DEVELOPMENT OF THE MULTI-SEGMENT LUMBAR SPINE FOR HUMANOID ROBOTS

by

Marko M. PENČIĆ*[*]**, ***Branislav A. BOROVAC*, *Dušan I. KOVAČEVIĆ*, and *Maja V. ČAVIĆ

Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia

Original scientific paper
DOI:10.2298/TSCI151005040P

The paper presents the development of the multi-segment lumbar structure based on the human spine. The research is performed within the project based on the development of socially acceptable robot named "SARA". Two approaches for the spine realization of humanoids exist: multi-joint viscoelastic structures (5-10 joints) that have variable flexibility, and structures that consist of one joint – torso/waist joint, which has low elasticity and high stiffness. We propose multi-joint flexible structure with stiff, low backlash and self-locking mechanisms that require small actuators. Based on kinematic-dynamic requirements, the dynamical model of the robot is formed. Dynamical simulation is performed for several postures of the robot and the driving torques of lumbar structure is determined. During the development of the lumbar structure, 16 variant solutions are considered. Developed lumbar structure consists of three equal segments, it has 6 DOF (2 DOF per segment) and allows movements of lateral flexion ±30° and torsion ±45°, as well as the combination of these two movements. In the development phase, the movements of flexion/extension are excluded, for the bending of the body forward to an angle of 45° is achieved by rotation in the hip joints. Proposed solution of the lumbar structure is characterized by the self-locking of mechanisms (if for any reason actuators stop working, lumbar structure retains in the current posture), low backlash (high positioning accuracy and repeatability of movements), compactness, high carrying capacity, and small dimensions.

Key words: *multi-segment lumbar spine, mechanical design, robot modeling, FEM modeling, humanoid*

Introduction

In the future, humanoid robots will operate in human environment and will perform numerous and complex tasks. Therefore, robots must be absolutely safe for humans and environment. The human body is a musculoskeletal and viscoelastic structure that has variable flexibility and approximately 350 degrees of freedom (DOF). On the other hand, most robots that are developed have rigid torso and consequently their mobility is limited and unnatural. Spine flexibility is essential for achieving human-like movements. Robots that have a flexible spine can absorb shocks and mechanical impacts during movement and therefore are safer when making physical contact with humans or objects. Because of the spine, upper body movements can be achieved without moving the lower body, that allows the diversity of the

---

[*] Corresponding author: mpencic@uns.ac.rs

robot movements and increases robot's arms reach. Humanoids which have one degree of freedom in the torso (trunk rotation left-right) require 26.5% less energy during walking than robots with rigid torso [1].

This paper presents the development of the multi-segment lumbar structure for humanoid robots based on the human spine. The research is performed within the project based on the development of the socially acceptable robot named *SARA*, that presents a mobile anthropomorphic platform for the research of socially acceptable behavior of the robot. This research includes interaction between humans and robots, gesticulation, recognizing emotions and their expressions, robot behavior in non-structural environment, *etc*. The robot will be able to communicate, verbally and non-verbally.

Spinal column – structure and mobility

Spinal column (*columna vertebralis*) is a multi-joint structure and a basic part of the axial skeleton which extends along the back side of the neck and trunk [2]. It is built of bones that are placed on top of one another and called vertebrae. Vertebrae are not commensurate. The total number of vertebrae is 33. Joint structures of spinal column are cervical, thoracic, and lumbar part – 24 vertebrae. (fig. 1) [3]. The spinal column, viewed laterally, has the form of an elongated letter *S*. The movements of the spinal column are enabled with intervertebral joints and intervertebral discs that are inserted between two adjacent vertebrae. Due to the elastic part of these discs, it is possible to perform locomotor activities of spinal column and better amortization, *i. e.* to adjust quickly from the shocks it is continually exposed to. A large number of different muscles and ligaments are involved in the movements of the spinal column. Spinal column provides stability and body posture in an upright position, allows movements of the head, neck and trunk, maintains and transmits loads from the upper limbs to the pelvis, reduces and absorbs impacts and shocks, and protects the spinal cord from damage. Hence, the spinal column has to be strong, stable and sufficiently movable. The movements between individual vertebrae have a very small range. However, the mobility of the spinal column is large in general, for it represents the sum of numerous small movements that are performed in 23 movable joints. The following movements can be distinguished in the region of the spinal column: flexion - bending forward and extension – bending backward (fig. 2a), lateral flexion – side bending (fig. 2b) and torsion – rotation (fig. 2c). The largest mobility of

