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Pneumatically Actuated Torsion Motor for the Transverse Rehabilitation of the Neck Joint

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Abstract: Work-related musculoskeletal disorders affect a large number of people, diminishing inter alia, their workplace efficiency. For this reason, rehabilitation procedures and equipment are called for, designed to expedite the swift reintegration of patients into daily activity. Within this context, this paper proposes a novel constructive solution of a device that ensures rehabilitation through the transverse passive mobilization of the neck joint. This paper introduces a torsion motor actuated by two pneumatic muscles that ensure sufficient adaptability of the device to, for example, conduct patient exercise within the boundaries of pain supportability. Based on the research results, recommendations are offered for the optimum operation of the rehabilitation equipment.

Keywords: rehabilitation equipment; neck joint; pneumatic muscle; compliance

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1. Introduction

Musculoskeletal disorders—MSDs—represent the main cause of workplace absences and the loss of productivity in EU member states [1]. The most frequent biomechanical risk factors that cause MSDs include, among others, unjustified repetition of uncomfortable movements and posture [2]. Recent clinical research has shown that teenagers experiencing persistent musculoskeletal disorders are exposed to the risk of chronic pain at an adult age [3].

Musculoskeletal disorders that include muscles, tendons, ligaments, joints, peripheral nerves and blood vessels and that are caused by workplace-specific tasks and the difficult conditions of the working environment are called work-related musculoskeletal disorders—WMSDs [4]. The risk factors for WMSDs are static and non-ergonomic postures, repetitive movements, excessive use of bodily force, vibrations, mechanical compression and temperature. The data supplied by the Great Britain Labor Force Survey (2021) reveal a number of about 470,000 registered workers who suffer from work-related musculoskeletal disorders. The majority of complaints were located in the neck (45%), back (39%) and inferior extremities (16%) [5].

The neck joint is one of the areas of the human body that is frequently affected by WMSDs. The cervical spine, consisting of the first seven vertebrae, is one of the most complex human articulations. The muscles involved in this articulation are numerous and each has its role in both moving and stabilizing the joint. The rehabilitation procedures of this joint need to address the motor state (muscle tonus) and the sensorial state (proprioception), as well as the psychological, social and professional status of the patient. The pain occurring in the neck joint ranks eighth in the pathology of young people aged 15 to 19; neck joint pain exceeds any other well-known health problems in teenagers, like substance abuse, traffic accidents and asthma [6].

Dysfunctionalities caused by trauma to the neck joint have a high rate of functional recovery, and thus allow for a swift reintegration of patients into everyday professional or home life. The development of efficient therapeutical methods has improved the duration of recovery and reduced the failure rate of treatment. A significant role in achieving swift patient recovery is the deployment of dedicated equipment for the rehabilitation of the complex neck joint.

Repetitive movements are known to have a positive impact on improving muscle force and motion coordination in patients with neurological and/or orthopedic disorders [7]. In the case of manual rehabilitation, the performance is difficult to quantify, and the physical therapist's assessment of patient progress during sessions is often subjective. This is one of the reasons for deploying mechanized methods of physical recovery therapy.

An alternative to manual rehabilitation is robot-assisted recovery. Robotic rehabilitation systems allow for the exact measurement of various parameters, like the duration of the exercise, forces, torques, etc. Thus, these systems allow for an objective evaluation of patient progress. Because of their interaction with humans, the concept of such robots has to meet a set of requirements completely different from industrial robots that operate in structured environments. These requirements include safety, conformity and gentle and easy deployment [8].

One of the procedures applicable in the rehabilitation of the neck joint is based on continuous passive motion—CPM. In this case, the affected joints are mobilized by way of external mechanized devices, with patient effort not being needed. The role of CPM is to prevent the generation of fiber tissue and reduce joint stiffness. The structure of a CPM-based rehabilitation device (robotic system) allows for the application of optimum recovery motions to the affected segment. Articular passive mobilization involves control of the applied forces, amplitudes, velocities and accelerations of movements, as well as of the duration and frequency of rehabilitation exercises. Due to the possibility of adjusting these parameters between certain limits, the rehabilitation exercises can be adjusted to the clinical state and the pain threshold of the patient [9].

