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# DESIGN AND SIMULATION OF SPINE AFFECTED BY SCOLIOSIS AND PROPOSITION OF DYNAMIC BRACE

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**Abstract**—This paper deals with 2D, and 3D simulations of a human equipped with back bone pitch and roll joints to study the advantages of having such a mechanism for daily human-like movements. A comparison between a normal spine and deformed spine due to scoliosis is made. The contribution of this paper consists of designing the mechanism for correcting abnormal postures of the human spine, taking into account the specifications of forward, backward and left/right sideways bending amplitudes. The mechanism is composed of a bottom platform and a top platform connected by two articulated arms and a vertical central rod.

**Index Terms**—Kinematics, Dynamics, Joints, Forces, Parallel mechanism

## I. INTRODUCTION

### A. Human spine description

The human vertebral column extends from the skull to the pelvis and is made up of 33 individual vertebrae [1]. The vertebrae are stacked on top of each other. They are grouped into four regions (Fig. 1):

- Cervical region
- Thoracic region
- Lumbar region
- Sacrum and coccyx

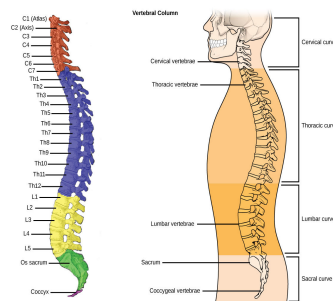


Fig. 1. Human Spine

The cervical and lumbar regions enjoy the greatest freedom of movement. In the thoracic region, motion is more limited. Motions of a human spine are characterized by the actuation planes that are the sagittal plane, coronal plane, and axial plane (Fig. 5). The basic movements of the spine can be classified by using planes, as follows:

- In Sagittal plane: Flexion and Extension
- In Coronal plane: Right and Left Lateralization
- In Longitudinal plane: Rotation

Deformity of spine is any abnormality of the formation, alignment, or shape of the vertebral column. Among the deformities there is scoliosis.

### B. Spine of the adolescent idiopathic scoliosis (AIS)

A scoliosis curve [2] usually looks a bit like a backward C shape and involves the spine bending sideways to the right, which is also called dextroscoliosis. Sideways spinal curvature on the left side of the back is more like a regular C shape and called levoscoliosis. Scoliosis is categorized into several types depending on the cause and age of the curve development, 2 to 3 per cent of the population can be affected by scoliosis [3]. Here are four common types of scoliosis curves (Fig. 2):

- Right thoracic curve
- Right thoracolumbar curve
- Right lumbar curve
- Double major curve

The two parts affected by scoliosis are the thorax and lumbar regions.

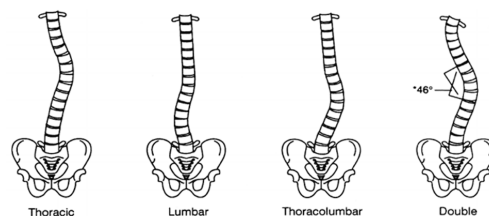


Fig. 2. Four common types of scoliosis curves

A diagnosis of scoliosis is confirmed when the Cobb [4] angle is 10 degrees or greater, which is measured through a standard radiographic examination. X-rays of the entire spine are taken to evaluate the front and side curvature. The Cobb angle is used on x-ray to measure the angle between the most angulated vertebrae that make up the curvature. Lines are drawn on the x-ray or a computer program assists to calculate the angle. Most scoliosis curves are between 10 to 40 degrees in magnitude. Although radiographic measurements

are used to decide treatment, a small degree of error exists when comparing radiographs. A change of 5 degrees is usually needed to document an actual change in curve progression.

Treatment options for idiopathic scoliosis could include: observation, bracing and surgery. Bracing is the application of external corrective forces onto the spine and trunk. It can be rigid or flexible. But conventional rigid braces have problems:

- Difficult to move
- Lower self-esteem
- More fatigue and lower compliance
- Heavy, non-breathable and uncomfortable

These braces are designed to be worn 16 to 23 hours a day. And as the child grows, the required external forces to correct the abnormal posture change along the length of the curve and over the course of treatment. Our objective is to achieve a dynamic brace. It is actuated by 2 motors placed on adjacent rings to control the force or position applied on the human body. In this paper we propose to investigate the kinematics design of a vertebral column for human. Two kinds of experiments are carried out, one experiment of normal spine and another experiment of deformed spine. Simulation experiments let to choose the motors of the dynamic brace.

