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Pneumatically Operated Equipment for the Rehabilitation of the Neck Joint

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Abstract
The aim of this study is to present a solution for the rehabilitation of the neck joint using a pneumatically operated device. Neck pain or musculoskeletal imbalances require rehabilitation as fast and as adaptable as possible to the individual patient's situation. The paper presents the diagram of principle of a novel neck joint rehabilitation equipment and its geometrical model. Further discussed are the limits of its movement and the required characteristics of the three pneumatic muscles used for actuation.

Keywords
Neck joint; rehabilitation equipment; pneumatic muscle; rehabilitation;

1. Introduction

The neck joint is one of the most complex joints in the human body, is located in the area of the cervical spine, and consists of seven vertebrae. Neck disorders affect patients' lives by reducing their range of movement. Fortunately, most conditions are recoverable by means of therapeutic methods, such as repetitive movements to improve motion coordination and muscle strength [1] generated either manually by a physiotherapist or by a robot-based rehabilitation system. Such a system must meet some absolutely necessary characteristics such as gentleness, safety, compliance and ease of use [2]. Principally Continuous Passive Motion (CPM) is used for the rehabilitation of the neck joint, aimed at reducing its stiffness and generating fibrous tissue by mobilizing it with the help of mechanized devices. The main characteristic of equipment based on the method of passive joint mobilization is compliance, *i.e.* adaptability in any situation. Although electrically powered equipment meets this characteristic, it is necessary to invest in sensors and proper design of control diagrams. The excessive use of sensors attached to rehabilitation equipment is avoided by deploying adjustable compliant actuators (ACA) like the pneumatic muscle which, due to the compressibility of air, is compliant.

The conducted market and literature research has not identified any complex, pneumatically actuated equipment for rehabilitation of the neck joint in multiple directions. Thus, this paper presents a newly developed equipment for neck joint rehabilitation. The paper is structured in two sections: 1.) overview of the equipment; 2.) description of the geometrical model and the two modules of the equipment: rotation in the transverse plane and movement in the sagittal and frontal planes.

2. Overview of pneumatic muscle-powered rehabilitation equipment

2.1. Movements of the neck joint in the three anatomical planes

As previously mentioned, the neck joint is one of the most complex joints of the human body. Therefore, prior to conceiving adequate rehabilitation equipment, it is important to determine the movements performed by the neck joint in the corresponding anatomical planes. A further essential aspect to be considered concerns the limits of such movements. As shown in (Fig. 1), the three anatomical planes of the human body are the sagittal, frontal and transverse ones.

In the sagittal plane, flexion is performed with an angular limit of 50° and extension with an angular limit of 60°. In the frontal plane, lateral flexion to the left and to the right can be performed with angular limits of 45° in each direction. In the transverse plane left and right rotation by 80°, respectively, can be achieved.

It is also necessary to know the forces and moments developed by the muscles of the neck joint. (Table 1) shows the maximum moments required for each type of movement, to be generated by the proposed equipment [3].

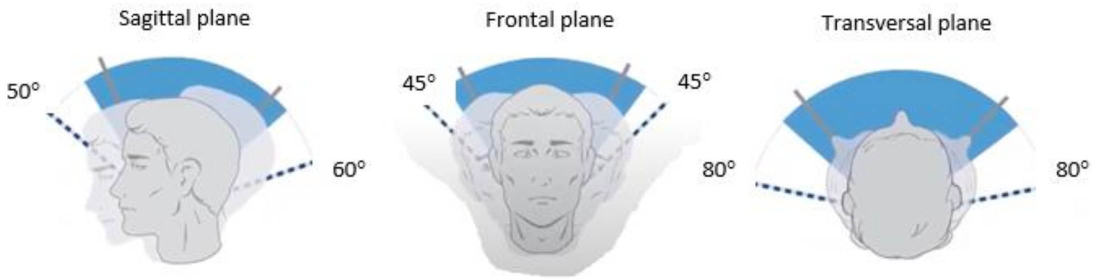
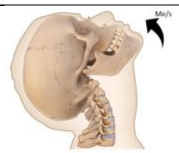
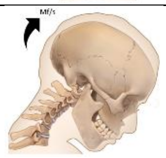
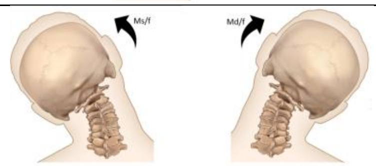
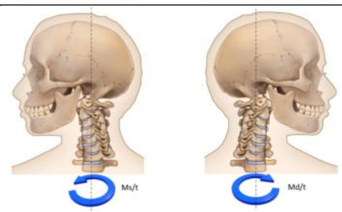