A major requirement to be met by the rehabilitation equipment is compliant behavior, that is, the capability to adapt rapidly to any given concrete situation determined by the state of the patient that may differ from the initially considered one. Electrically actuated equipment meets this requirement to a smaller extent, as ensuring compliant behavior would entail costly systems due to significantly increased sensorization and complex control diagrams.

At present, on the market, there are some types of equipment used for the rehabilitation of the neck joint based on different operational principles. David Health Solutions Ltd. of Finland developed electrically actuated special devices for neck extension [10]. The equipment facilitates the extension and lateral flexion of the cervical spine by activating the lateral extensor and flexor muscles. NecksLevel Glide is a further neck joint rehabilitation device also deployable at a patient's home. The generated motions are cervical extension, flexion and rotation. NecksLevel devices are delivered with a set of three to six resistance bands designed to relieve muscle tension and increase the range of motion [11].

Cervical collars or braces are a special category of neck joint rehabilitation equipment. An example is the Twinklepoch cervical traction device, actuated pneumatically by means of an electrical minicompressor. The eight inflatable chambers of the device open up the inter-vertebrae spaces and release the compressed nerves [12]. The Ludwig Katrin cervical collar, developed by Guangzhou New Design Biotechnology Co., Ltd., Guangzhou, China, is also actuated pneumatically and can also be used at the patient's home for the extension of the cervical spine [13]. Studies on the efficiency of cervical collars reveal that the intensity of the pain experienced by the patients decreased significantly after four weeks of utilization [14].

BTE Technologies proposes complex rehabilitation equipment for the neck joint that generates movements in the frontal, sagittal and transverse planes. The device, called Multi-Cervical Unit (MCU), is actuated electrically and was designed for "patients suffering from neck pain, whiplash-associated disorders (WAD) and general cervical spine disorders". All characteristics of the joint movements are compared to the reference values and saved to the computer, thus ensuring a good traceability of each patient's progress [15].

DBC of Finland is another producer of neck joint rehabilitation equipment. DBC's range of equipment includes the Multi-Purpose Low-Friction Unit (MLU), the Cervical Extension (CE) and the Cervical 3-Dimensional Rotation (C3R) units that generate elliptical bidimensional motions in the sagittal plane or linked motions of posterior sliding and rotation by the transverse axis [16].

All identified neck joint rehabilitation devices are designed for utilization either by the patients in their homes or in specialist clinics under the guidance of a physical therapist. They are conceived for manual or, in most cases, electrical actuation. The extremely few pneumatically actuated devices available are generally used to immobilize the neck joint in a certain position. However, a complex compliant rehabilitation device that allows motions along several directions could not be identified in the researched literature. Based on these findings, this paper presents a torsion motor consisting of two pneumatic muscles conceived for the actuation of a device that generates neck joint rehabilitation motions in the transverse plane. The novelty brought by this paper consists of the description of the torsion motor, i.e., its construction and operation and the presentation of its performance with an emphasis on its compliance. The utilized pneumatic muscles are known for their inherently compliant behavior, broadly recognized as safe actuators for devices that assist or interact with humans. In the growing field of rehabilitation robotics, adjustable compliant actuators are implemented because of their ability to minimize large forces due to shock, and to safely interact with the user. More and more applications in rehabilitation devices demand a different set of design specifications, for which the use of compliant actuators can be beneficial as compared to the traditional stiff actuation schemes.

This paper is organized into six sections. The introduction is followed by Section 2 which presents the biomechanics of the neck joint, with an emphasis on transverse motions. The purpose of this section is to provide the input data required for designing rehabilitation equipment. Section 3 presents the operational principle of the proposed torsion motor. The kinematic diagram of the rehabilitation equipment is presented and the phases of its functioning are described. Section 4 includes the static analysis of the torsion motor and the determination of its performance. Also presented are the calculations of torsional rigidity and compliance, two essential properties of medical rehabilitation equipment. In Section 5, the obtained results are discussed and recommendations for the operation of the equipment are formulated. Section 6 features the main conclusions of this study.