The paper is organized as follows. Section II describes the kinematics of the parallel spine mechanism. Section III is dedicated to simulation and results. Section IV is devoted to conclusion and perspectives.

## II. TRAJECTORY PLANNING AND INVERSE KINEMATICS OF HUMAN MOTION

### A. Model of human

A spine is a complex remarkable mechanical structure. It transmits the weight of the upper body to the pelvis and is subjected to internal forces whose magnitudes are many times the entire body weight depicts the human model used for simulation in the sagittal plane  $(x, z)$ . The model is constituted by rectangular segments, namely head, trunk, pelvis, femurs, tibias and arms. Masses and heights of the different body parts are derived from a human kid-size model. Total height is 1.40 [m]. Total mass is  $M_T=40$ [Kg] without pitch joints in the vertebral column.

This mass increases by  $0.01 M_T$  for each pitch joint. The trunk is composed of a thorax and a lumbar part when there are a least two pitch joints. The mass of the thorax is equal to the mass of the trunk when the robot has no articulated spine.

Table I gives masses and heights of the different parts. The trunk is composed of a thorax and a lumbar part. Foot mass was taken into account in the tibias. Arms are connected to the shoulders at the top of the thorax.

In order to investigate the influence of the number of vertebrae on sitting movement, a dynamics study of the model in the sagittal plane using Newton-Euler equations was conducted in [7]. The motion algorithm uses the pseudo-inverse technique. The input trajectory to be tracked is defined as

$$F = [x_G, x^{pelvis}, z^{pelvis}, \theta^{pelvis}] \quad (1)$$

| Part                 | Masses [Kg]              | Height [m]                         |
|----------------------|--------------------------|------------------------------------|
| Head                 | 0.08 $M_T$               | 0.07 $H_T$                         |
| Arms(2)              | 0.1 $M_T$                | 0.47 $H_T$                         |
| Tibias(2)            | 0.12 $M_T$               | 0.27 $H_T$                         |
| Thighs(2)            | 0.18 $M_T$               | 0.22 $H_T$                         |
| Pelvis               | 0.02 $M_T$               | 0.04 $H_T$                         |
| Trunk                | $(0.5+0.01\delta_j) M_T$ | 0.4 $H_T$                          |
| Vertebra pitch joint | 0.01 $M_T$               | $\frac{1}{12} H_{Trunk}$           |
| Lumbar part          | $N_v 0.01 M_T$           | $H_{Trunk} - H_{Thorax}$           |
| Thorax               | $M_{Trunk}$              | $(1 - N_v \frac{1}{12}) H_{Trunk}$ |

TABLE I  
MASSES AND HEIGHTS OF BODY PARTS ( $\delta_j = 1$  IF  $N_j \neq 0$ )

Given the input above, the algorithm must compute all joint angles  $(\beta^i)$ :

- At  $t=0$ , calculate initial  $\beta_{t=0}^i$ ,  $F_{t=0}$ , and Jacobian  $J_{t=0}$ .
- For each next position  $F_{next}$  of input trajectory,
  - 1)  $\Delta F \leftarrow F_{next} - F(t)$ .
  - 2) Calculate pseudo-inverse  $J^+$  from Jacobian  $J$ .
  - 3)  $\Delta\beta \leftarrow J^+ \Delta F$ .
  - 4)  $\beta(t + \Delta t) \leftarrow \beta + \Delta\beta$ .
  - 5) Calculate  $F(t + \Delta t)$  using  $\beta(t + \Delta t)$  from forward geometric model.
  - 6) Calculate Jacobian  $J$  using  $\beta(t + \Delta t)$  for next step.

Where  $F$  is the force applied by segment  $i$  to  $i - 1$ , and  $(\beta^i)$  is the joint angle, between segment  $i - 1$  and  $i$ .