Fig. 1. Movements of the neck joint in the three anatomical planes and their limits

Table 1. Maximum moment required for each plane according to the type of movement

Type of movement	Maximum moment required [N·m]	Illustration
Sagittal extension	24	
Sagittal flexion	20	
Frontal left-right lateral flexion	20	
Transverse left-right rotation	10	

The information presented above has underlain the development of the new equipment for neck joint rehabilitation.

2.2. Presentation of the geometrical model of the rehabilitation equipment

The working principle of the rehabilitation equipment is presented in Fig. *2*. The main components of the equipment are highlighted, namely the cylindrical support for immobilizing the patient's head, the torsional pneumatic motor driven by two pneumatic muscles for achieving movements in the transverse plane, the pneumatic motor for achieving movements in the sagittal/frontal plane. Fig. *3* shows the geometrical model of the rehabilitation equipment created by integrated 3D CAD/CAM/CAE PTC Creo software [4].

The equipment is supported by a profile bar (Bosch) of square 80×80 mm cross section and 1000 mm length. At the top, rigidly attached to this vertical support is a horizontal crossbeam, also made of (Bosch) profile bars (80×40 mm). This structure supports the two rotating modules.

2.2.1. Presentation of the transversal plane rotation mode of the rehabilitation equipment

To perform transverse rotation the equipment consists of a torsional motor which including two pneumatic muscles (4) as shown in Fig. *4*. Their operation is similar to that of human muscles, based on the agonist-antagonist principle, similar to the flexion and extension movements of the forearm.

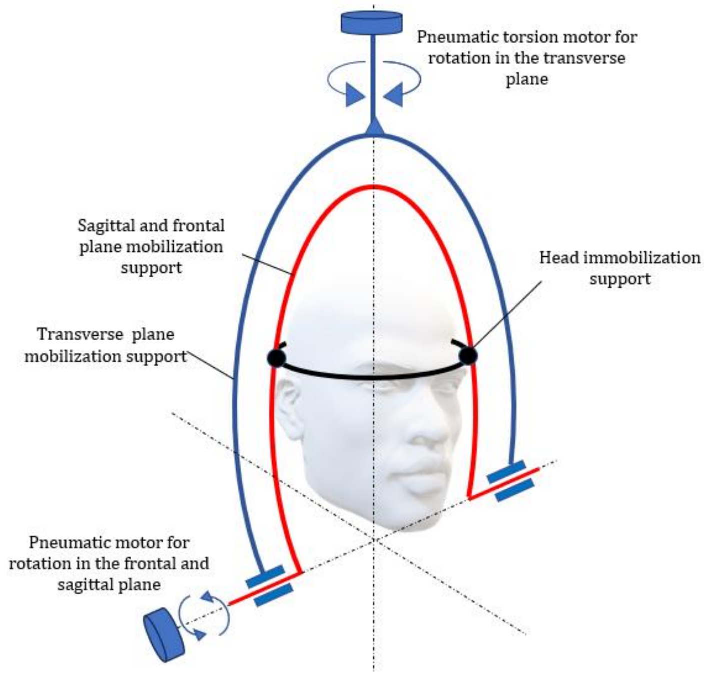


Fig. 2. Working principle of the rehabilitation equipment

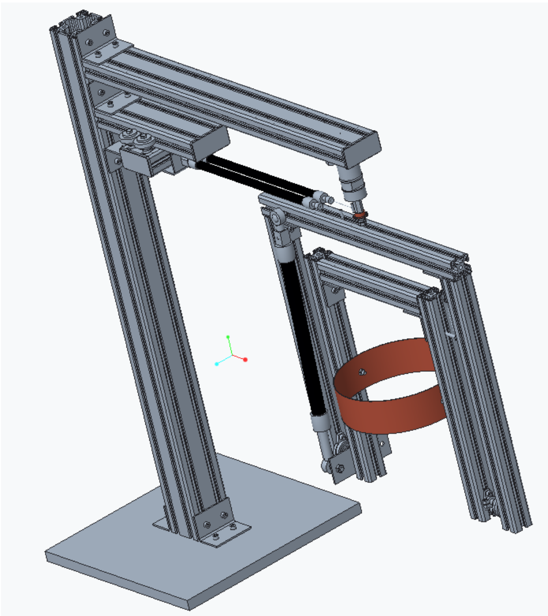


Fig. 3. Neck joint rehabilitation equipment (3D view)

