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DEVELOPMENT OF THE MULTI-SEGMENT
LUMBAR SPINE FOR HUMANOID ROBOTS

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The paper presents development of multi-segment lumbar structure based on the human spine. The research is performed within the project based on development of socially acceptable robot named "SARA". Two approaches for 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 dynamical model of robot is formed. Dynamical simulation is performed for several postures of the robot and driving torques of lumbar structure are determined. During development of the lumbar structure 16 variant solutions are considered. Developed lumbar structure consists of three equal segments, it has 6 DOFs (2 DOFs per segment) and allows movements of lateral flexion ±30° and torsion ±45°, as well as the combination of these two movements. In 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 self-locking of mechanisms (if for any reason actuators stop working, lumbar structure retains 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*

1. 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 musculoskeletal and viscoelastic structure that has variable flexibility and approximately 350 degrees of freedom (DOFs). 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 diversity of the 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 development of multi-segment lumbar structure for humanoid robots based on human spine. The research is performed within the project based on development of socially acceptable robot named "SARA", that presents a mobile anthropomorphic platform for research of socially acceptable behavior of the robot. This research includes interaction between humans and robots, gesticulation, recognizing of emotions and their expressions, robot behavior in unstructural environment etc. The robot will be able to communicate, verbally and nonverbally.

1.1. Spinal column - structure and mobility

Spinal column (*columna vertebralis*) is multi-joint structure and 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

Figure 1. The human spine

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 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. 2-a), lateral flexion - side bending (Fig. 2-b) and torsion - rotation (Fig. 2-c). The largest mobility of 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 lumbar spine in the

a)   b)   c)

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

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

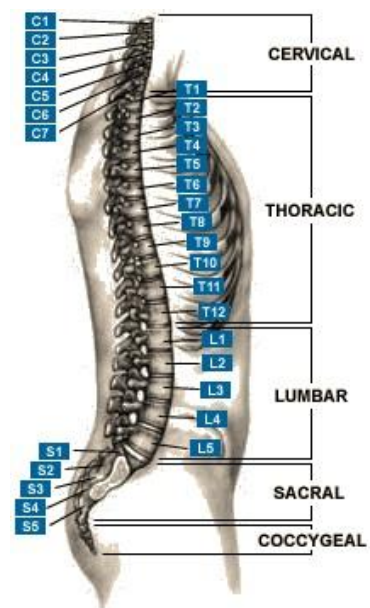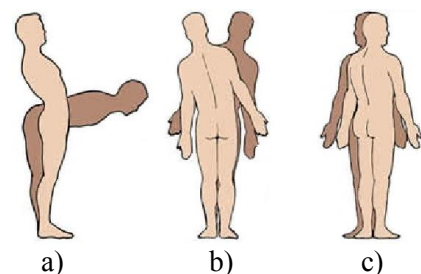the left and to the right side. The movements of torsion is approximately 20°, which is 10° for each side [4,5].

1.2. State of the art

In [6] the robot "Cla" is presented which has a flexible spine. The spine has 15 DOFs and consists of 5 ball-and-socket joints and 8 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 are embedded actuators that pull tendons. Each tendon has a tension sensor. In [7] the robot "Kenta" is presented with flexible spine that is inspired by human spine and has 30 DOFs. The spine consists of 10 ball-and-socket joints (3 DOFs 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 - advances version of Kenta robot. In [9] the humanoid "Kotaro" is presented, that also has a flexible spine which has 15 DOFs and consists of 5 ball-socket-joints, 6 vertebrae and 3 ribs. Each vertebra has at least 4 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 significant force at the time of releasing accumulated energy. In [10] the humanoid "Kojiro" is presented - the advanced version of Kotaro robot. In [11] the humanoid "Armar III" is presented which has torso joint with 3 DOFs 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 which has waist joint with 3 DOFs (roll, pitch and yaw rotations). It consists of a differential mechanism that allows pitch and roll movement and drive for yaw movement. The differential mechanism is based on parallel kinematics and consists of 4 pulleys, cables and 2 actuators. The drive for yaw movement consists of 1 actuator, pulleys and cables.