### B. Simulation and results

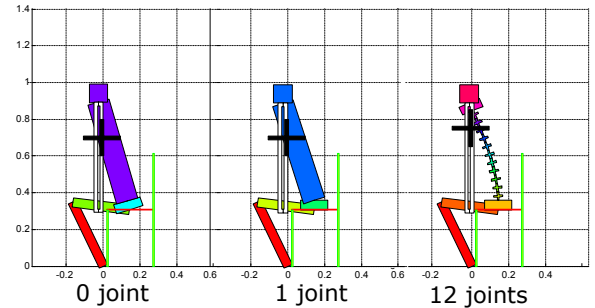


Fig. 3. Sitting up straight. This motion lasts 3 [sec].

The experience consists of sitting down on the chair Fig. 3. This simulation aims to determine the influence of the number of vertebra pitch joints in matter of force applied in the vertebrae. The cervical region, sacrum and coccyx are fixed. The vertebrae are placed in the lumbar and thoracic region between the first lumbar vertebra and the 7th vertebra of thorax, the region most affected by the (AIS). The experiment of sitting down was carried out with 0 vertebrae, with 1 vertebra and with 12 vertebrae in the spine.

Fig. 4 shows the thorax inclination for different number of pitch joints. The inclination of trunk increases significantly when the number of vertebra joints increases. From 12 joints, there is an increase of nearly 60% of thorax inclination compared with the configuration without articulated spine.

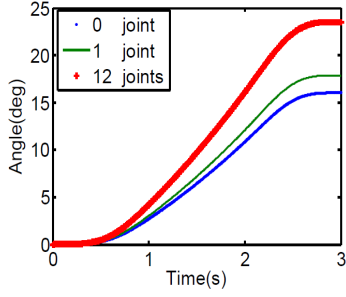


Fig. 4. Inclination (degrees) of thorax in sitting down motion.

Simulation experiments of sitting down carried out in the sagittal plane have shown that pitch joints in the vertebral column is so important. Rigid brace can limit the motions of kid. According to experiments we propose to work with 12 joints placed in the trunk.

### III. DYNAMIC SIMULATION OF NORMAL AND DEFORMED SPINE

#### A. Dynamics

Fig. 5 shows the actuation planes. In this section the counterclockwise torque  $T_a$  about centre of gravity produced by the applied force  $F_a$  is calculated:

$$T_a = F_a \cdot L_T \quad (2)$$

Where  $L_T$  is the length of child from centre of gravity to head and equal to  $0.70[m]$ .

The opposite restoring torque  $T_b$  due to the upper body's weight is:

$$T_b = P \cdot D \quad (3)$$

Where  $D$  is the diameter of waist and assuming that the masse of upper body of the child is  $20[kg]$ , his weight  $P$  is:

$$P = 40.9.8 = 392[N] \quad (4)$$

for  $D = 0.101[m]$  and  $T_b = 43.12[N.m]$ . The restoring torque produced by the weight of upper body is tehrefore  $[N.m]$  Trunk is on the verge of toppling when the magnitudes of these two torques are equal; that is:

$$T_a = T_b \quad (5)$$

So the force required to move trunk of child in sagittal plane is :

$$T_a = 43.12/0.70 = 61.6[N] \quad (6)$$

By bending the torso the center of gravity will be shifted away and as the result will the restoring torque be increased.

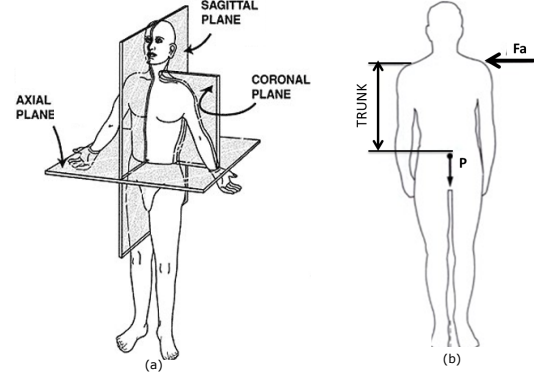


Fig. 5. (a) Sagittal plane, coronal plane, and axial plane. (b) Force applied to person to move in sagittal plane

#### B. A cad model for motion simulation

In this paper a simple model is proposed for the lumbar and thoracic parts of a spine. In this model we consider that all solicitations of the spine are vertically applied at the center of the vertebra. The 3D model has been elaborated in ADAMS with the aim to run a dynamic simulation for computing motion properties and reaction forces Fig. 6. In ADAMS the discus has been modeled as a body that is attached to the assembled vertebrae. Joint between all discs is spherical. This joint is very near to the real type of link between vertebrae. First simulation consists of tilting the entire body to the right

