastic intervertebral discs with Pfirrmann grade-dependent material parameters, linear elastic bone tissue with Young's moduli related to the local bone density, and the seven major ligaments per spinal motion segment modeled as unidirectional, non-linear materials. The models were adjusted to represent a L4-L5 posterior lumbar interbody fusion surgery, *i.e.* following laminectomy and resection of the intervertebral disc, two trussed titanium interbody cages were positioned and a pedicle screw-rod construct was implemented. All patient specific models were subjected to a compressive follower load combined with a pure moment to simulate physiological flexion-extension movement. Local strain values at the surface of the cage, as well as functional dynamics of the total lumbar spine segment were quantified for each individual patient.

Results and discussions: <work in progress> Resulting load-deflection curves of the total lumbar spine segment and of each individual functional spinal unit showed the expected behavior, indicating load carrying of the cages, but considerable differences in range of motion were found between the four patients. Local strain patterns at the surface of the trussed titanium cages varied in distribution and magnitude with load case and patient case (order of absolute local strains: 0-1000 $\mu\epsilon$). Similar trends could be observed for the contact pressure of the cages on the vertebral endplates (order of contact pressures: 0-40 MPa). Fig. 1 shows how the strain patterns on the surface of the cage varied with load cases within one patient. In the stance position, absolute strain values hardly exceed the value of 100 $\mu\epsilon$. In extension and flexion movement, the strains increase at the posterior and anterior site of the cage, respectively. Especially in the flexed spine, relevant surface strains start to arise. <work in progress>