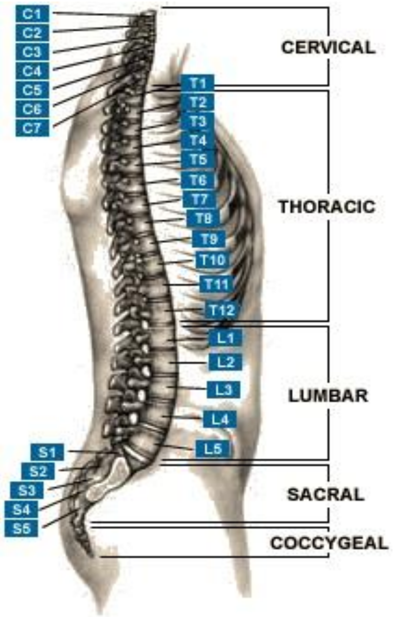


Figure 1. The human spine

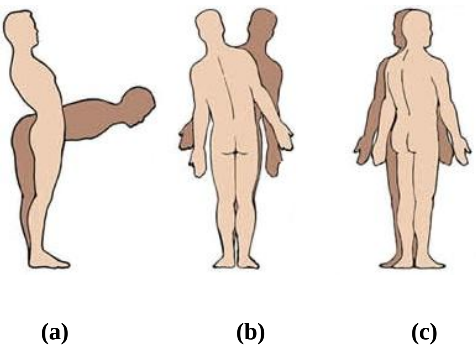

(a) (b) (c)

Figure 2. The human spine movements: (a) flexion/extension, (b) left/right side bending, and (c) left/right torsion

the spinal column is in the cervical area, then in the lumbar, and the smallest in thoracic area of the spinal column. The mobility of the lumbar spine in the sagittal plane – laterally, for the movements of flexion is approximately 40°, and for the movements of extension is approximately 30°. Total movement of lateral flexion is approximately 50°, that is 25° to the left and to the right side. The movements of torsion are approximately 20°, which is 10° for each side [4, 5].

State of the art

In [6] the robot *Cla* is presented, having a flexible spine. The spine has 15 DOF and consists of five ball-and-socket joints and eight tendons. Between each two joints there is a part of silicone rubber that acts like a human spine disc. The height of each rubber part is slightly larger than the distance between two adjacent joints, and therefore the rubber parts generate pressure on the joints. The spine retains stability due to elastic forces of the rubber parts. Two parts exist on the upper and the lower part of the spine, such as the clavicle and pelvis, in which there are embedded actuators that pull tendons. Each tendon has a tension sensor. In [7] the robot *Kenta* is presented with the flexible spine that is inspired by human spine and has 30 DOF. The spine consists of 10 ball-and-socket joints (3 DOF per joint), 11 vertebrae, 3 ribs and 40 muscles (tendons). Vertebrae are made with the opposite inclination and with their composition, the appearance of an *S* shape of the spine has been obtained. Between each two of the vertebrae there is an intervertebral disc – silicone rubber and ligaments – tension springs. The height of each rubber disc is slightly larger than the distance between two adjacent vertebrae. The rubber discs generate pressure on joints and ligaments are pulling them. Spinal control of movements is achieved by 40 tendons, each of which has a tension sensor. In [8] the humanoid *Kenji* is presented – advancing the version of the Kenta robot. In [9] the humanoid *Kotaro* is presented, also having a flexible spine which has 15 DOF and consists of 5 ball-socket-joints, 6 vertebrae and 3 ribs. Each vertebra has at least four points that fasten the tendons and allow the independent movements of each joint. Between each vertebra there is a viscoelastic element of silicone rubber (as a disc) and the tension springs (as ligaments). During the spine bending, the elastic elements generate force that opposes gravity and thereby help actuators. Likewise, the advantage of elastic elements is in achieving a significant force at the time of releasing the accumulated energy. In [10] the humanoid *Kojiro* is presented – the advanced version of the Kotaro robot. In [11] the humanoid *Armar III* is presented, which has a torso joint with 3 DOF of three serial linked mechanisms. The mechanisms have low backlash gears (harmonic drive and ballscrew) whose rotation axes intersect in one point. Torso joint has a high positioning accuracy and repeatability of movements, low elasticity and high stiffness. In [12], *iCub* robot is presented, with a waist joint with three DOF (roll, pitch and yaw rotations). It consists of a differential mechanism that allows the pitch and roll movement and the drive for yaw movement. The differential mechanism is based on parallel kinematics and consists of 4 pulleys, cables and 2 actuators. The drive for the yaw movement consists of 1 actuator, pulleys and cables.