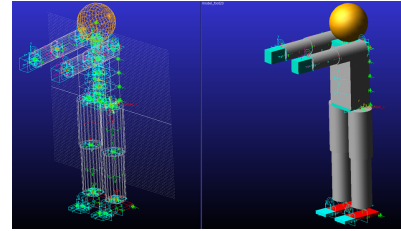


Fig. 6. A 3D ADAMS model of all body. Masses and heights of the different body parts are derived from a human kid-size model.

and left and calculating the forces applied to the column in the thoracic and lumbar region. Fig. 7 shows the simulation with ADAMS and the result of vertical forces applied in vertebrae for the left bending motion and Fig. 8 shows the simulation with ADAMS and the result of vertical forces applied in vertebrae for the forward motion. Regarding the simulations, vertical forces applied to the thoracic and lumbar vertebrae vary between  $130[N]$  and  $107[N]$  for the left bending motion. Results correspond to the equation (6). When the distance between force and vertebra is small, the magnitude of force is more important.

For the forward/backward motion forces vary between  $350[N]$  and  $300[N]$ . To compare the normal and deformed spine caused by scolios, we change the place of the spherical joint in vertebral column to simulate the thoracolumbar

deformation. Fig. 9 shows the translation of the vertebrae in spine simulated with ADAMS, and the results of forces applied to vertebrae for the same motions forward, backward and left/right bending.

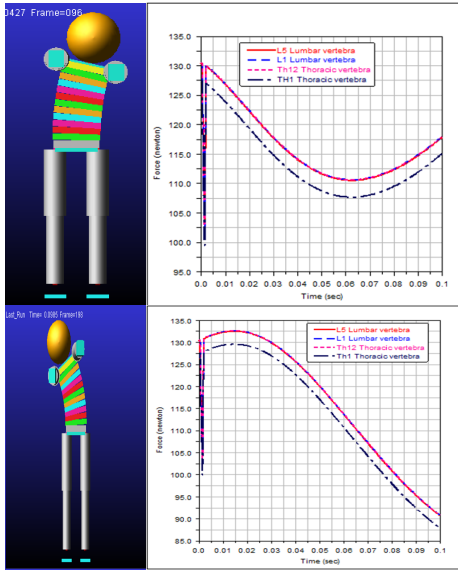


Fig. 7. Forces applied to the vertebrae for the left bending motion

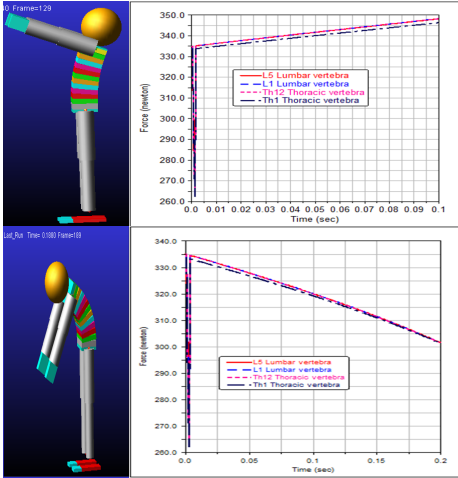


Fig. 8. Forces applied to the vertebrae for the forward motion

Regarding the simulations done to the deformed spine, forces applied to the vertebrae for the left/right bending motion are more important than the force in the normal spine. Forces achieve  $137[N]$ . In the next section we propose a mechanism to correct the abnormal posture change along the length of the curve.

#### IV. PARARELL TILTING MODULE FOR CORRECTING POSTURE

##### A. Kinematic model

Mechanism was simulated with ADAMS Fig. 11. It is fixed in the lumbar and thoracic region. The parallel mechanism [8],