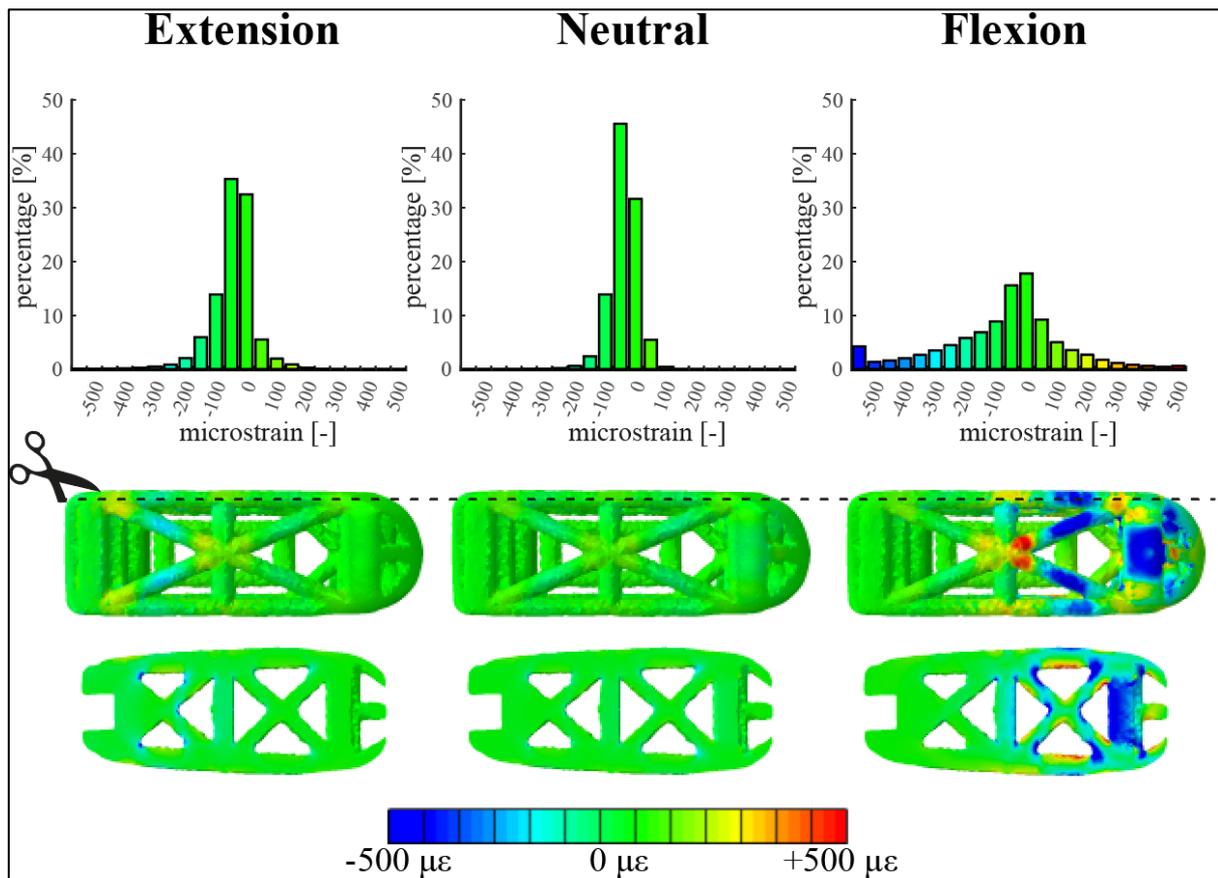


Figure 1. Visualization and quantification of the local strain patterns on the surface of the trussed interbody fusion cage for one patient in different load cases.

Conclusions: <work in progress> Local strain patterns in a trussed titanium interbody fusion cage vary considerable within the cage and between patients. In all cases, however, at least in some regions of the cage the strains were in a range that is known to promote bone formation. By combining the results for the four patients, it may be possible to develop a modified unique design with a more homogenous strain distribution. Alternatively, in case pre-operative CT scans are available, it may be possible to make patient-specific designs that are tailored to stimulating bone formation. <work in progress>

Acknowledgment: The research for this paper was financially supported by the Prosperos project, funded by the Interreg VA Flanders-the Netherlands program, CCI grant no. 2014TC16RFCB046. Additionally, we acknowledge the MYSPINE project (no. 269909) funded from the European Union Seventh Framework Program for access to the existing patient database.

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Acute effects of a single bout of a game-based real-time biofeedback training on 3D trunk movement in patients with chronic non-specific low back pain

Juliane Mueller^a, Daniel Niederer^b, Sarah Tenberg^a, Lukas Oberheim^a, Alina Moesner^a, Steffen Mueller^a

^a Professorship for Physiotherapy: Exercise Science and Applied Biomechanics, Department of Computer Science – Therapy Sciences, Trier University of Applied Sciences, Germany

^b Department of Sports Medicine and Exercise Physiology, Goethe University Frankfurt, Frankfurt am Main, Germany

Introduction: Improving movement control might be a promising treatment goal during chronic non-specific low back pain (CLBP) rehabilitation. As external (bio)feedback is needed for this therapy approach, new health technologies based on movement sensors, in combination with game-based tasks, are promising. This study evaluated the acute effects of a single bout of game-based real-time feedback intervention on 3D trunk movement in patients with CLBP.

Materials and Methods: Thirteen (8 female, 5 male) patients with CLBP (41±16 years; 173±10 cm height; 78±22 kg body weight; VAS LBP 3.3±2.5 cm) were included in this randomized cross-over trial with two arms (intervention/rest-time).

All participants performed three identical measurements (M1/M2/M3) focusing on trunk movement in lateral flexion during upright standing: first, maximum movement of the trunk in lateral flexion was assessed (3 repetitions in both directions (right/left)). Secondly, a target trunk movement to an angle of 20° in lateral flexion was performed (angle reproduction, 10 repetitions in each direction (right/left)). In between the three measurements (M1/M2/M3), the 12-min intervention and the 12-min-rest-time was undertaken in random order; no additional wash out time was included. The game-based real-time feedback intervention was applied using a sensor-based movement game. The intervention included movements in flexion/extension, lateral flexion as well as trunk rotation while participants were guiding an avatar through different worlds with an individualized range of motion.

The main outcomes (assessed at M1/M2/M3) were maximum trunk range of motion (°; RoM; 3 repetitions) in lateral flexion as well as the deviation [°] from a target trunk angle of 20° (mean deviation) in lateral flexion (right/left). In addition, the RoM (°) of the secondary movement planes (rotation; extension/flexion) were analyzed during maximum lateral flexion movement. The outcomes were measured by use of a skin marker-based 16-camera optical 3D motion capture system, using a 2-segment-model consisting of 15 markers (upper trunk, lower trunk).

During the entire protocol, back pain was monitored by visual analogue scale (0-10cm; assessment in regular intervals; VAS >7cm = termination criterion).

Firstly, the measured data were analyzed for a potential carryover effect between the two periods (rest - intervention): the sums of the measured outcome values after each period (M2/M3) are calculated and an unpaired t-test for group comparison was applied. Secondly, pre-to-post intervention data were pooled and analyzed by one-way analyses of variances (dependent samples) to account for acute interventional effects.