Two approaches can be found in literature for realization of humanoid robots spine: multi-joint viscoelastic structures (15-30 DOFs; variable flexibility; problems that appear are sensors reliability, controlling and repeatability of movement) and structures that consist of one joint - torso/waist joint (3 DOFs; low elasticity and high stiffness whereby for the drive are needed powerful and large actuators). We propose 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 current posture.

2. Multi-segment lumbar spine

Lumbar structure should enable movements of lateral flexion and torsion. 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. The thoracic spine will be immovable and it is provided for embedding the electronics and mechanisms for lifting shoulders. The established requirements are shown in the tab. 1. Besides of the kinematic-dynamic requirements and constraints, additional requirements are: self-locking of the mechanisms, low backlash (provides high positioning accuracy and repeatability of movements) and the compactness of the 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/sec

2.1. Forces and torques

In Fig. 3 are shown 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. 3-a) 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 multi-segment structure.
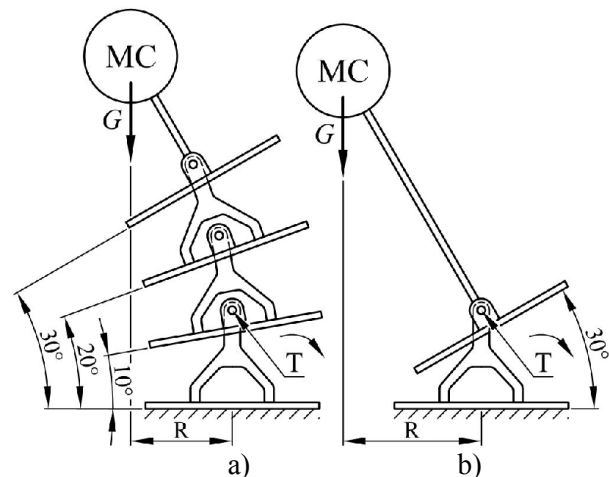

Figure 3. The lumbar structure: a) multi-joint and b) with one joint - torso/waist joint

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, shoulders lifting mechanism, arms etc will be fasten on lumbar structure. These mechanisms are in development phase and their mass is assumed at 25 kg. The posture and the movements of the upper limbs can additionally, and sometimes significantly load lumbar structure which is examined on a dynamical model of the robot.

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 by 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 solid representation of real system since all the most significant effects that can arise in highly coupled and highly nonlinear system such a real humanoid robot is taken into account.
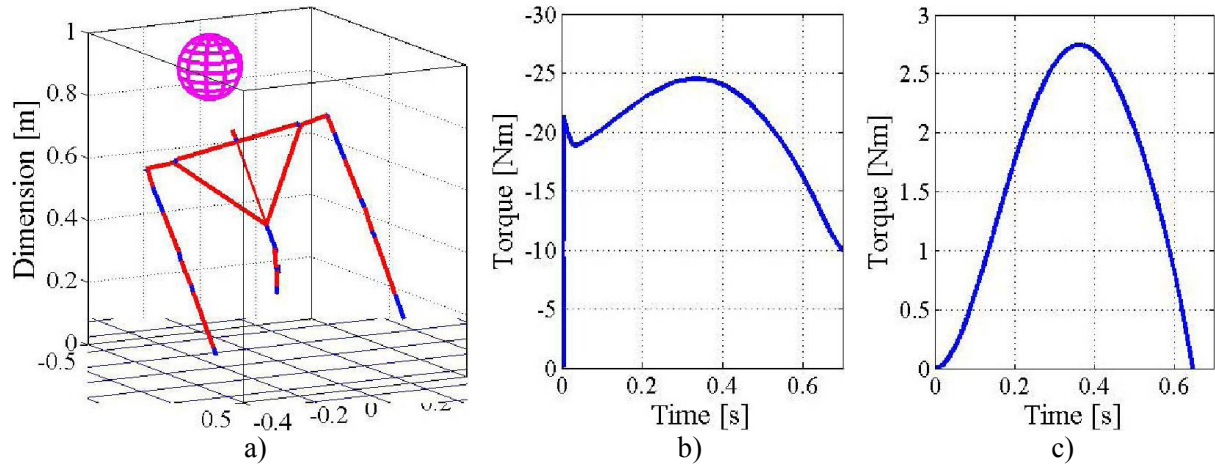