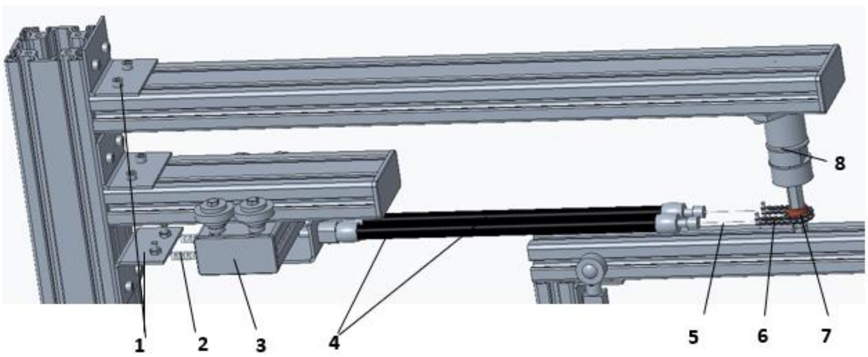


Fig. 4. Upper part of the equipment

The rotation of the head in the transverse plane is achieved by the antagonistic operation of the two pneumatic muscles, by the simultaneous contraction of one of the muscles and the relaxation of the other. The free ends of the two muscles are connected by a Gall chain (6), passed over a chain wheel (7). The design of the assembly took into account the moments of inertia of the head and its support. The torsional motor was designed upon analysing the forces and moments required for the rotation by the vertical axis, as shown in Fig. *5*.