Two approaches can be found in literature for the realization of the humanoid robot spine: multi-joint viscoelastic structures (15-30 DOF; variable flexibility; problems that appear are sensor reliability, controlling and repeatability of movement) and structures that consist of one joint – torso/waist joint (3 DOF; low elasticity and high stiffness whereby for the drive powerful and large actuators are needed). We propose a multi-joint flexible structure with stiff, low backlash and self-locking mechanisms which require small actuators. This kind of solution provides high positioning accuracy and repeatability of movements, and also has self-locking ability, hence if for any reason actuators stop working, spine retains in the current posture.

Multi-segment lumbar spine

Lumbar structure should enable movements of lateral flexion and torsion. The movements of flexion/extension are excluded, since the bending of the body forward, to an angle of 45°, is achieved by rotation in the hip joints. The thoracic spine will be immovable and it is provided for embedding the electronics and shrug mechanism. The established requirements are shown in tab. 1. Besides the kinematic-dynamic requirements and constraints, additional requirements are: self-locking of mechanisms, low backlash (provides high positioning accuracy and repeatability of movements) and the compactness of mechanisms (the number of segments and the total height of the lumbar structure directly depend on the size of mechanisms), high load carrying capacity and reliability.

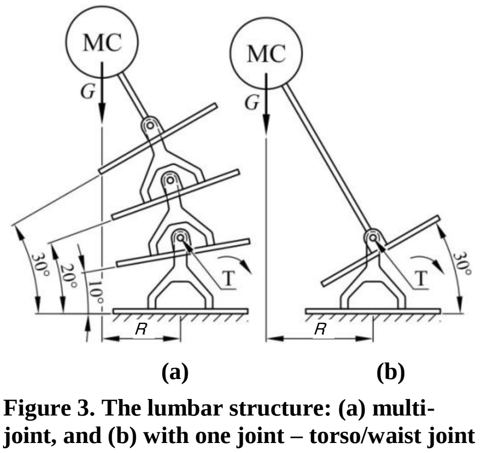
Table 1. Requirements

Parameter		Data
Weight above lumbar spine		25 kg
Maximum height		200 mm
Number of segments		3 and more
Movements	Lateral flexion	±30°
	Torsion	±45°
	Angular velocity	0.35 rad/s

Forces and torques

Fig. 3 shows lumbar structures inclined at the angle of 30°. Both structures, in vertical posture, have the same height from the center of mass (MC) to the base. The first structure (fig. 3a) consists of three equal segments, wherein each segment is inclined, one toward another, at an angle of 10°, for a total of 30°. The second structure (fig. 3-b) consists of one segment, inclined at an angle of 30°. It can be concluded from the picture that the force arm *R* is higher in the lumbar structure which consists of one segment (for example torso/waist joint) and is significantly lower with a multi-segment structure. The multi-segment structure provides a wider range of mobility. For smaller force arm, smaller torques are required to actuate the joints. Therefore, it is possible to apply smaller actuators (in power and dimensions), which have the direct influence on the size of mechanisms, *i. e.* of lumbar structure.

During dynamical behavior of the robot, lumbar structure is loaded with variable forces and torques. Head, neck, shrug mechanism, arms, *etc.*, will be fasten on a lumbar structure. These mechanisms are in the development phase and their mass is assumed to be 25 kg. The posture and the movements of the upper limbs can additionally, and sometimes significantly, load the lumbar structure which is examined on a dynamical model of the robot.