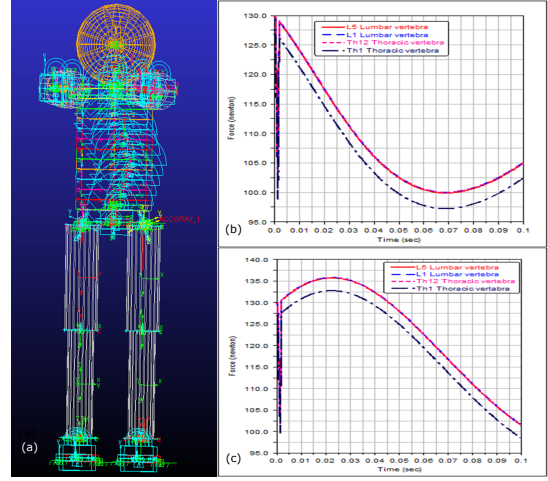


Fig. 9. Forces applied to the vertebrae for the left/right bending motion

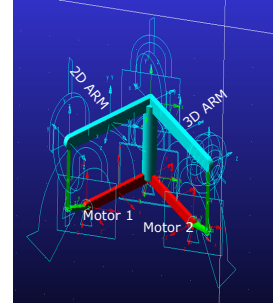


Fig. 10. Prototype fixed in the spine.

[9] consists of 2 platforms – one bottom platform  $CA_3B_3$  and one top platform  $OA_1B_1$ , that are linked by a central vertical rod  $CO$  and two arms arranged at  $90[deg]$  in the initial position (Fig. 11). The central rod  $CO$  is fixed and always remains vertical. It joins the top platform through a Universal joint whose drive is responsible for roll and pitch motion of the top platform. The arm  $A_1A_2A_3$  is planar and is composed of two segments, two revolute joints at  $A_2$  and  $A_3$ , and one Universal joint at  $A_1$ . This is the planar arm. The arm  $B_1B_2B_3$  also includes two segments, one revolute joint at  $B_3$ , one Universal joint at  $B_2$  and one ball joint at the attachment locus  $B_1$  with the top platform. This arm is 3D. The bottom platform is linked to coordinate frame  $R_0$ , centered at  $C$  with axes  $i, j$  and  $k$ . The top platform rotates about  $O$  and is linked to coordinate frame  $R'$ , frame centered at  $O$  whose axes are  $i', j'$  and  $k'$  (Fig. 12). The top platform can be pitched about fixed axis  $j$  by angle  $\theta_{10}$ , and rolled about axis  $i'$  by angle  $\theta_{21}$ .

The two active joints are the revolute joints at  $A_3$  and  $B_3$ . The associated rotation angles are denoted by  $\alpha$  and  $\beta$ .

The length  $d_4$  and  $\ell_4$  are approximately half the lengths  $d_1$  and  $\ell_1$  respectively. This means that the motor axes should be located in the middle with respect to the trunk half width and the trunk half depth respectively.

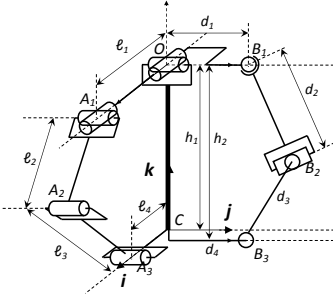


Fig. 11. Perspective view of parallel mechanism in initial position. The central rod is fixed and rigid. It is attached to the top platform by a Universal joint at  $O$ . The mechanism is actuated by two revolute joints, each of them is located at the bottom of each arm. The two arms are arranged at  $90 [deg]$ . The arm  $A_1A_2A_3$  is planar and remains in the  $(xz)$  plane. It is composed of two revolute joints and one U-joint. The other arm  $B_1B_2B_3$  is initially in the  $(yz)$  plane, and does not remain in this plane if the top platform rolls.

| Parameter         | 3D arm | 2D arm |
|-------------------|--------|--------|
| $\frac{d_1}{h_1}$ | 0.625  | 2.3    |
| $\frac{d_2}{h_2}$ | 0.625  | 0.625  |
| $\frac{d_3}{h_3}$ | 0.56   | 1.91   |
| $\frac{d_4}{h_4}$ | 0.20   | 0.20   |

TABLE II

NORMALIZED PARAMETERS OF 3D AND 2D ARM

### B. Geometric Intrepatation

$\tau_1^S$  and  $\tau_2^S$  are the torques exerted on the axis  $i'$  and  $vectj$  (Figure 12) in the central rod that the serial mechanism should compensate since these bonds are motor in this case, we can write:

The two motions are obtained by giving the angular inputs for the pitch/roll joint of the top platform, namely  $\theta_{10}$  and  $\theta_{21}$ . The platform is bent  $10[deg]$  forward, then  $10[deg]$  backward and left/right bending.