Results and discussions: For the main outcomes no significant carryover effects were present ($p > 0.05$). In addition, no significant change from pre to post intervention for angle reproduction or maximum RoM (e.g. lower trunk segment; right side/lateral flexion: 10.3°±4.9° (pre) / 9.4°±4.4° (post)) for both segments occurred

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($p > .05$). Besides, the upper trunk segment showed a significant reduction of RoM for trunk extension/flexion (sagittal plane) from pre to post intervention ($4.4^\circ \pm 4.4^\circ / 3.5^\circ \pm 1.29^\circ$; $p=0.02$).

Conclusions: Although no acute intervention effect could be found for trunk motion analysis in the main movement plane (lateral flexion), the changes of the secondary movement planes might indicate reduced evasive motion (rotation; flexion/extension) and therefore, represent improved trunk motion control in patients with CLBP even after a single bout of a game-based real-time biofeedback training.

Accounting for biomechanical measures does not enhance the prediction of curve progression in adolescent idiopathic scoliosis

Tito Bassani¹, Andrea Cina¹, Dominika Ignasiak², Noemi Barba³, Fabio Galbusera¹

¹IRCCS Istituto Ortopedico Galeazzi, Milan, Italy. LABS, Laboratory of Biological Structures Mechanics

²Institute for Biomechanics, ETH Zurich, Zurich, Switzerland

³Department of Chemistry, Materials and Chemical Engineering “Giulio Natta”, Politecnico di Milano, Milan, Italy

Introduction: Adolescent idiopathic scoliosis (AIS) is a three-dimensional deformity of the spine occurring in the general population with prevalence between 2 and 3%. A major clinical challenge is the difficulty of predicting curve progression at initial presentation. The early detection of progressive curves can indeed offer the opportunity to better target effective non-operative treatments, reducing the need for surgery and the risks of related complications. Recently, predictive models for the early detection of scoliosis progression in subjects before growth spurt have been developed. These models accounted for geometrical parameters describing the global spine and local descriptors of the scoliotic curve, but neglected potential contributions from biomechanical measures such as trunk muscle activation and intervertebral loading, which could provide additional advantageous information.

Materials and Methods: The present study exploits a musculoskeletal model of the thoracolumbar spine with articulated ribcage, developed in AnyBody software and recently adapted and validated for the subject-specific characterization of the spinal alignment in mild scoliosis. A dataset of 100 AIS subjects with mild scoliosis and in pre-pubertal age at first examination, and recognized as stable (60) or progressive (40) after at least 6-months follow-up period was exploited. Anthropometrical data and geometrical parameters of the spine (describing the global spine and the 3D shape of the primary scoliotic curve) at first examination, as well as biomechanical parameters (trunk muscle activation and intervertebral force inside the curve) from musculoskeletal modelling replicating the spinal alignment in standing position, were accounted for as possible predictors of the progression of scoliosis. Six predictive modelling approaches based on different algorithms for the binary classification of stable and progressive cases were compared. The best fitting approaches were exploited to evaluate the effect of accounting for the biomechanical parameters on the prediction of the scoliosis progression. The classification performance between two sets of predictors was compared: accounting for anthropometrical and geometrical parameters only; considering in addition the biomechanical ones.

Results and discussions: The median accuracy of the best fitting algorithms ranged from 0.76 to 0.78. No differences were found in the classification performance by including or neglecting the biomechanical parameters. The median sensitivity was 0.75, and that of specificity ranged from 0.75 to 0.83.

Conclusions: Accounting for biomechanical measures from musculoskeletal modelling did not enhance the prediction of curve progression, thus not supporting a potential clinical application at this stage.

Biomechanical Analysis of Complications Following T10-Pelvis Spinal Fusion: A Population Based Computational Study

Christian Rodriguez¹, Rachit Kumar¹, Sachin Gupta¹, Dennis Anderson², Comron Saifi¹

¹ University of Pennsylvania, Philadelphia, PA, USA; ² Beth Israel Deaconess Medical Center, Boston, MA, USA

Introduction: Proximal junctional kyphosis (PJK) and failure (PJF) are challenging complications of long fusion constructs for the treatment of adult spinal deformity. Few studies have investigated the biomechanics of long spinal fusions, none of which accounted for anatomical variation. This study seeks to use a large cohort to understand the biomechanical stresses proximal to the upper instrumentation of a T10-pelvis fusion.