Figure 4. Dynamical simulation: a) stick diagram: arms next to the body; lumbar spine: lateral flexion 30° + torsion 45°, b) max. torque - lateral flexion 30° and c) max. torque - torsion 45°
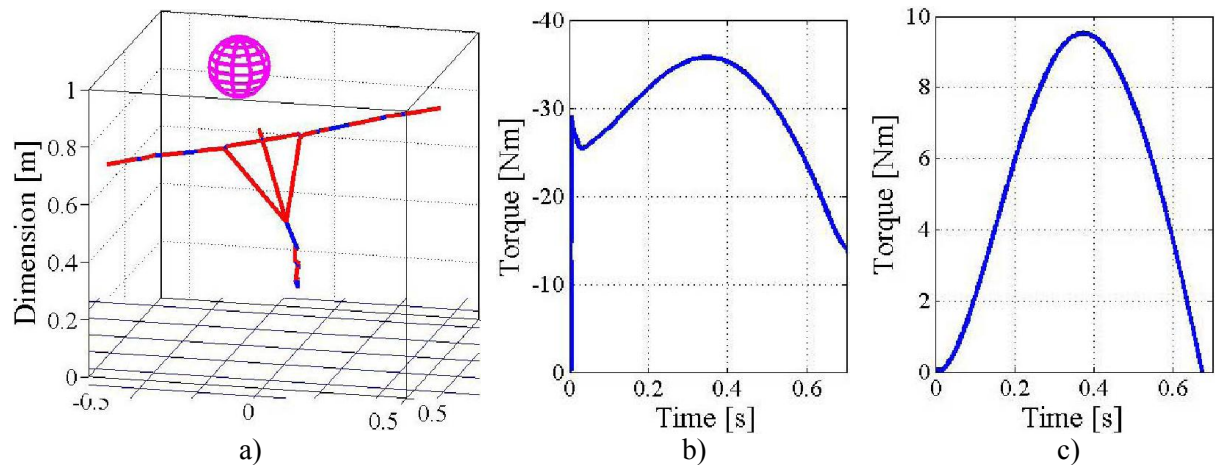
Figure 5. Dynamical simulation: a) stick diagram: arms spread out; lumbar spine: lateral flexion 30° + torsion 45°, b) max. torque - lateral flexion 30° and c) max. torque - torsion 45°
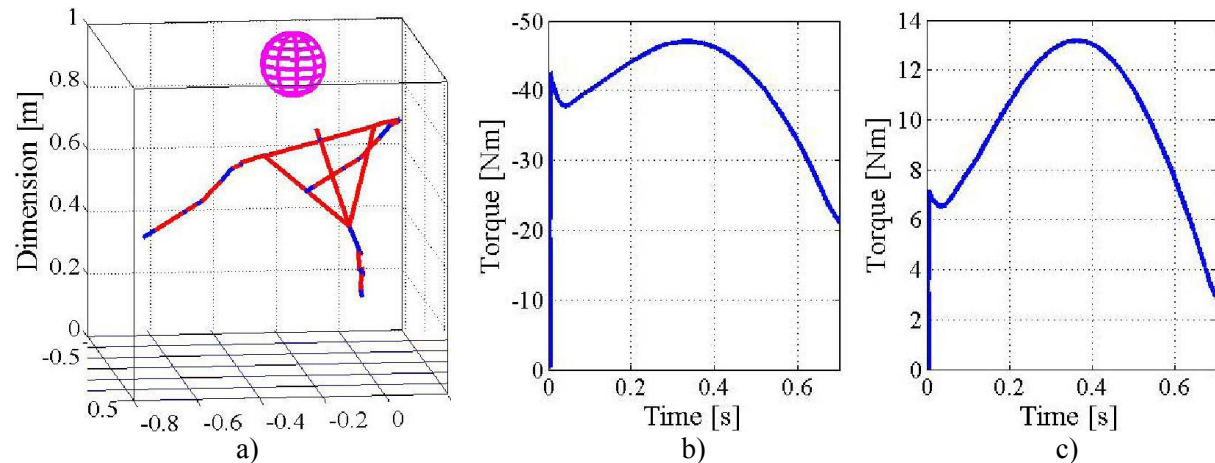