2. Biomechanics of the Neck Joint in the Transverse Plane

The neck is the part of the body that connects the head to the torso and it plays a significant role in the articulation of the head and spine. The neck is located between the cephalo-thoracic and the cervicothoracic lines and consists of the cranio-vertebral joints, in particular, of the left and right atlantooccipital joints (the superior joint) and the medial and lateral atlantoaxial (that make up the inferior joint). The atlantooccipital joints link the atlas (C1) with the occipital by means of the articular capsule and the anterior and posterior atlantooccipital membranes. The medial atlantoaxial joints are of pivot type, while the lateral atlantoaxial joints are plane. The neck joint allows motion in the three anatomical planes, namely frontal, sagittal and transverse, as shown in Figure 1.

The emphasis in this paper is on the motion in the transverse plane, that is, the left-to-right rotation of the head (Figure 2).

The neck joint rehabilitation equipment is dimensioned based on the values of the anthropometric parameters (indices) of the human head. Anthropometric indices are the quantitative measurements of the segments of interest in the human body. These values are needed for determining the dimensions, proportions and composition of the studied segments. In the case of the human head, the parameters of interest are mass, cranial perimeter, the dimensions of the head in the three anatomic planes, etc.

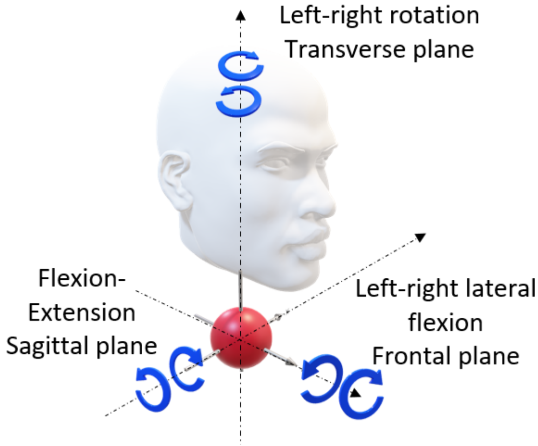

Figure 1. Motions of the biomechanical model of the neck joint.

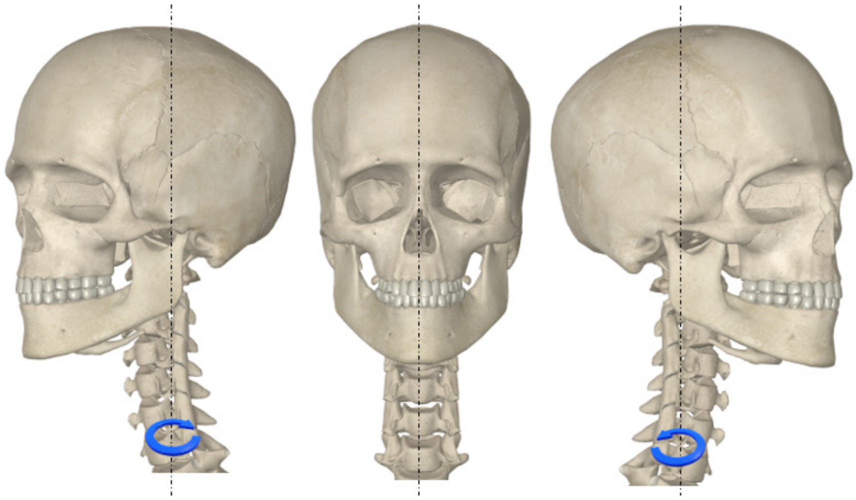

Figure 2. Left-to-right rotation of the head in the transverse plane.

The human head weighs approximately 5 kg and is supported by the seven neck vertebrae and the approximately 20 muscles that are responsible for moving the head and holding its weight. According to an anthropometric study carried out in the US, the average circumference of the human head is estimated at 57 cm in males and 55 cm in females [17]. Another study conducted by Newcastle University in the UK shows the average circumference of the human head at 57.2 cm in males and 55.2 cm in females, respectively, with the average dimension varying proportionally to the individual's height [18].

In the literature, average values for all these anthropomorphic indices are provided, with the data obtained by statistical processing. These data are shown in Figure 3 and Table 1.

In the transverse plane, the neck joint carries out left-to-right rotations of angular amplitudes of ±80°.