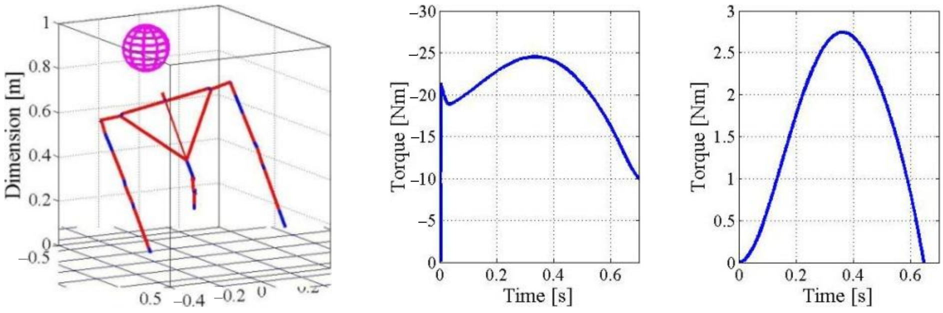
(a) **(b)**

Figure 3. The lumbar structure: (a) multi-joint, and (b) with one joint – torso/waist joint

The robot modeling software we used [13] has the capability of forming a dynamic model composed of a set of opened and closed kinematic chains, and the possibility of realizing and disrupting contact between the robot and surrounding objects. The software is based on the concept of a free-flying mechanism, which consists of one or more kinematic chains whose links are interconnected to revolute joints with one degree of freedom. The dynamic model of the robot also integrates the model of the DC motors with the permanent magnet, for driving each of the robot's joints. The models derived from this software provide a solid representation of the real system, since all the most significant effects that can arise in highly coupled and highly nonlinear system, such a real humanoid robot, are taken into account.

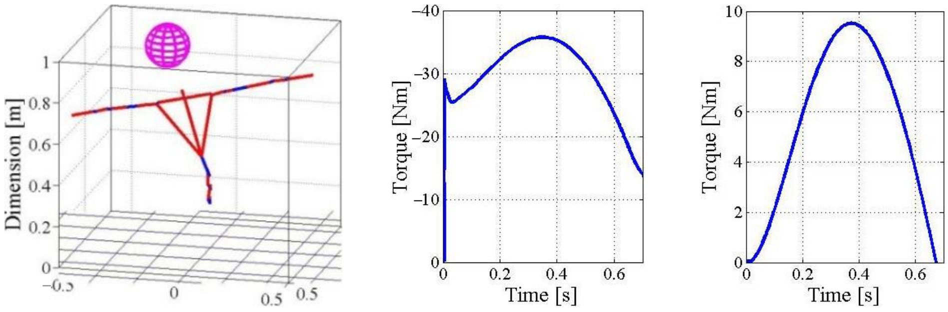
The dynamical model of the robot contains head, neck, arms, thoracic and lumbar part of the spine (assumed weight of all parts is 30 kg). Lumbar part is movable and consists of three segments – joints and has two DOF per segment. All other joints of the robot are immovable – fixed. Angular velocity of joints is 0.35 rad/s and angular acceleration 0.7 rad/s^2. The initial posture of the lumbar structure is lateral flexion –30° + torsion –45° and final posture is lateral flexion 0° + torsion 0°. Dynamical simulation is performed for three different cases, depending on the posture of the robot's arms.

The first analysis (fig. 4a) is performed when the robot's arms are next to the body (in fig. 4b and fig. 4c maximal torques for lumbar structure movements are shown). The second (fig. 5a) analysis is performed when the arms are spread out – laterally (in fig. 5b and fig. 5c maximal torques for lumbar structure movements are shown). The third (fig. 6a) analysis is performed when the robot's arms are in front of the body (in fig. 6b and fig. 6c maximal torques for lumbar structure movements are shown).