Figure 6. Dynamical simulation: a) stick diagram: arms in front of the body; lumbar spine: lateral flexion 30° + torsion 45°, b) max. torque - lateral flexion 30° and c) max. torque - torsion 45°

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 2 DOFs per segment. All other joints of the robot are immovable - fixed. Angular velocity of joints is 0.35 rad/sec and angular acceleration 0.7 rad/sec^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. 4-a) is performed when the robot's arms are next to the body (in Fig. 4-b and Fig. 4-c are shown maximal torques for lumbar structure movements). The second (Fig. 5-a) is performed when the arms are spread out - laterally (in Fig. 5-b and Fig. 5-c are shown maximal torques for lumbar structure movements). The third (Fig. 6-a) analysis is performed when the robot's arms are in front of the body (in Fig. 6-b and Fig. 6-c are shown maximal torques for lumbar structure movements). 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.

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

2.2. Mechanical design

During 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. 7-a – serial linked structure that has three equal segments and 2 DOFs per segments. Lumbar structure allows the movements of lateral flexion ±30°, which is ±10° per segment (Fig. 7-b) and torsion ±45°, which is ±15° per segment (Fig. 7-c), and as well as the combination of these two movements. The total height of this prototype is 218 mm, 150 mm in diameter and weight of 7.2 kg (which is 2.4 kg per segment).
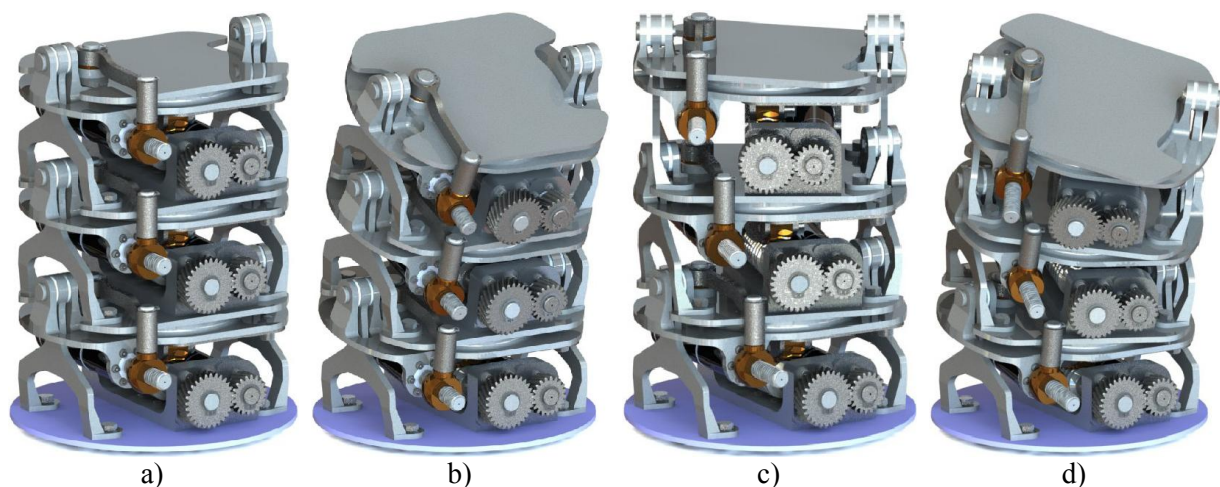