Materials and Methods: The pre-fusion models were subject-specific thoracolumbar spine models that incorporate the height, weight, spine curvature, and muscle morphology measurements of 250 individuals from the Framingham Heart Study Multidetector CT Study. To create post-fusion models, the subject-specific models were further modified to eliminate motion between the intervertebral joints from T10 to the pelvis. Simulated static postures included neutral standing, axial rotation, trunk flexion, and 'pushing a force'. Both increased segmental mobility and unchanged segmental mobility were modeled for each simulated motion. OpenSim analysis tools were used to calculate the medial lateral shear force, anterior posterior shear force, and compressive force on the T9 vertebra during the static postures.

Results and discussions: Differences between pre-fusion and post-fusion T9 biomechanics were consistent between increased segmental mobility and unchanged segmental mobility conditions. For all static postures, compression decreased ($p < 0.001$). Anterior-posterior shear force significantly increased ($p < 0.001$) during axial twist and significantly increased ($p < 0.001$) during trunk flexion. Medial lateral shear force significantly increased ($p < 0.001$) during axial twist.

Conclusions: This computational study provided the first use of subject-specific models to investigate the biomechanics of long spinal fusions. Patients undergoing T10-Pelvis fusion were predicted to have increased shear forces and decreased compressive force at the T9 vertebra, independent of change in segmental mobility. Despite its limitations, this computational model shows potential for the investigation of spinal fusion biomechanics in order to reduce the risk of PJK or PJF.

Table 1: Population Based Cohort Summary Information

	Men (n=125)		Women (n=125)		All (n=250)	
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
Age (years)	64.7 ± 14.0	41-88	64.3 ± 13.6	43-90	64.5 ± 13.8	41-90
Height (m)	1.74 ± 0.07	1.59-1.92	1.60 ± 0.06	1.47-1.76	1.66 ± 0.10	1.59-1.92
Mass (kg)	85.2 ± 14.2	47.2-122.9	70.7 ± 14.8	43.5-127.0	77.9 ± 16.2	43.5-127.0
Body mass index (kg/m ²)	28.1 ± 4.2	16.0-40.0	27.6 ± 5.7	16.2-49.5	27.9 ± 5.0	16.0-49.5
T ₄ /T ₁₂ Cobb angle (°)	33.6 ± 9.0	14.4-53.0	37.1 ± 10.0	14.8-61.4	35.3 ± 9.7	14.4-61.4
L ₇ /L ₄ Cobb angle (°)	-15.3 ± 8.0	-38.2-3.8	-19.4 ± 10.7	-46.2-3.8	-17.4 ± 9.6	-46.2-3.8

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Table 2: Descriptive Statistics of Spinal Loading Forces

Force Direction	Posture	Unfused Model Force (N)	Fused Model Force (Decreased Spine Angle) (N)	Fused Model Force (Maintained Spine Angle) (N)
Vertical Compression	Standing	351.4 (82.3)	324.4 (65.1)	--
	Axial Twist	1583.5 (151.0)	1169.6 (159.6)	1162.7 (145.0)
	Trunk Flexion	889.2 (148.5)	735.4 (128.8)	719.3 (129.1)
	Pushing a Force	584.3 (89.2)	475.1 (95.1)	--
Anterior-Posterior Shear	Standing	-16.2 (27.8)	-10.4 (35.2)	--
	Axial Twist	23.2 (110.0)	204.3 (119.1)	169.0 (115.5)
	Trunk Flexion	93.3 (54.4)	143.7 (76.1)	133.8 (76.4)
	Pushing a Force	-74.7 (36.0)	-34.0 (52.0)	--
Medial-Lateral Shear	Standing	-0.0395 (0.346)	-0.00883 (0.114)	--
	Axial Twist	-115.8 (27.4)	-157.1 (35.2)	-234.8 (44.3)
	Trunk Flexion	-1.09 (1.81)	-0.779 (1.66)	-0.692 (1.62)
	Pushing a Force	-0.728 (1.46)	-0.148 (0.684)	--

All values reported as Mean (Standard Deviation)

For anterior-posterior shear, anteriorly directed shear forces are positive. For medial-lateral shear, leftward shear forces are positive.

