XVII International Symposium on Computer Simulation in Biomechanics
July 28th – 30th 2019, Alberta, Canada

SUBJECT SPECIFIC MULTISCALE MODELLING FOR THE STUDY OF LUMBAR PATHOLOGIES

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INTRODUCTION

Spinal pathologies such as lower back pain or scoliosis are common debilitating conditions. Little is known about their development, but it is believed that the mechanical environment of the spine plays an important part in the way they progress. Computational approaches are a promising technique to study the mechanical aspect of these pathologies, as they allow time dependent hypothesis testing without putting the patient at risk. In order to investigate how spine structures deform and adapt to their mechanical environment, a multiscale simulation pipeline coupling musculoskeletal (MSK) and finite element (FE) modelling was developed. The preliminary results presented here indicate how spinal structures can adapt to a loading envelope representative of activities of daily life for a healthy subject. A first case study of bone remodeling under altered loading potentially induced by back pain in the lumbar region is also presented.

METHODS

The modelling pipeline combines a full body MSK model and a structural FE model of the lumbar spine, both based on data from a single healthy male volunteer with no spinal medical history. To ensure consistency and compatibility between the two models, muscle insertions, muscle moment arms, bone geometries and joint locations are derived from MRI images of the full body at high resolution (pixel size: 1.41mm, slice thickness: 1mm). Full body kinematics were recorded using a passive optical motion capture system (Vicon Nexus) with a comprehensive marker set of 77 markers for a range of tasks involving movements of the spine representative of an active lifestyle. Activities include walking at normal pace, walking up and down stairs, sit-to-stand and stand-to-sit, and lifting tasks with twisting movements of the spine in both standing and sitting positions. Surface electromyography (sEMG) was used to record activations of 14 muscles of the lower limbs and lumbar spine during these tasks.

The MSK model is developed in OpenSim and composed of 23 rigid bodies with a total of 43 degrees of freedom (DOF). The lumbar spine has five articulated vertebrae linked to a three-segment thoracic and cervical spine. Each lumbar joint is modelled as a 3-DOF rotational joint with a bushing element to account for the intervertebral disc stiffness [1]. Upper limbs are included for mass properties. 564 muscle actuators represent 94 muscles of the lower limbs and lumbar spine.

To estimate muscle and joint reaction forces for the recorded movements, a MSK simulation pipeline is used. Inverse kinematics and inverse dynamics provide joint angles and moments. A static optimization (SO) problem consisting in minimizing the sum of the muscle activations squared is then solved to estimate muscle forces. A joint reaction forces (JRF) analysis is finally performed to compute contact forces and moments in the joint structures. The MSK model is assessed by comparing the computed muscle activations with the recorded sEMG signals and the calculated JRF with in-vivo measurements from the literature [2-4]. The estimated muscle forces and JRF are used as loading conditions for the FE model.

The FE model is developed in Abaqus with a structural approach, which is believed to be more physiologically relevant and computationally efficient than traditional continuum modelling. Cortical bone is modelled using shell elements with an initial uniform thickness and trabecular bone is represented by a randomized network of truss elements with an initial uniform radius and a minimum connectivity of 16. The structure of the bone is then optimized to withstand the loads applied to the vertebrae using the bone adaptation algorithm developed in the research group [5-8]. A free boundary condition approach [9,10] based on the kinematic degrees of freedom and forces obtained from the MSK simulations is used to load the vertebrae. By using a loading envelope based on a wide range of everyday life activities, the bone structure obtained after adaptation is representative of healthy bone.

This healthy bone model is the starting point of the first case study presented here. For this case study, it is assumed that a patient suffering from low back pain will opt not to routinely perform lifting tasks. This will alter the mechanical environment of vertebrae. Bone adaptation is performed using the healthy vertebrae as a starting point with this altered loading envelope to study how bone would remodel and adapt in this low back pain scenario.

RESULTS AND DISCUSSION

The MSK model has been assessed and can be used for further simulations in the current combined approach. JRF obtained from MSK simulations are in agreement with in-vivo measurements from the literature for static positions of the spine (flexion, extension, lateral bending and axial rotation) with a maximum relative error of 16% for lateral bending at L4-L5. Muscle activations estimated during MSK simulations broadly follow the activation pattern from sEMG signals.