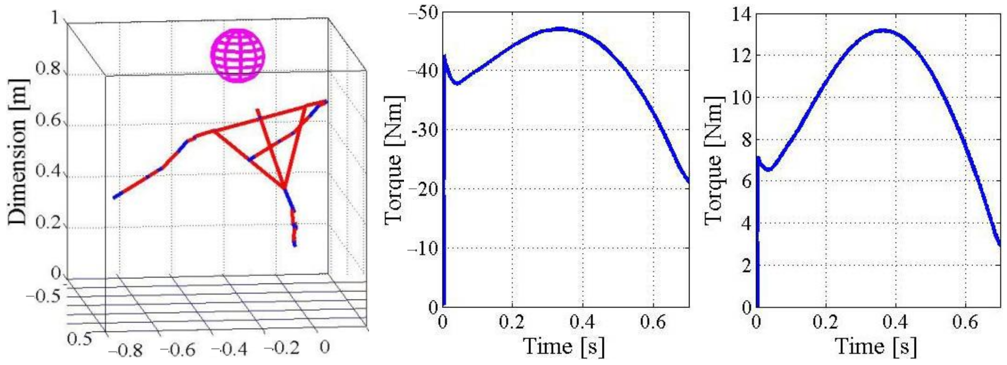
(a) **(b)** **(c)**

Figure 4. Dynamical simulation: (a) stick diagram: arms next to the body; lumbar spine: lateral flexion 30° + torsion 45°, (b) max. torque – lateral flexion 30°, and (c) max. torque – torsion 45°



(a) **(b)** **(c)**

Figure 5. Dynamical simulation: (a) stick diagram: arms spread out; lumbar spine: lateral flexion 30° + torsion 45°, (b) max. torque – lateral flexion 30°, and (c) max. torque – torsion 45°



(a) **(b)** **(c)**

Figure 6. Dynamical simulation: (a) stick diagram: arms in front of the body; lumbar spine: lateral flexion 30° + torsion 45°, (b) max. torque – lateral flexion 30°, and (c) max. torque – torsion 45°

Table 2. Maximal torques of lumbar structures depending on arms posture of the robot

Posture of the arms	Lateral flexion 30° [Nm]	Torsion 45° [Nm]
Next to the body	24.5	2.7
Spread out	35.7	9.5
In front of the body	47	13.2

The results of the robot's dynamical simulation are shown in tab. 2. Torques for mechanisms calculation are: 47 Nm – for lateral flexion movements and 13.2 Nm – for torsion movements.

Mechanical design

During the development of the lumbar structure, 16 variant solutions were considered [14]. Based on the technical and economic parameters the solution is chosen, and is shown in fig. 7a – serial linked structure that has three equal segments and 2 DOF per segment. Lumbar structure allows the movements of lateral flexion ±30°, which is ±10° per segment (fig. 7b) and torsion ±45°, which is ±15° per segment (fig. 7c), as well as the combination of these two movements. The total height of this prototype is 218 mm, 150 mm in diameter and the weight of 7.2 kg (which is 2.4 kg per segment).

(a) **(b)** **(c)** **(d)**

Figure 7. The lumbar structure: (a) upright posture, (b) lateral flexion 30°, (c) torsion (rotation) 45°, and (d) lateral flexion 30° + torsion 45°