It is important to know the forces and torques developed by the neck muscles in order to understand the relationship between muscle function and the pathology of this joint. Patients suffering from neck pain often present diminished strength in their neck; correspondingly, strength training is associated with the diminishing of pain. The torques generated by the rotation in the transverse plane of the neck joint range between 6 ± 3 N·m and 10 ± 3 N·m, according to research reported in [19,20]. For the design of the torsion motor presented in this paper, the torque in the transverse plane was set at 10 N·m.

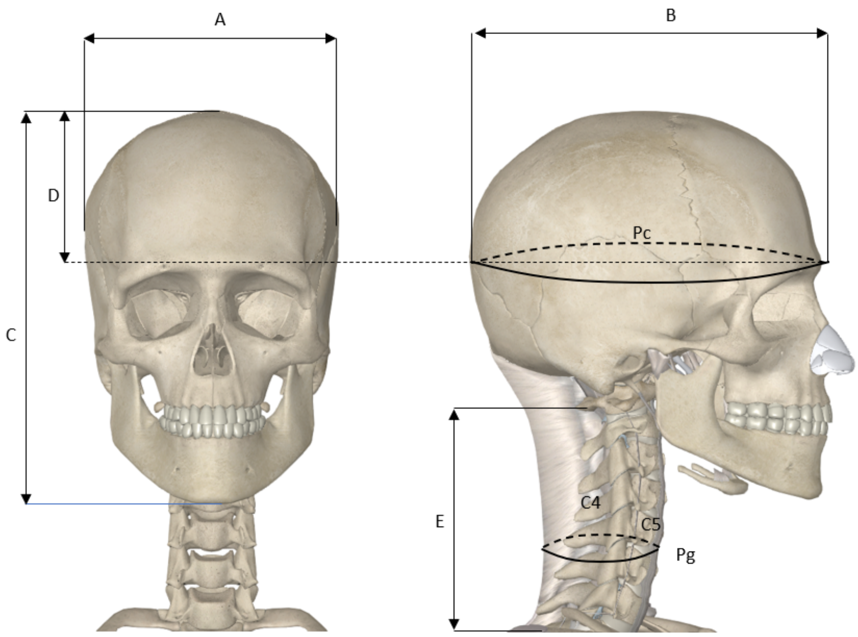

Figure 3. Anthropometric measurements of the human head and neck.

Table 1. Anthropometric indices of the human head and neck.

Maximum width of the head, typically above and behind the ears (A) [cm]	Males Females	16.5 15.8
Horizontal distance from the frontmost point of the forehead to the back of the head (B) [cm]	Males Females	21.7 20.7
Vertical distance from the lower part of the chin to the top of the head (C) [cm]	Males Females	25.5 23.8
Vertical distance from the depression of the nasal root to the top of the head (D) [cm]	Males Females	12.9 12.2
Circumference of the head (Pc) [cm]	Males Females	57 55
Mass of the head [kg]		5
Circumference of the neck (Pg) [cm]	Males Females	39.5 32.8
Length of the neck (E) [cm]	Males Females	10.8 10.6

3. Operational Principle of the Torsion Motor Conceived for the Transverse Rehabilitation Equipment of the Neck Joint

Figure 4 shows the kinematic diagram for the left-to-right rotation of the neck joint in the transverse plane. The actuation and control of the torsion motor will be devised according to the following schematic.

The patient's head is immobilized in a cylindrical support and is rotated together with this support on a vertical axis. The diameter of the cylindrical support is adjustable and thus allows for the mobilization of the neck joint of patients with different dimensions of their heads. The entire mechanical structure will be built from light aluminum profiles.

The rotation is generated by a torsion motor actuated by two pneumatic muscles. By working antagonistically, the muscles generate a rotation of $\pm 80^{\circ}$ amplitude and also maintain a specific intermediary position in the actuated system.

Regarding the actuation and control of the torsion motor, the reached position will be confirmed by a rotary encoder. The signals are picked up by the I/O controller WeAct Black Pill V2.0. Each pneumatic muscle is controlled by a VPPI proportional pressure regulator. Depending on the position to be achieved, the controller will control by means of an analogic signal from the proportional pressure regulator, VPPI (manufactured by Festo, Germany). The position commands can be given from either a laptop or a joystick, as the I/O module has the corresponding digital inputs.