The angles for the joint motors, namely  $\alpha$  and  $\beta$  are calculated thanks to the inverse geometric model [8]. Figure 14 shows the trajectories of platform pitch and roll angles  $\theta_{10}$  and  $\theta_{21}$  and the related motor angles  $\alpha$  and  $\beta$  in the case of pitch inclination motion.

To reduce torques in the parallel mechanism, it is therefore necessary to reduce these two ratios as possible so, globally, by considering the full scope of inclinations from specifications [10]. Intuitively through the geometrical interpretation, the area of triangle  $A_1A_2A_3$  should be reduced compared to the triangle  $OA_1A_2$ . This can be achieved by increasing the length  $A_1A_2$  over  $A_2A_3$ , and increasing the length  $OA_1$  from  $OC$ . However, not to "make" flat triangles, and ensure that  $A_1A_2$  does not come too align with  $OA_1$  and therefore remains as close as possible to the orthogonal to  $OA_1$ .

### C. Simulations and result

The prototype was simulated with ADAMS and trajectory planning is designed with Matlab-SIMULINK, which is used to control the ADAMS model [9]. Prototype is used to correct

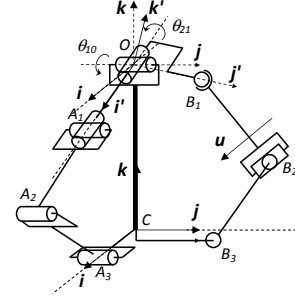


Fig. 12. Perspective view of parallel mechanism after pitch and roll rotations.

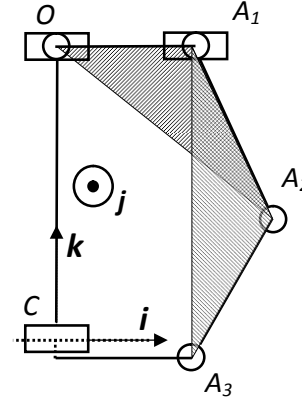


Fig. 13. Geometric interpretation of the ratio of the couple  $A_3$  mechanism parallel to the torque of the serial mechanism in  $O$ . The ratio of the mixed product is the ratio of the area of the triangle  $A_1A_2A_3$  on the  $OA_1A_2$ .

the posture of the spine in two plane: sagittal and coronal plane. Fig. 15 shows the torque of the two motors of roll joint to move spine in the sagittal plane. Maximal torque of the 3D arms is  $10[N.m]$  and torque of the 2D motor is constant and is about  $6[N.m]$ . Fig. 16 shows the torque of the two motors of pitch joint to move spine in the coronal plane. Maximal torque of the 3D arms is  $10[N.m]$  and torque of the 2D motor is constant and is about  $8[N.m]$ .

Mechanism was simulated with Solidworks. All joints come from the HPC company Fig. 17. For both active joints electric motors are used. The variation of torque with speed obtained with ADAMS allows to select the motors that best suit our needs. We use Maxon motors, because these actuators are lightweight and one of them meets our requirements: the *RE25G*. The characteristics of the motors are given in table III.

## V. CONCLUSION AND PERSPECTIVES

In this paper, a model for the human spine is proposed for analyzing applied forces on the intervertebral discs through a suitable motion simulation. Comparison between normal and deformed spine caused by the scoliosis was done and shows that forces change in the second case. The contributions of this work can be considered as: a new model for the human spine, where the spine properties has been used as characteristics of

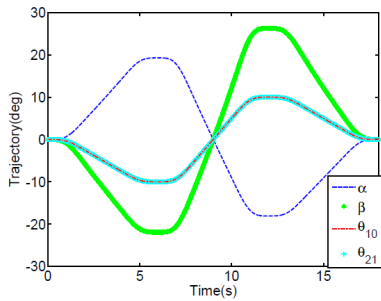


Fig. 14. Angle trajectories  $\theta_{10}$  and  $\theta_{21}$  of platform and the related motor angles  $\alpha$  and  $\beta$  for the pitch inclination motion..