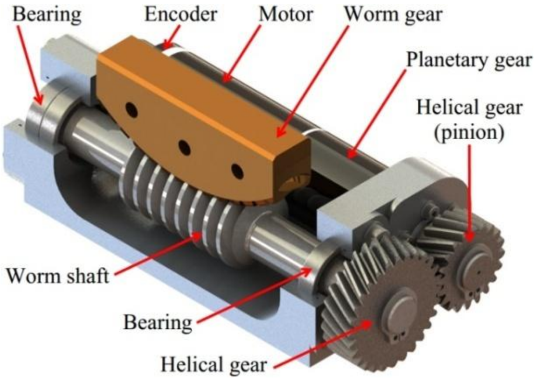


Figure 8. Lateral flexion mechanism

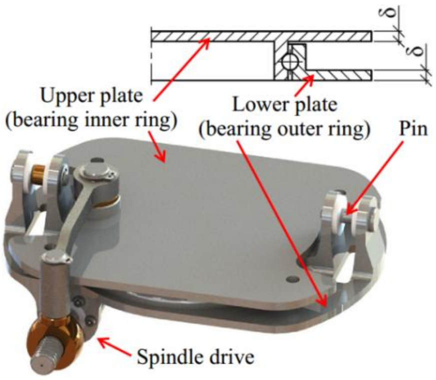


Figure 9. Torsion mechanism

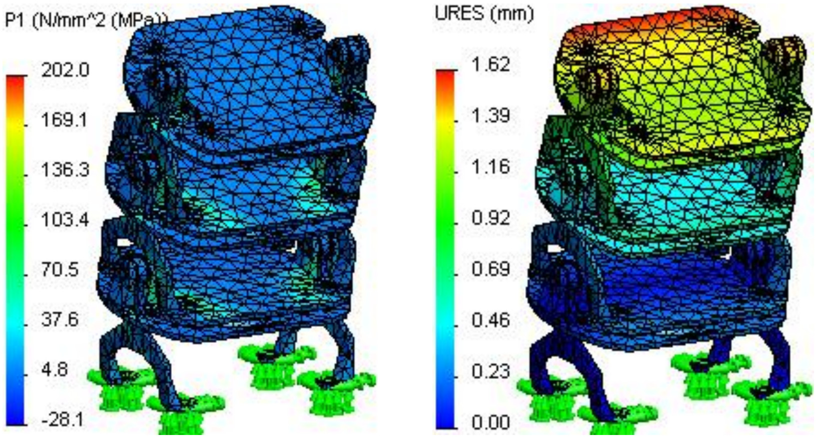
In fig. 8, the mechanism for lateral flexion movements is shown. It consists of a DC motor and two toothed gearings – helical and worm gearing. The compactness of the mechanism is achieved by placing the motor parallel to the worm shaft and using the worm gear with reduced dimensions (whole worm gear has 64 teeth, but for small rotation range of ±10° there are 12 teeth in usage; therefore, only that segment of the worm gear is used). The worm gearing has low backlash, because 5 teeth of the worm gear are in mesh with the worm shaft. Hence, high positioning accuracy and repeatability movements of mechanism are achieved. The worm gearing is self-locking so that, if for any reason motors stop working, lumbar structure retains the current posture. The movements of torsion are enabled by the drive which consists of DC motor, short screwed spindle and axial bearing (fig. 9). Trapezoidal screwed spindle is fastened on the motor shaft. This kind of mechanism (spindle drive) allows transformation from rotational into a linear motion. It has a large carrying capacity, low backlash, and it is self-locking. The axial bearing consists of an inner ring – the upper bearing plate, and the outer ring – lower bearing plate. It is designed by the technology of radial bearings with four points of contact, and it is axially inseparable. Rotating the upper bearing plate relative to the lower bearing plate is achieved by the spindle drive mechanism. Technical characteristics of mechanisms are shown in tab. 3.

Table 3. Drive technical characteristics

Lateral flexion mechanism - datasheet		
Maxon motor EC-4 pole 22	Power [W]	90
	Torque [mNm]	53
Planetary gear GP22-HP	Reduction	53
	Torque [Nm]	3
	Efficiency [%]	59
Encoder 16 EASY	Channels	3
	Counts per turn	1024
Helical gears	Reduction	1.4
	Module [mm]	1
	Helix angle [°]	20
Worm shaft and worm gear	Reduction	64
	Module [mm]	1.5
	Lead angle [°]	4.76
Torsion mechanism - datasheet		
Maxon motor EC-max 22	Power [W]	25
	Torque [mNm]	22.7
Planetary gear GP22-HP	Reduction	20
	Torque [Nm]	2.4
	Efficiency [%]	70
Encoder MR-ML	Channels	3
	Counts per turn	512
Screwed spindle	Trapezoidal	10x2