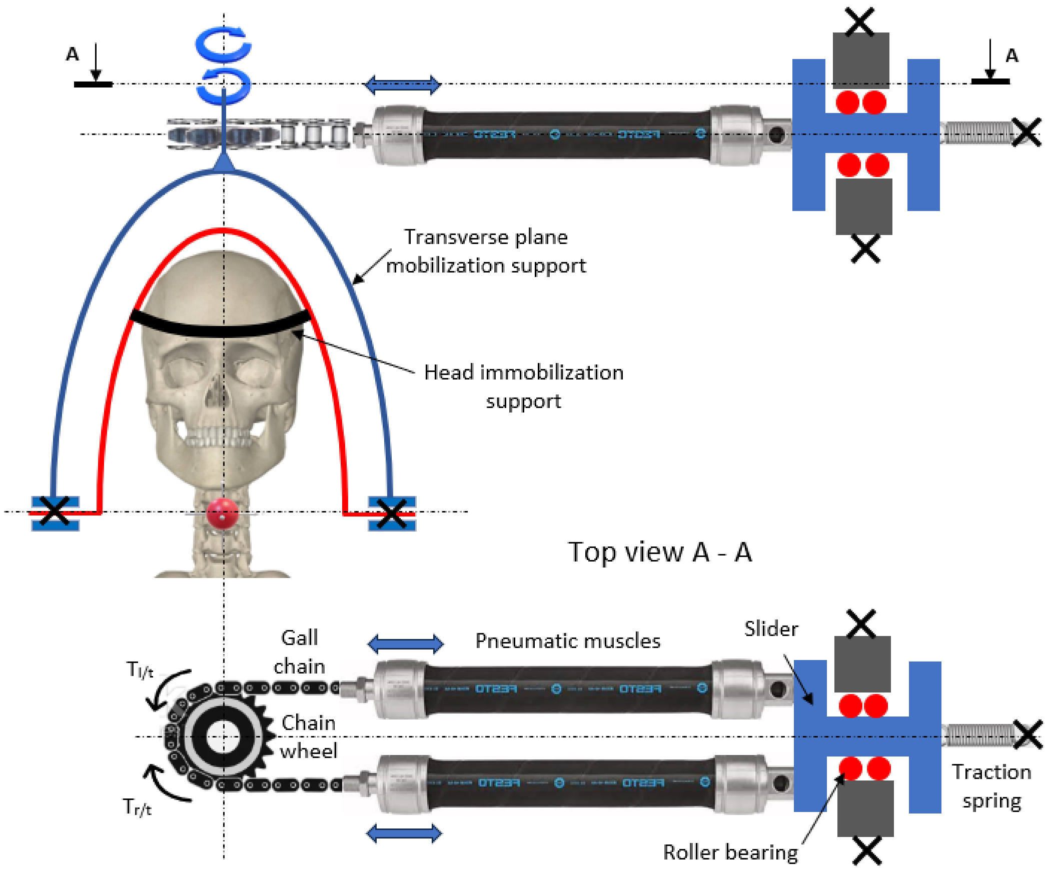


Fig. 5. Construction of the torsional motor

The variation curves of the forces developed by the two pneumatic muscles are shown in Figure 6. The first muscle, charged with air, is considered active, while the second, discharged muscle is considered passive. The feed pressure of the two muscles ranges from 0 bar to 6 bar. In the graph the specific axial contraction ε is read on the abscissa from left to right for the active muscle and from right to left for the second, passive, muscle.

The chain wheel (7) in Fig. *4* causes the rotation of the mobilization frame in the transverse plane.

2.2.2. Overview of the sagittal and frontal motion mode of the rehabilitation equipment

The transverse mobilization frame (1) in Fig. *7* supports the second, sagittal/frontal mobilization frame (2). The connections between the two mobilization frames are achieved by means of bearings and shaft supports (4, 5).

The sagittal and frontal movements of the neck joint are performed by the inner mobilization frame of the rehabilitation equipment (2) alone, with the help of a single pneumatic muscle (3).

In the two planes, rotation in both directions is performed at an angle ω when the pneumatic muscle is charged with air at different pressures. The length of the pneumatic muscle as well as the magnitude of the developed forces are modified by the variation of the feed pressure.

The two planes of motion are represented in Fig. *8*, and the required limits for these are shown in Table 2.

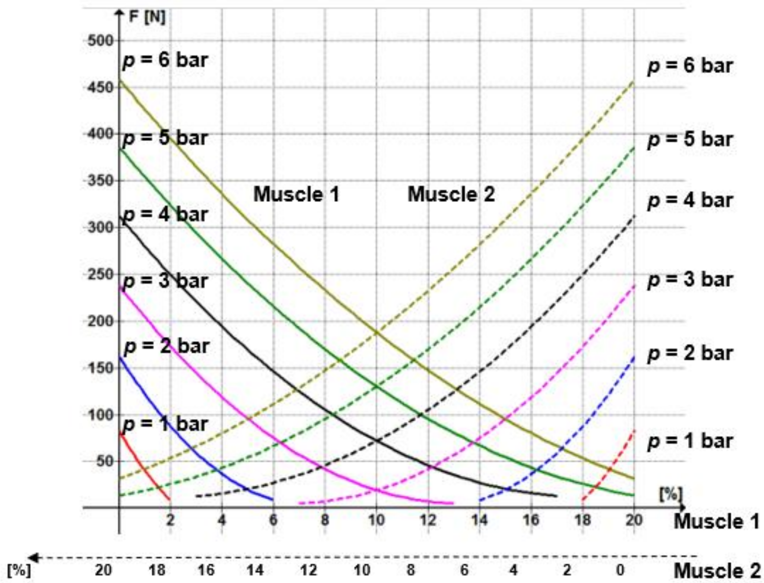


Fig. 6. Characteristic diagrams of the pneumatic muscles that form the torsional motor