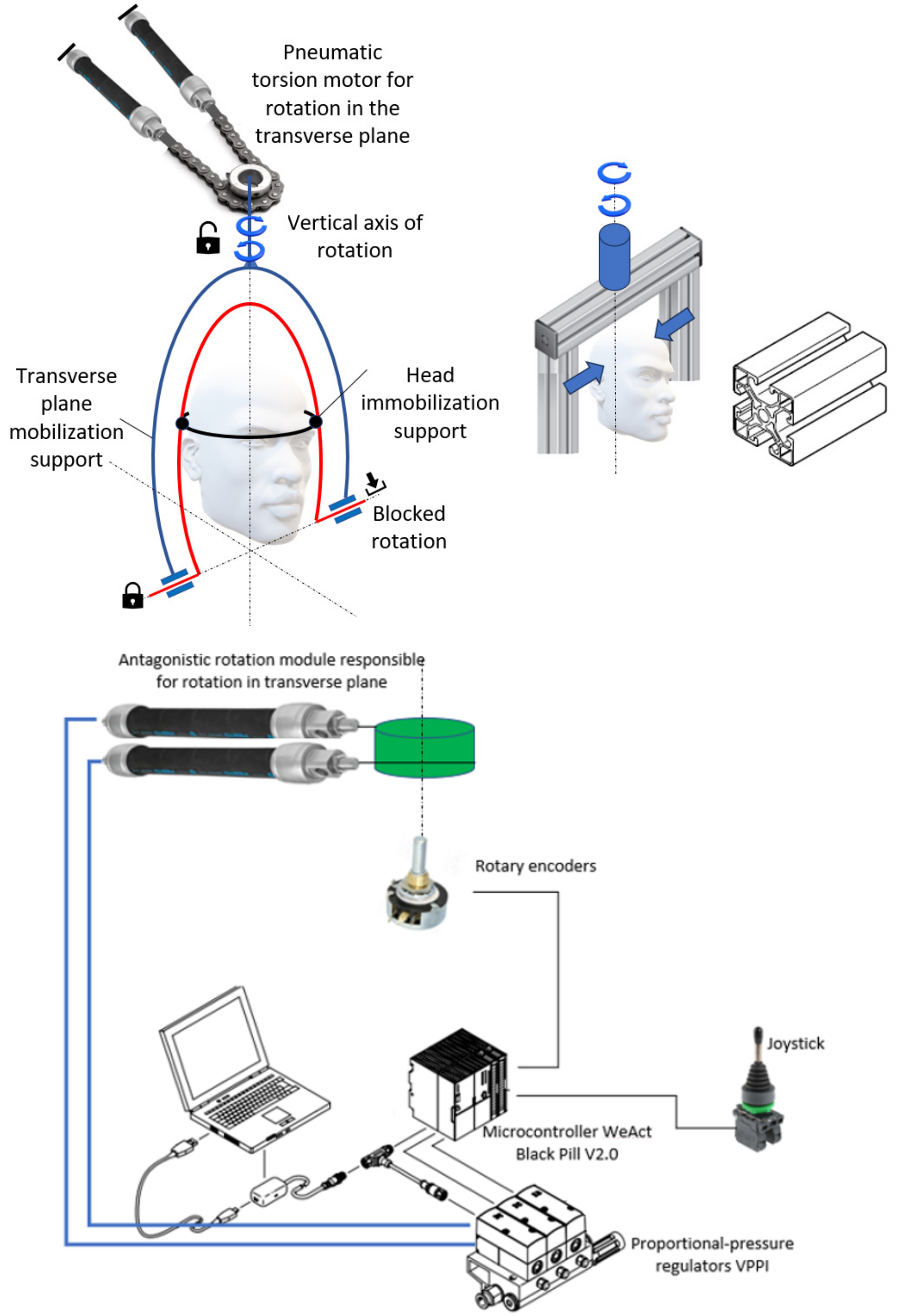

Figure 4. Rotation generation in the transverse plane. Actuation and control of the torsion motor.