Adapted vertebrae obtained with the bone adaptation algorithm for the healthy scenario show a main structural pattern, where the trabecular elements with larger radii are oriented vertically to withstand the compressive load in standing positions. A secondary pattern of elements withstanding medio-lateral and antero-posterior forces generated by the lumbar muscles during lifting tasks can be seen in the pedicles and transverse processes. Trabecular elements with smaller radii are also present throughout the vertebrae with no particular orientation (Fig 1A, 1B).

In the back pain scenario, the vertebrae are not loaded for lifting tasks anymore. The bone is less stimulated and trabecular elements reduce in size and number in the pedicles and transverse processes. Trabecular elements of the lamina and articular processes have been removed by the adaptation algorithm (Fig 1B, 1C). This suggests that avoiding lifting activities when suffering from low back pain can lead to weakness of the bone in these regions.

CONCLUSIONS

The simulation pipeline developed in this study combines multiscale modeling techniques for a patient specific approach. It already shows potential applications for predicting bone remodeling under mechanical loadings specific to pathological conditions, and will be used in other case studies on spinal conditions and aging.

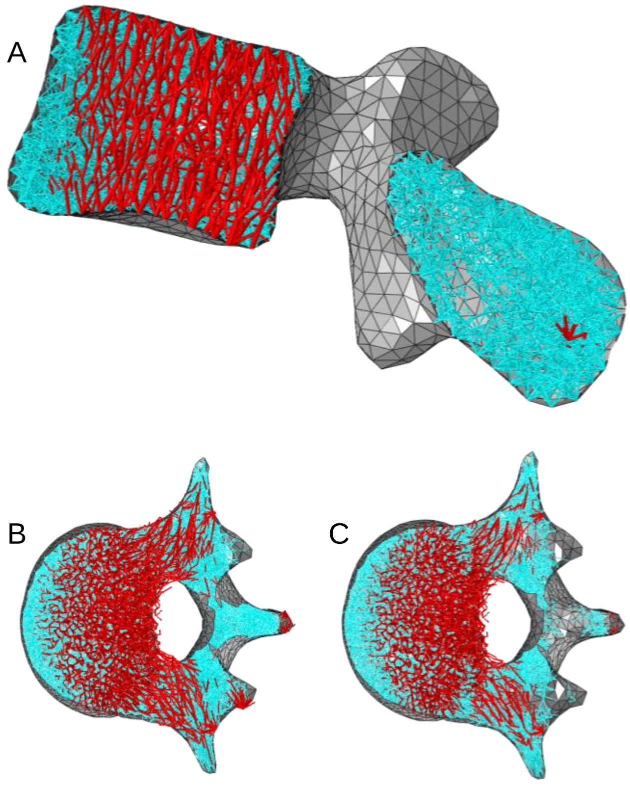

Fig 1: Lumbar 4. (A: medial view, adapted in a healthy scenario. B: proximal view, adapted in a healthy scenario. C: proximal view, adapted in the back pain scenario.) Cortical bone is in grey. Trabecular elements of smallest radius are in blue. Trabecular elements of larger radius are in red.

REFERENCES

1. Christophy M et al., *Multibody Syst Dyn*, **30**(4):413-432, 2012.
2. Wilke HJ et al., *Spine*, **24**:755-762, 1999.
3. Rohlmann A et al., *J Biomech*, **33**(11):1170-79, 2008.
4. Schultz A et al., *Spine*, **7**:390-397, 1982.
5. Phillips ATM, *Eng Comp Mech*, **165**(2):147-154, 2012.
6. Phillips ATM, et al., *Int Biomech*, **2**(1):43-61, 2015.
7. Villette CC, et al., *Biomech Model Mechanobiol*, **16**(6):2077-91, 2017.
8. Zaharie DT, et al., *J Biomech Eng*, **140**(9):1001-12, 2018.
9. Phillips ATM, *Med Eng Phys*, **29**(7):739-748, 2007.
10. Phillips ATM, et al., *Med Eng Phys*, **31**(6):673-680, 2009.

ACKNOWLEDGEMENTS

This study is funded by a Skempton Scholarship from the Department of Civil and Environmental Engineering at Imperial College London.