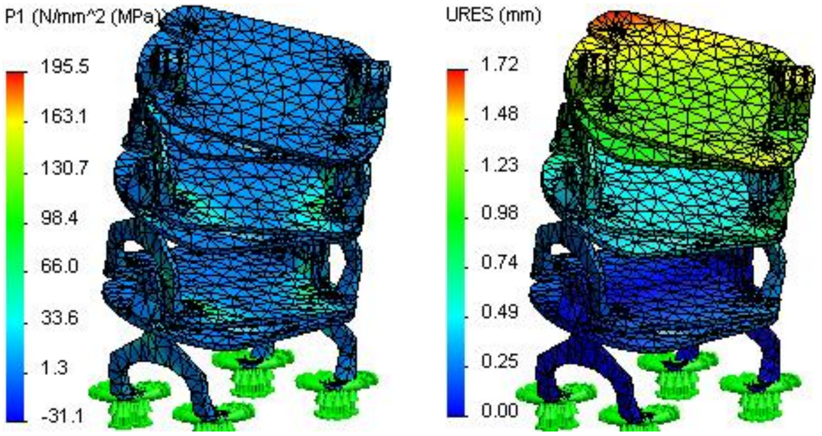
The FEM modeling

The FEM model is formed in the *SolidWorks* software using 3-D finite element with contour and transitional conditions that simulate the real behavior of links and joints. Using the FEM analysis, principal stresses and resultant displacements are examined, depending on the posture of structure and bearing dimensions – thickness δ (fig. 9). Numerical analysis is performed in accordance with the assumption of a completely linear behavior of the structure. From the FEM model, the entities for which it is assumed not to have significant influence on the stress-deformity image of the object are excluded. To that effect, the idealized model is formed, where pins and screws are approximated with rollers. The discretized model is developed based on the model zone and the adjusted number of contact surface elements. It consists of 44.370 nodes and 25.940 finite elements in the form of a tetrahedron. The mass and center of gravity of the robot upper limbs are approximated with the ball weight of 30 kg at a distance of 250 mm from the lumbar structure. The material of the structure is the carburizing steel 16MnCr5. In figs. 10 and 11 the results of the FEM analysis of the lumbar structure for posture lateral flexion 30° and lateral flexion 30° + torsion 45° are shown.



(a) (b)

Figure 10. The FEM modeling: (a) lateral flexion 30° – principal stresses, (b) lateral flexion 30° – resultant displacement



(a) (b)

Figure 11. The FEM modeling: (a) lateral flexion 30° + rotation 45° – principal stresses and (b) lateral flexion 30° + rotation 45° – resultant displacement

Tab. 4 shows the result overview for the FEM analysis based on which it is concluded that the principal stresses are within the limit of elasticity for the applied material (factors of safety are above 2.6) and that the resultant displacements of bearing plates are relatively large (1.6-2 mm). Large resultant displacements of the upper bearing plate would likely cause the vibrations of the lumbar structure, which would adversely affect the functionality, control and repeatability of movement. Because of relatively large displacements, the next phase of the prototype development will include a geometrical nonlinear FEM analysis.

Table 4. The FEM modeling of the lumbar structure

Posture of the lumbar structure	Plate thickness δ [mm]	Principal stresses			Resultant displacement ures [mm]	Factor of safety ($\sigma_{\text{Limit}}\, \sigma^{-1}$) >1
		σ_1 [Nmm^{-2}]	σ_2 [Nmm^{-2}]	σ_3 [Nmm^{-2}]		
Lateral flexion 30°	2.5	213.9	–50.1	–219.5	1.84	2.69
	3	207.0	–45.1	–215.9	1.69	2.74
	3.5	202.0	–39.2	–215.1	1.62	2.75
Lateral flexion 30° + torsion 45°	2.5	206.7	–50.2	–207.3	2.01	2.69
	3	199.7	–46.4	–206.2	1.84	2.86
	3.5	195.5	–43.3	–205.4	1.72	2.88

Conclusions

In the paper, the development of the multi-segment lumbar structure for humanoid robots is presented within the project in which a socially acceptable robot named *SARA* is being developed. The literature reviews that two approaches exist for the realization of the spine for a humanoid robot: multi-joint viscoelastic structures (5-10 joints) that have variable flexibility and structures that consist of one joint – torso/waist joint, which have low elasticity and high stiffness. We propose a multi-joint flexible structure with stiff, low backlash and self-locking mechanisms that require small actuators.

Based on the kinematic-dynamic requirements, the dynamical model of the robot is formed. Dynamical simulation is performed for several postures of the robot, based on which the driving torques of the lumbar structure are determined. During the development of the lumbar structure, 16 variant solutions have been considered. The developed lumbar structure consists of three equal segments and has six DOF (two DOF per segment). Multi-segment lumbar structure allows movements of lateral flexion ±30° and torsion ±45°, as well as the combination of these two movements. In the development phase, the movements of flexion/extension are excluded, for the bending of the body forward, to an angle of 45°, which is achieved by the rotation in the hip joints. The proposed solution for the lumbar structure is characterized by the self-locking of mechanisms, low backlash (high positioning accuracy and repeatability of movements), compactness, high carrying capacity and small dimensions.

