G Model
JAB 149 No. of Pages 8
ARTICLE IN PRESS
Journal of Applied Biomedicine xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Journal of Applied Biomedicine
journal homepage: www.elsevier.com/locate/jab

Original Research Article

Biomechanical evaluation of human lumbar spine in spondylolisthesis

Kamil Joszko[a], Marek Gzik[a], Wojciech Wolański[a], Bożena Gzik-Zroska[b], Edyta Kawlewska[a,*]

[a] Silesian University of Technology, Faculty of Biomedical Engineering, Department of Biomechatronics, Zabrze, Poland
[b] Silesian University of Technology, Faculty of Biomedical Engineering, Department of Biomaterials and Medical Devices Engineering, Zabrze, Poland

ARTICLE INFO

Article history:
Received 4 July 2016
Received in revised form 7 June 2017
Accepted 12 October 2017
Available online xxx

Keywords:
Spondylolisthesis
Dynamic model
Lumbar spine
Multibody
Madymo

ABSTRACT

One of the least known conditions of the lumbar spine in terms of biomechanics is spondylolisthesis which causes many serious consequences for the patient. This research aimed to perform a mechanical analysis of the origins of spondylolisthesis and its impact on the biomechanics of the lumbar section of the spine. Within the framework of this study, a physiologically model of the lumbar spine was created in the MADYMO software. In the next stage a slip of vertebra L4 was simulated by means of a controlled forward displacement of the vertebral body of vertebra L4. 10 variants of spondylolisthesis (W1–W10) of different degrees were subjected to a biomechanical evaluation. In maximum bending of the physiological spine at an angle of 27° the value of the shear force amounted to 1.9 kN, while for the spine affected by spondylolisthesis with slip grade W9 at the maximum bending of 34° the shear force amounted to 5.5 kN. It was observed that the lumbar spine with the simulated spondylolisthesis had greater mobility in comparison with the physiological spine, which was shown by maximum bending angles (physiological 27°, W9 34°).

Introduction

Research premises

Health ailments connected with the spine are mainly caused by the degeneration of the intervertebral disc, joints surfaces and post-traumatic changes. Despite numerous studies, the diseases of the spine still pose a major problem. Moreover, it is expected that with the further civilization development and ageing society such illnesses will only continue to grow. The research of the lumbar section of the human spine is a frequent subject of scientific deliberations. The interest in this field has increased also in Poland in the past years. Nevertheless, there are still many issues connected with the lumbar spine which remain unsolved. The authors were motivated to undertake the research on this issue by the mass occurrence of pain and ailments in the lumbar spine in patients. This condition is connected with technological development and related lifestyle, prolongation of working hours and lack of active leisure. In spite of many educational programmes aiming to increase the public awareness in this scope, the pain of the back is one of the most common reasons for seeing the doctor. One of the most frequent conditions occurring in the lower section of the spine is spondylolisthesis, which is a form of a chronic instability of the vertebral column. It consists in the displacement of the column of vertebrae in relation to the vertebra located below it (Hanson et al., 2002; Labelle et al., 2004; Natarajan et al., 2003; Sairyo et al., 2001). The etiology of its occurrence in terms of biomechanics has not been fully studied yet. The knowledge of the mechanism of its origin will have a vital importance for the improvement of treatment of such conditions.

Objective of this work

The objective of the research was defined as follows: to determine forces occurring in this segment of the spine for different degrees of progression of the vertebral body slip. In order to implement this objective, a dynamic model of the human lumbar spine was developed using a method of multibody systems. The determination of spinal loads in dynamic conditions enabled a better understanding of the mechanism of spondylolisthesis occurrence. Performed researchers were carried out with the cooperation with neurosurgeon, who indicates the specific patient with isthmic spondylolisthesis on the L4–L5 level. According to the

* Author for correspondence: Silesian University of Technology, Faculty of Biomedical Engineering, Department of Biomechatronics, Roosevelta 40, 41-800 Zabrze, Poland.
E-mail address: edyta.kawlewska@polsl.pl (E. Kawlewska).

https://doi.org/10.1016/j.jab.2017.10.004
1214-021X/

Please cite this article in press as: K. Joszko, et al., Biomechanical evaluation of human lumbar spine in spondylolisthesis, J. Appl. Biomed. (2017), https://doi.org/10.1016/j.jab.2017.10.004

new classification of the spine deformity (Labelle et al., 2009; Labelle and Mac-Thiong, 2011; Mac-Thiong et al., 2012) considering patient can be classified to type 2 of isthmic spondylostisthesis. This is very rare case, but the preoperative surgical planning is usually used for custom cases. It was also another reason for doing this research because of the lack of reports in the literature.

Material and methods

A numerical model of the lumbar spine was formulated in the MADYMO software using a method of the dynamics of multibody systems. This method consists in modelling of objects by means of a chain of rigid bodies linked by kinematic pairs. Individual rigid bodies are described by mass, inertia moments and the position of the gravity centre. Moreover, in the kinematic pairs the bonds between the bodies are defined as well as their position in relation to a reference coordinate system. Both the bodies and the kinematic bonds are described by means of a series of physical parameters making it possible to solve movement equations of the whole system (1):

$$Mx_t + C\dot{x}_t + Kx_t = P_t \qquad (1)$$

where:

M – system mass matrix;

K – system stiffness matrix;

C – system damping matrix. This matrix is most often adopted in a form of the so-called proportional damping (depending on K and M matrices);

P_t – vector of external loads of the system;

x_t – vector of linear displacement;

$\dot{x}_t$ – vector of linear velocity;

x_t – vector of linear acceleration.