The rehabilitation exercises of the neck joint by continuous passive motion (CPM) entail very small speed rotation motions, of three to six cycles/minute (meaning 20/cycle s to 10 s/cycle) or less (see McKenzie's method of rehabilitation). Taking into consideration the response time of pneumatic muscles (<0.1 s), in the case of applying a rotation maximum speed of the neck joint, the imposed rotation angle may be exceeded by 1.6°, which is a very small value. Cases may occur where the patient's joint becomes rigid when reaching certain rotation angles and pain occurs when going beyond such angles is forced. In such cases, however, the compliance of pneumatic muscles is capable of absorbing the shock generated by exceeding such limits, thus considerably diminishing patient discomfort. In order to restore the neck joint to its full functionality, CPM exercising is meant to gradually generate rotations that reach the physiologically normal limits. Thus, the patient is bound to experience some discomfort, inherent to any physical rehabilitation process, while pain intensity will be cushioned by the pneumatic muscles' compliance.

Additionally, the rotation system in the transverse plane is also provided with a rotary encoder that transmits the information regarding the angular position to a microcontroller, thus ensuring the necessary precision.

The construction of the torsion motor is determined by the forces and torques required for the rotation by the vertical axis. The resisting force to the motion developed by the neck muscles is determined based on the general schematic shown in Figure 5.

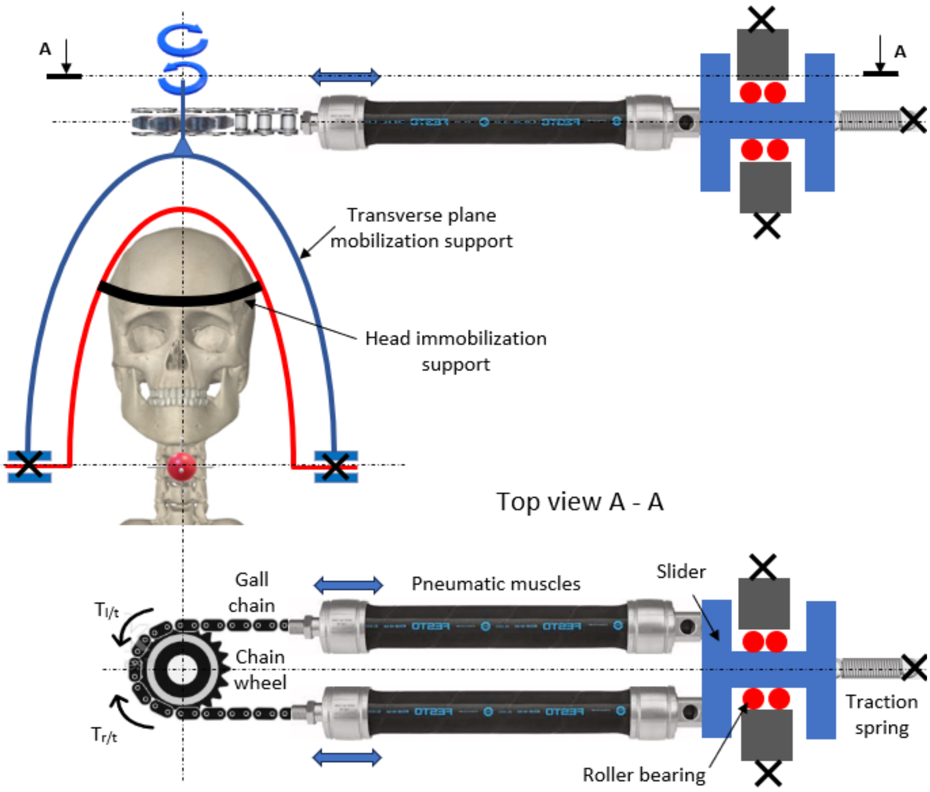

Figure 5. Construction of the torsion motor.

The two pneumatic muscles work antagonistically, meaning that when one muscle contracts, the other relaxes and vice versa. While one of the muscles is fed compressed air and causes the mobile assembly of the rehabilitation device to rotate, the other muscle operates like a brake, being able to stop the motion in a position of balance. At motion in the other direction, the roles of the two muscles are reversed. For example, in order to rotate to the right in the transverse plane, the upper muscle contracts and the lower one relaxes.

The free ends of the two pneumatic muscles are attached to a Gall chain that runs over a chain wheel. The rotation of the wheel in one or the other direction generates the motion of the mobile assembly designed for the transverse rehabilitation of the neck joint.