The FEM model of the lumbar structure is formed. The FEM analysis is performed, where principal stresses and resultant displacements are examined depending on the posture of the structure and bearing dimensions. Principal stresses are within the limit of elasticity for the applied material (factors of safety are above 2.6). Based on the FEM analysis, the problem of relatively large resultant displacements of bearing plates (1.6-2 mm) exists.

Further work on the development of the lumbar structure (besides the existing movements of lateral flexion and torsion) will include embedding joints in the pelvis area for the movements of flexion/extension. It will, besides widening the range of spinal posture and robot's arms reach, contribute to the movements of the robot being diverse, more natural and human-like movements. In further development of the lumbar structure, it is necessary to solve the problem of large resultant displacements of upper bearing plate. Embedding of joints for the movements of flexion/extension will additionally increase loads and structural stresses, which is necessary to examine on a new dynamical model of the robot and the FEM model of the lumbar structure.

Acknowledgment

This work was funded by the Ministry of Education and Science of the Republic of Serbia under the contract III44008 and by the Provincial Secretariat for Science and Technological Development under the contract 114-451-2116/2011.

References

[1] Or, J., Humanoids Grow a Spine: The Effect of Lateral Spinal Motion on the Mechanical Energy Efficiency, *IEEE Robotics and Automation Magazine*, *20* (2013), 2, pp. 71-81

[2] Mihalj, M., *Anatomija coveka* (*Humans Anatomy,* in Serbian), Educa, Novi Sad, Serbia, 2001

[3] Obradović, D., *et al*., *Osteologija za studente medicine* (*Osteology for Medicine Students,* in Serbian), Zmaj, Novi Sad, Serbia, 2003

[4] Nikolić, D., *Kineziologija* (*Kinesiology,* in Serbian), College of Health Studies, Ćuprija, Serbia, 2007

[5] Gudović, R., Stefanović, N., *Sistematska i topografska anatomija grudnog kosa*, (*Anatomy of the Thorax: Systematic and Topographic Approach*, in Serbian), Ortomedics, Novi Sad, Serbia, 2003

[6] Mizuuchi, I., *et al*., A Flexible Spine Human-Form Robot – Development and Control of the Posture of the Spine, *Proceedings*, International Conference on Intelligent Robots and Systems, Maui, Hawaii, USA, 2001, pp. 2099-2104

[7] Mizuuchi, I., *et al*., The Design and Control of the Flexible Spine of a Fully Tendon-Driven Humanoid "Kenta", *Proceedings*, International Conference on Intelligent Robots and Systems, Lausanne, Switzerland, 2002, pp. 2527-2532

[8] Mizuuchi, I., *et al*., A Reinforceable-Muscle Flexible-Spine Humanoid "Kenji", *Proceedings*, International Conference on Intelligent Robots and Systems, Edmonton, Canada, 2005, pp. 692-697

[9] Mizuuchi, I., *et al*., Development of Musculoskeletal Humanoid Kotaro, *Proceedings,* International Conference on Robotics and Automation, Orlando, Fla., USA, 2006, pp. 82-87

[10] Mizuuchi, I., *et al*., An Advanced Musculoskeletal Humanoid Kojiro, *Proceedings*, International Conference on Humanoid Robots, Pittsburgh, Penn., USA, 2007, pp. 294-299

[11] Albers, A., *et al*., Armar III – Design of the Upper Body, *Proceedings*, International Conference on Humanoid Robots, Genova, Italy, 2006, pp. 308-313

[12] Hinojosa, W. M., *et al*., Performance Assessment of a 3DOF Differential Based Waist Joint for the "iCub" Baby Humanoid Robot, *Proceedings,* International Conference on Robot and Human Interactive Communication, Hatfield, UK, 2006, pp. 195-201

[13] Potkonjak, V., *et al*., General Model of Dynamics of Human and Humanoid Motion: Feasibility, Potentials and Verification, *International Journal of Humanoid Robotics, 3* (2006), 2, pp. 21-48

[14] Penčić, M., *Razvoj modula lumbalnog dela kicme za humanoidne robote* (*Development of the Lumbar Spine Module for Humanoid Robots*, in Serbian), M. Sc. thesis, University of Novi Sad, Novi Sad, Serbia, 2012

Paper submitted: October 5, 2015
Paper revised: November 13, 2015
Paper accepted: December 30, 2015