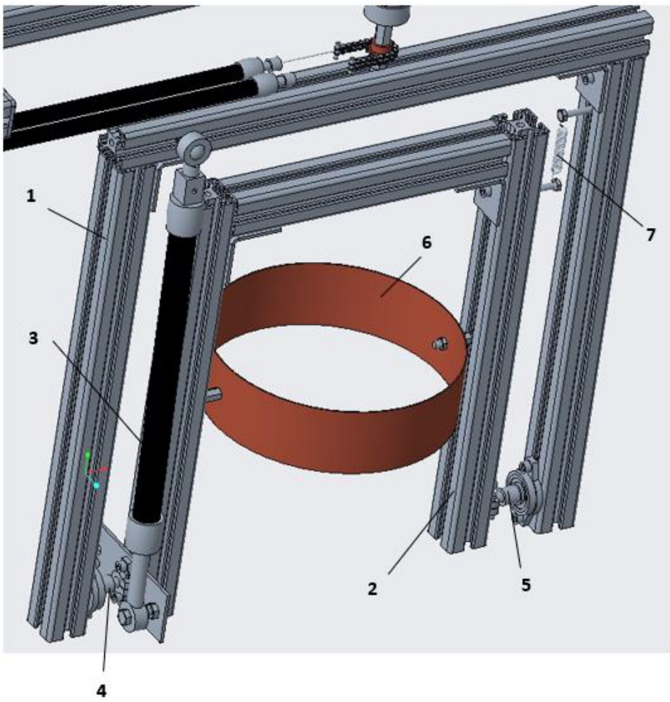


Fig. 7. Assembly of neck joint mobilization frames and head support

Table 2. Maximum allowed limits and moments for the two planes of motion

Plane	Limits of motion	Maximum allowed moments
Sagittal plane	- flexion: 50°; - extension: 60°.	12 N·m
Frontal plane	- left/right lateral flexion: 45°	20 N·m

The forces developed by the pneumatic muscle differ depending on the feed pressure of the muscle and its stroke. In the frontal plane a rotation at an angle $\omega = 45°$ requires an axial contraction of the pneumatic muscle of $\Delta L = 495 - 459.13 = 35.87$ mm. Similarly, for motion in the sagittal plane by a maximum angle $\omega = 60°$, $\Delta L = 43.93$ mm, as shown in Figure 9. The axial contractions of the pneumatic muscle are achievable when the pneumatic muscle is fed pressures between 2 and 6 bar.

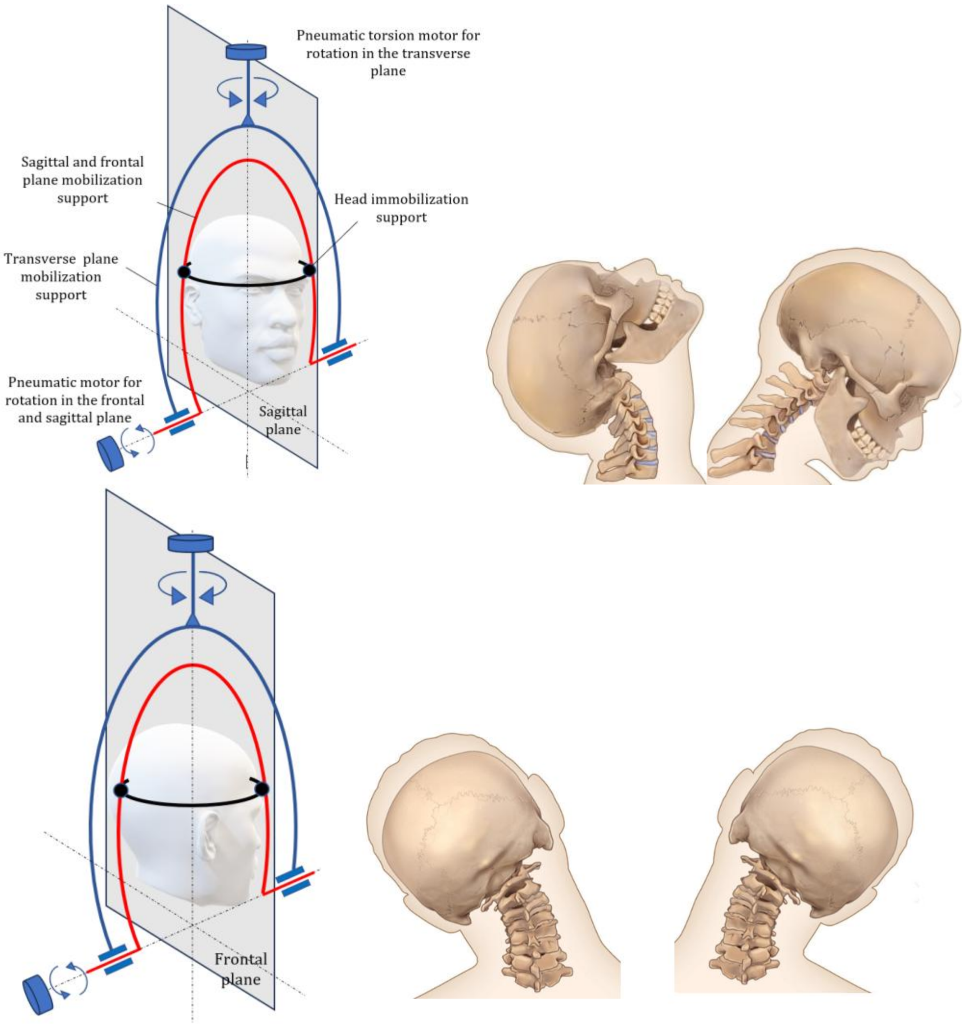


Fig. 8. Immobilization of the head for rotation in the sagittal and frontal planes