The authors' previous experience in the scope of modelling in biomechanics (Wolański et al., 2013a) as well as awareness of the issues connected with IT methods used for numerical computation constituted the basis of the applied simplifications. The process of modelling was preceded by literature studies in the scope of the anatomy of the human lumbar spine, the properties of its individual elements as well as the methods of their modelling (Chosa et al., 2004; Konz et al., 2001; Natarajan et al., 2003; Sairyo et al., 2006a,b).

The initial phase of the modelling process omitted the anatomical elements whose influence on the behaviour of the lumbar vertebrae was of little importance in this case and whose modelling would only complicate the model. Therefore soft tissues surrounding the lumbar section were omitted, including: elements of the digestive, cardiovascular and nervous systems. The model consists of the following anatomical parts of the human lumbar spine: five lumbar vertebrae L1–L5, joints connections, intervertebral discs, ligamentous apparatus and sacral bone.

The geometry of individual vertebrae which build up the model was obtained on the grounds of CT images of a patient whose vertebral column in the lumbar section was physiologically correct. CT imaging made it possible to segment a very complex and elaborate geometry of vertebrae. This enabled the recreation of the system of load transfer by three main elements: vertebral bodies as well as superior and inferior articular processes, i.e. a natural triad of support. The geometry of individual vertebrae (L1–L5) along with the sacral bone (S1) served the purpose of the development of a dynamic model of the human lumbar spine in the MADYMO software. The modelling process adopted the following assumptions:

- structure of models of lumbar vertebrae and the sacral bone reflects their irregular shape which is symmetrical to the sagittal plane;
- vertebrae are treated as rigid bodies having six degrees of freedom (except for the sacral bone constituting an immovable basis) whose position and movement depend on the bonds and inertia forces;
- intervertebral discs connecting the vertebrae are treated as massless elastic and damping elements having a nonlinear characteristic of stiffness and damping;
- intervertebral joints are connected by means of elastic and damping elements with a nonlinear characteristic taking into account the features of both cartilages and joint capsules;
- ligaments are treated as massless elements of a stiffness characteristic which is active only during tension;
- model takes into consideration physiological loads caused by the natural position of the spine – compression and a forward bend – bending.

A numerical model for the calculation of a general motion Eq. (1) used a modified Euler's method with one stage and constant time step t_s. The position of a local coordinate system of individual rigid bodies in relation to the global coordinate system is defined by the following Eq. (2):

$$\underline{X}_i = \underline{r}_i + \underline{A}_i\underline{x}_i \qquad (2)$$

where:

$\underline{X}_i$ – matrix of the leading vector coordinates;

$\underline{r}_i$ – matrix of the coordinates of the vector connecting the beginnings of both coordinate systems;

$\underline{A}_i$ – matrix of direction cosines;

$\underline{x}_i$ – matrix of the coordinates of the displacement vector of the local coordinate system.

Numerical model formulation

In the analysis of dynamic interactions in the lumbar spine in a physiological system and in the case of pathological changes the researchers adopted models of lumbar vertebrae in a form of rigid bodies having six degrees of freedom whose position depended on the ligaments, intervertebral discs and joints surfaces. The geometry of individual vertebrae was developed on the basis of the data selected from computer tomography (CT) which had been performed as routine checks in the scope of diagnostic tests. The segmentation of the vertebrae was made in specialist Mimics software.

The geometry of the lumbar section vertebrae was subject to further processing in the LS-PREPOST software in order to build a dynamic model of the spine. After the transformation of the models of vertebrae and the sacral bone, the models were imported to the MADYMO software (Fig. 1). Individual vertebrae models were connected by means of elastic and damping elements which reflected different intervertebral structures. In such a way a

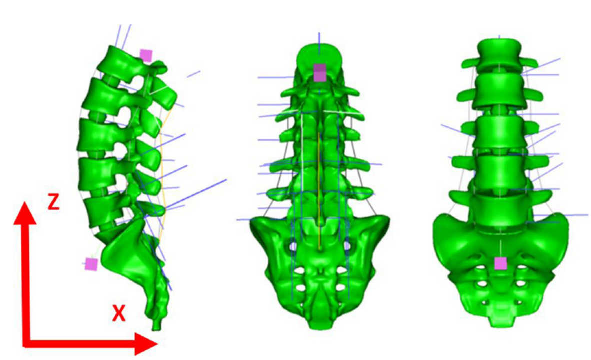

Fig. 1. Lumbar spine model developed in MADYMO software.

Please cite this article in press as: K. Joszko, et al., Biomechanical evaluation of human lumbar spine in spondylolisthesis, J. Appl. Biomed. (2017), https://doi.org/10.1016/j.jab.2017.10.004