Table 3: Post-Fusion Changes in Spinal Loading

Force Direction	Posture	Force (N) Change After Fusion (Decreased Spine Angle)	Force (N) Change After Fusion (Maintained Spine Angle)
Vertical Compression	Standing	-27.0 (2.9)**	--
	Axial Twist	-414.0 (11.3)**	-420.9 (10.3)**
	Trunk Flexion	-153.8 (7.2)**	-169.9 (7.1)**
	Pushing a Force	-109.2 (3.7)**	--
Anterior-Posterior Shear	Standing	-5.9 (1.1)**	--
	Axial Twist	181.1 (5.2)**	145.9 (5.2)**
	Trunk Flexion	50.3 (2.8)**	40.4 (3.0)**
	Pushing a Force	-40.7 (1.8)**	--
Medial-Lateral Shear	Standing	-0.0306 (0.020)	--
	Axial Twist	41.1 (2.0)**	119.0 (2.4)**
	Trunk Flexion	-0.312 (0.128)*	-0.399 (0.133)*
	Pushing a Force	-0.579 (0.084)**	--

All values reported as Mean (Standard Error)

For anterior-posterior shear, anteriorly directed shear forces are positive. For medial-lateral shear, leftward shear forces are positive.

* = $p < 5 * 10^{-2}$ for comparison of difference to 0 N (alpha not adjusted for multiple comparisons)

** = $p < 5 * 10^{-4}$ for comparison of difference to 0 N (alpha conservatively divided by 100 to correct for multiple comparisons, of which there were 18)

Biomechanical Evaluation of the Effect of Minimally Invasive Spine Surgery Compared with Traditional Approaches in Activities-of-Daily- Living

John Rasmussen¹, Kristoffer Iversen², Bjørn Keller Engelund², Sten Rasmussen³

¹Department of Materials and Production, Aalborg University, Aalborg, Denmark

²AnyBody Technology A/S, Aalborg, Denmark

³Department of Clinical Medicine, Aalborg University, and Aalborg University Hospital, Aalborg, Denmark.

Introduction: Lumbar spinal fusion is a surgical procedure where two or more of the spinal vertebrae are fused by means of mechanical devices and bone grafts. Presuming that the recovered patient will resume activities of daily living, the motion and load that previously took place between the fused vertebrae will be redistributed among adjacent spinal joints, possibly leading to increased loads on neighboring structures.

This paper investigates, by means of a computational model, Traditional Open Spine Surgery with a posterior approach (TOSS) versus Minimally Invasive Spine Surgery (MISS). Fascicles of the spinal musculature, such as m. erector spinae and m. multifidus that originate or insert on the fused bones, are generally sacrificed in TOSS, and the same is often the case for fascicles that cross the site at oblique angles, because they cannot be displaced sufficiently during the surgery. In the presence of a rigid, solid connection between the formerly articulating vertebrae, it is tempting to think that the local musculature is redundant and that its resection has little or no consequence. However, the biomechanical system of spinal muscles is complex with a multitude of fascicles spanning single or multiple joints to articulate and stabilize the spinal column. It is therefore likely that resection of the local muscles has consequences beyond the site.

Epidemiological studies typically do not have the resolution to distinguish between the details of the surgery and conditions in the individual patients, and statistics offer little to the causality of observed complications for each patient. Consequently, computer models have been used to make in-silico comparison of TOSS versus MISS. These models as well as the experimental techniques to measure human motions continue to evolve. The contribution of this paper is therefore to combine contemporary measurement and simulation techniques to investigate the consequences of MISS versus TOSS, and to do so in the context of activities-of-daily living represented by box lifting under a variety of circumstances.

Materials and Methods: A single, healthy subject (male, age 29, stature 1.89m, body weight 82kg) lifted boxes weighing 10 kg from the floor to two different heights of (A) 59 cm and (B) 158 cm respectively in a sagittal plane motion, and subsequently (C) from the floor to 59 cm height in a movement from left to right. The three motions are illustrated in Fig. 1.