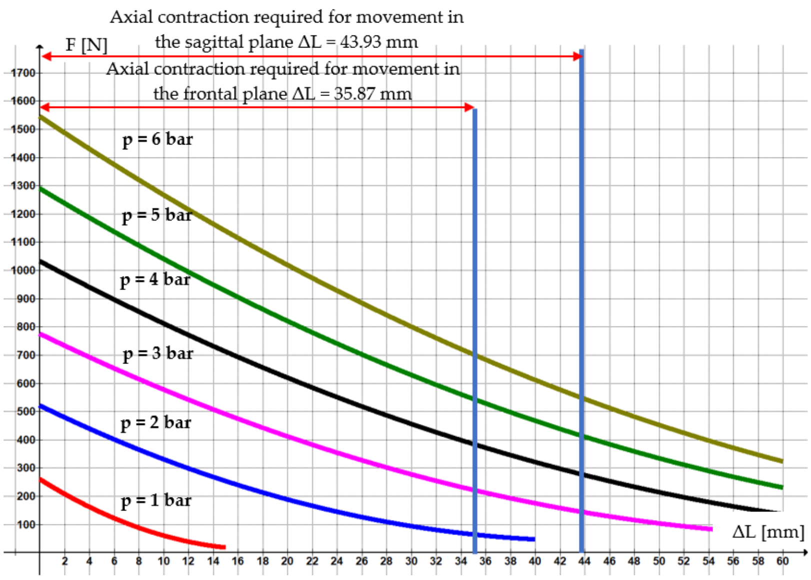


Fig. 9. Variation of the force developed by the pneumatic muscle for movements in the two planes

Figures 10 and 11 below show the variations of the rotational moments based on the axial contraction of the pneumatic muscle and the angle of rotation of the neck joint [5].

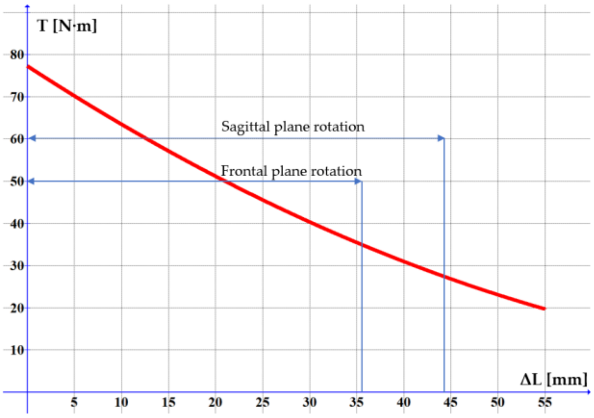


Fig. 10. Variation of the rotational moment versus axial contraction of the pneumatic muscle

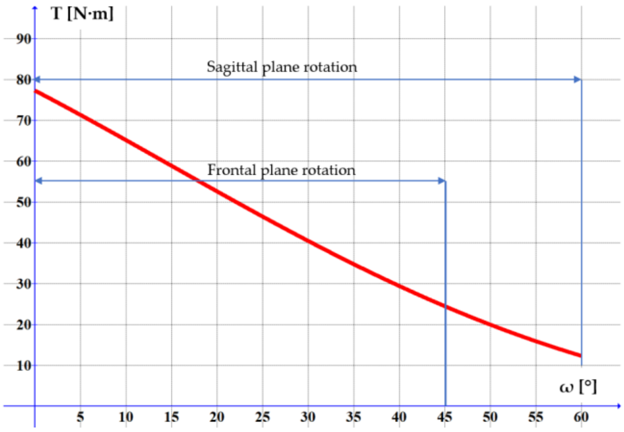


Fig. 11. Variation of the rotational moment versus the neck joint's angle of rotation in the sagittal/frontal plane

3. Conclusions

The proposed rehabilitation equipment allows rotations in the transverse, frontal and sagittal planes within the angular limits of a fully functional human body, ensuring accurate rotation angles and also compliant behaviour. The equipment is driven by three pneumatic muscles. The paper presents and discusses the constructive solution, working principle, and the variations of the rotational moments in dependence on the axial contraction of the pneumatic muscle and the rotational angle of the neck joint.

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