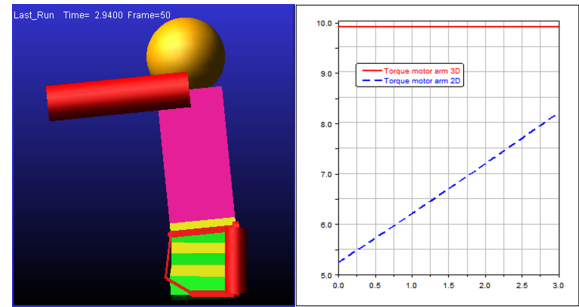


Fig. 16. Prototype used to correct the posture in the coronal plane.

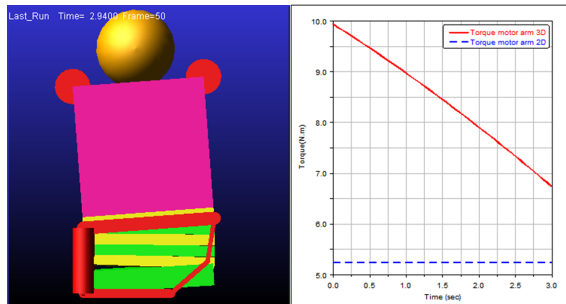


Fig. 15. Prototype used to correct the posture in the sagittal plane.



Fig. 17. Prototype simulated with SolidWorks.

a serial joint linked with spherical connectors. Also a parallel mechanism was proposed to correct the posture of the spine in two plane, sagittal and coronal plane. The next steps of this research will consist of the precise optimization of the parallel mechanism dimensions. And the realisation and motorisation of system.

The next steps of this research will consist of the precise optimization of the parallel mechanism dimensions. In addition the study will be extended to take into account several piled parallel mechanisms.

## REFERENCES

- [1] Kapandji - Physiology of the Joints: The Trunk and the Vertebral Column. Volume 3, February 2007.
- [2] A. H. W. V. Eeuwijk, S. Lobregt, F. A Gerritsen, A novel method for digital X-ray imaging of the complete spine, Philip Medical Systems, Netherlands, 2006.
- [3] S. M. Anderson, Spinal curves and scoliosis, Radiologic Technology, vol. 79(1), September/October 2007.
- [4] J. Zhang, E. Lou, L. H. Le, D. L. Hill, J. V. Raso, Y. Wang, Automatic Cobb measurement of scoliosis based on fuzzy Hough transform with vertebral shape prior, Journal of Digital Imaging, vol. 22(5), pp. 463-472, October 2009.
- [5] Schiller, J.R., Thakur, N.A. and Ebersson, C.P. (2010) "Brace management in adolescent idiopathic scoliosis", Clinical Orthopaedics and Related Research , 468(3), pp.670-678.
- [6] Aulisa, A.G., Guzzanti, V., Marzetti, E., Giordano, M., Falciglia, F. and Aulisa, L. (2014) "Brace treatment in juvenile idiopathic scoliosis: a prospective study in accordance with the SRS criteria for bracing studies-SOSORT award 2013 winner", Scoliosis,9(3).
- [7] M. Souissi, V. Hugel, P. Blazevic, "Influence of the number of humanoid vertebral column pitch joints in flexion movements", *Proceedings of The IEEE International Conference on Automation, Robotics and Applications*, 2011.
- [8] M. Souissi, V. Hugel, P. Blazevic, "Design optimization of parallel joint mechanism for humanoid spine", in: The 16th IEEE Mediterranean Electrotechnical Conference, 2012, pp. 997-1000.
- [9] M. Souissi, V. Hugel, P. Blazevic, "Modeling and simulation of humanoid robot spine vertebra", in: The 9th International Conference on Informatics in Control, Automation and Robotics (ICINCO), (2), 2012, pp. 415-418.
- [10] M. Souissi, V. Hugel, S. Garbaya, and J. Nassour "Minimized-Torque-Oriented Design of Parallel Modular Mechanism for Humanoid Waist", in: The 15th International Conference on Advances in Robot Kinematics (ARK) France 27-30/06 2016.

| Characteristic | Value       |
|----------------|-------------|
| Supply voltage | 12V         |
| Rated current  | 1.2 A       |
| No load speed  | 202 r / min |
| Load speed     | 156 r / min |
| Rated torque   | 10 Nm       |

TABLE III  
PARAMETERS OF THE MOTOR.