| a) | b) | c) | d) |

Figure 7. The lumbar structure: a) upright posture, b) lateral flexion 30°, c) torsion (rotation) 45° and d) lateral flexion 30° + torsion 45°
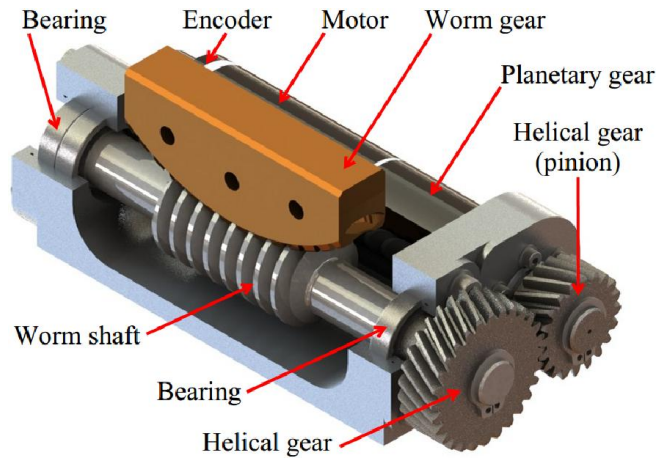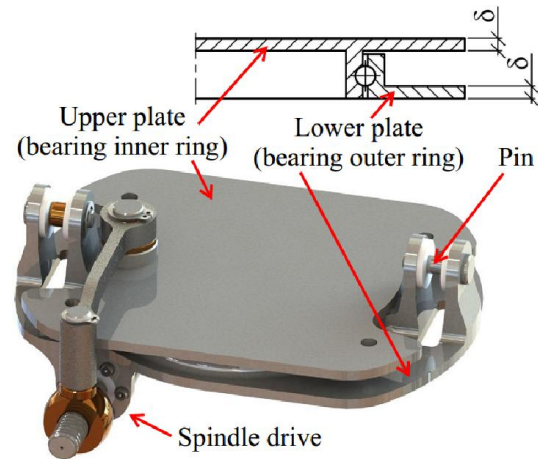
Figure 8. Lateral flexion mechanism   **Figure 9. Torsion mechanism**

In Fig. 8 is shown the mechanism for lateral flexion movements. 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 parallelly with worm shaft and the usage of worm gear with reduced dimensions (whole worm gear has 64 teeth, but for small rotation range of ±10° in usage are 12 teeth, therefore only that segment of worm gear is used). The worm gearing has low backlash, because the 5 teeth of the worm gear are in mesh with 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 current posture. The movements of torsion are enabled by drive which consists of DC motor, short screwed spindle and axial bearing (Fig. 9). Trapezoidal screwed spindle is fastened on 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 a four points of contact and it is axially inseparable. Rotating the upper bearing plate relative to the lower bearing plate is achieved by 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
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
Encoder MR-ML	Channels	3
	Counts per turn	512
Screwed spindle	Trapezoidal	10x2

3. FEM modeling

FEM model is formed in the "SolidWorks" software using 3D finite element with contour and transitional conditions that simulate the real behavior of links and joints. With FEM analysis are examined principal stresses and resultant displacements depending on the posture of structure and bearing dimensions - thickness δ (Fig. 9). Numerical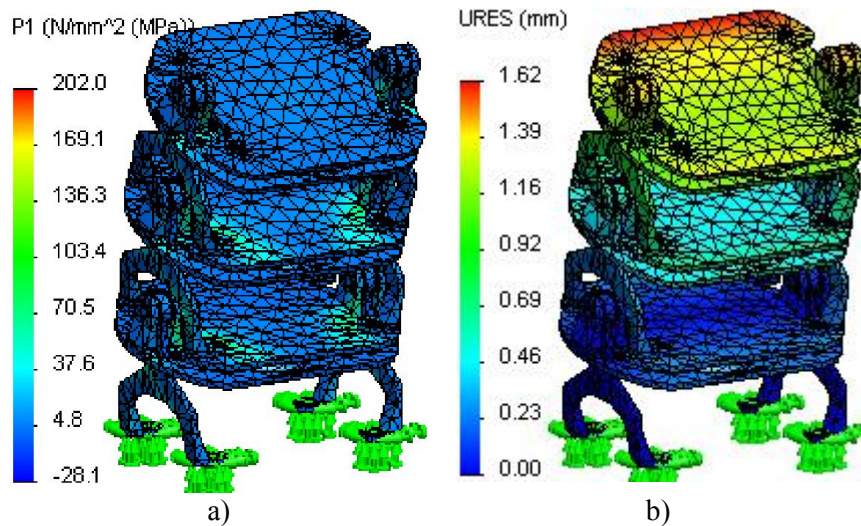 analysis is performed in accordance with the assumption of a completely linear behavior of structure. From FEM model entities are excluded for which is assumed not to have significant influence on stress-deformity image of the object. To that effect, idealized model is formed in whom pins and screws are approximated with rollers. The discretized model is developed based on the model zone and adjusted number
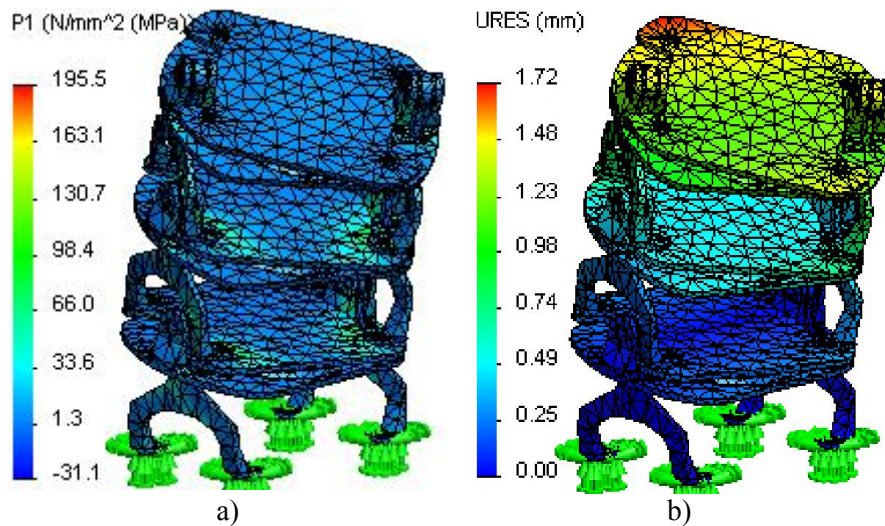