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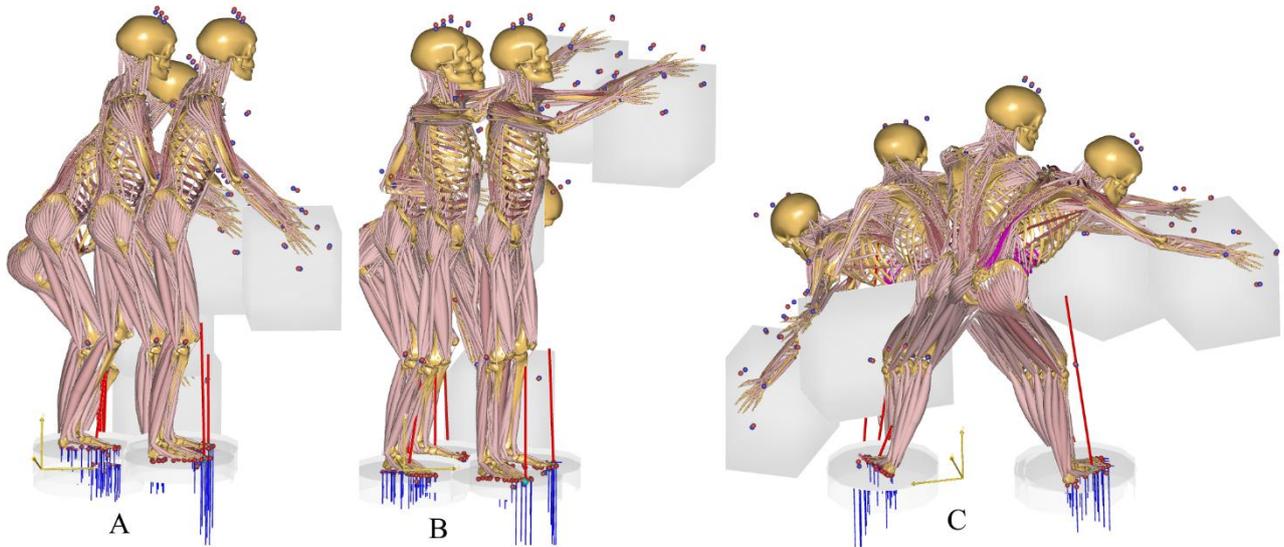


Figure 1. The three box lifting cases. A: from the floor to 59 cm height. B: from the floor to 158 cm height. C: sideways from the floor to 59 cm height.

Results and discussions: Preliminary results, which are still being processed, reveal a relatively small influence of either surgical approach in the spinal joint loads in the sagittal plane movements, A and B. However, in the sideways lifting case C, the fused spine exhibits significantly larger joint reactions and shown in Fig. 2.

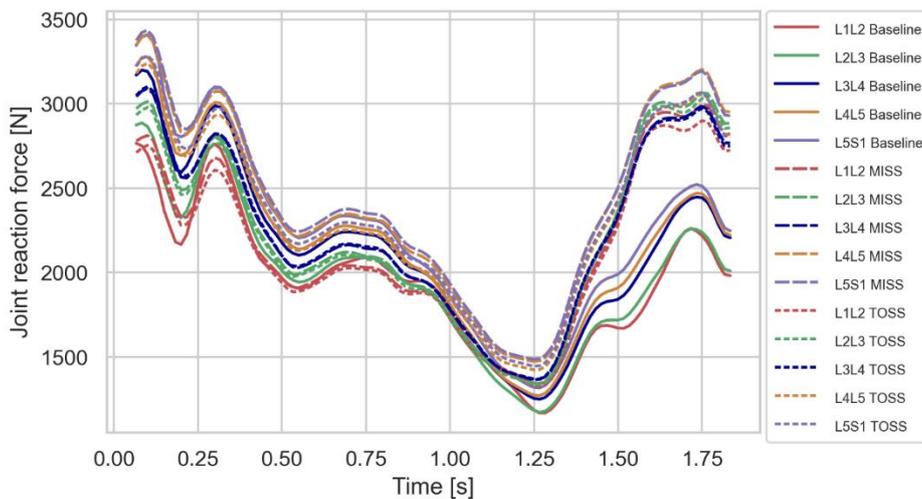
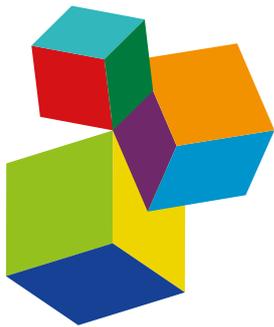


Figure 7. Joint reaction forces in lifting case C for the baseline case and fusion of L3L5 in MISS and TOSS cases respectively.

Conclusions: Preliminary results indicate larger influence of the fusion in non-sagittal plane movements. The difference between the surgical approaches remains to be deduced from the analysis results.

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