Figure 10. FEM modeling: a) lateral flexion 30° - principal stresses, b) lateral flexion 30° - resultant displacement

of contact surface elements. It consists of 44.370 nodes and 25.940 finite elements in the form of a tetrahedron. Mass and center of gravity of the robot upper limbs are approximated with ball weight of 30 kg at a distance of 250 mm from lumbar structure. Material of the structure is carburizing steel 16MnCr5. In Fig. 10 and Fig. 11 are shown the results of FEM analysis of lumbar structure for posture lateral flexion 30° and lateral flexion 30° + torsion 45°. In tab. 4 the result overview is shown for FEM analysis based on which is concluded that the principal stresses are within the limit of elasticity for applied material (factors of safety are above 2.6) and that 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

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

the functionality, control and repeatability of movement. Because of relatively large displacements, the next phase of prototype development will include a geometrical nonlinear FEM analysis.

Table 4. FEM modeling of the lumbar structure

Posture of the lumbar structure	Plate thickness δ [mm]	Principal stresses			Resultant displacement u_{res} [mm]	Factor of safety $(\sigma_{Limit}/\sigma) > 1$
		σ_1 [N/mm^2]	σ_2 [N/mm^2]	σ_3 [N/mm^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

4. Conclusion

In the paper is presented development of multi-segment lumbar structure for humanoid robots within the project in which is developing socially acceptable robot named "SARA". With reviewing literature is determined that exist two approaches for the realization of spine for humanoid robot: 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 dynamical model of robot is formed. Dynamical simulation is performed for several postures of the robot, based on which driving torques of lumbar structure are determined. During development of the lumbar structure 16 variant solutions are considered. Developed lumbar structure consists of three equal segments and has 6 DOFs (2 DOFs 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 development phase, the movements of flexion/extension are excluded, for the bending of the body forward, to an angle of 45°, is achieved by the rotation in the hip joints. Proposed solution of lumbar structure is characterized by self-locking of mechanisms, low backlash (high positioning accuracy and repeatability of movements), compactness, high carrying capacity and small dimensions.

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

Further work on the development of lumbar structure (besides the existing movements of lateral flexion and torsion) will include embedding of joint in pelvis area for the movements of flexion/extension. It will, besides widening 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 lumbar structure is necessary to solve the problem of large resultant displacements of upper bearing plate. Embedding of joint for movements of flexion/extension, additionally will increase

loads and structural stresses, which is necessary to examine on a new dynamical model of robot and FEM model of the lumbar structure.

Acknowledgement

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