The construction of the torsion motor includes two pneumatic muscles of DMSP-10-300N-RM-CR type (manufactured by Festo, Esslingen, Germany) with the following dimensions: interior diameter = 10 mm; length of the active part = 300 mm. The maximum specific axial contraction of these muscles ε_{max} is 20% of the initial length. Thus, at 6 bar pressure, the maximum contraction of the muscles is ΔL_{max} = 60 mm. The maximum developed force is 476.8 N, corresponding to a pressure of 6 bar and a specific axial contraction of 0%. The response time at inflation of these pneumatic muscles is about 0.15 s; this feature, however, is not important in the case of medical rehabilitation exercise.

The maximum torque required for rotating the human head in the transverse plane ($T_{l,r/t}$) is 10 N·m. Further taken into account are the torques of inertia of the head and its support. By approximating a spherical shape of the head of mass m = 5 kg and radius r = 0.09 m, the corresponding torque of inertia is

$$J_c = \frac{2}{5} \cdot m \cdot r^2 = \frac{2}{5} \cdot 5 \cdot 0.09^2 = 0.0162 \text{ kg} \cdot \text{m}^2 \quad (1)$$

MuscleSim v. 2.0.1.5 software developed by Festo provides for these muscles the values of the developed forces versus feed pressure and specific axial contraction. The data provided by the software are used to plot the variation graphs of the forces developed by the two antagonistic muscles versus compressed air pressure and specific axial contraction (Figure 6).

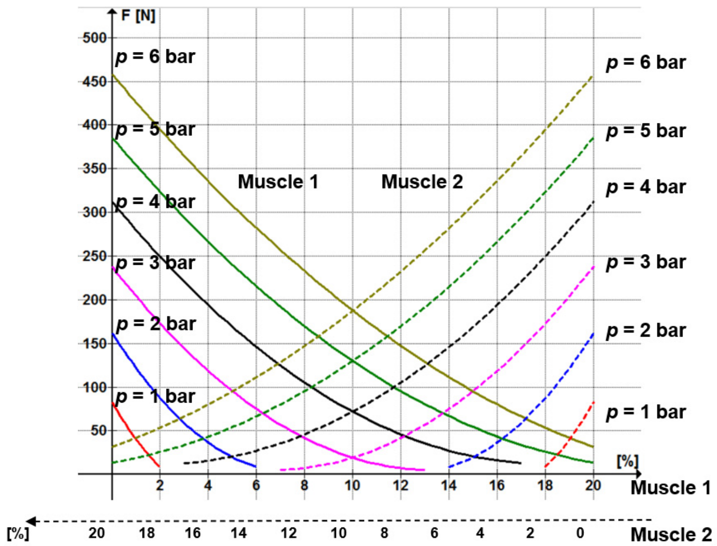

Figure 6. Diagrams of the antagonistic pneumatic muscles.

In the figure above, the continuous lines are the variation curves of the forces developed by the active muscle that is fed compressed air. The dashed lines are the variation curves of the forces developed by the passive muscle that releases air. The horizontal axis of the graph represents specific axial contraction ε and is to be read from left to right for the active muscles and from right to left for the passive ones, respectively.

The working principle of the torsion motor is presented in Figure 7.

The rotation in the transverse plane of the mobilization frame of the neck joint entails a sequence of phases. In the initial phase, the muscles are not charged with air, the pressure being p = 0 bar. The traction spring maintains the tension of the entire mobile assembly of the rehabilitation device, consisting of the two pneumatic muscles, the Gall chain and the slider.

In the second phase, the two muscles are charged with air up to a pressure of $p_0 = p_{max}/2$. Consequently, the two muscles are prestressed simultaneously and contract axially (shorten) each by $\Delta L_{max}/2$. The slide moves to the left by a distance of $\Delta L_{max}/2$ until it hits a fixed stroke limiter. The specific axial contraction (ε_0) of the two muscles is

$$\varepsilon_0 = \frac{\frac{\Delta L_{max}}{2}}{L_i} \cdot 100 = \frac{\Delta L_{max}}{2 \cdot L_i} \cdot 100 \quad [\%], \quad (2)$$

where L_i is the initial length of the two pneumatic muscles (p = 0 bar).

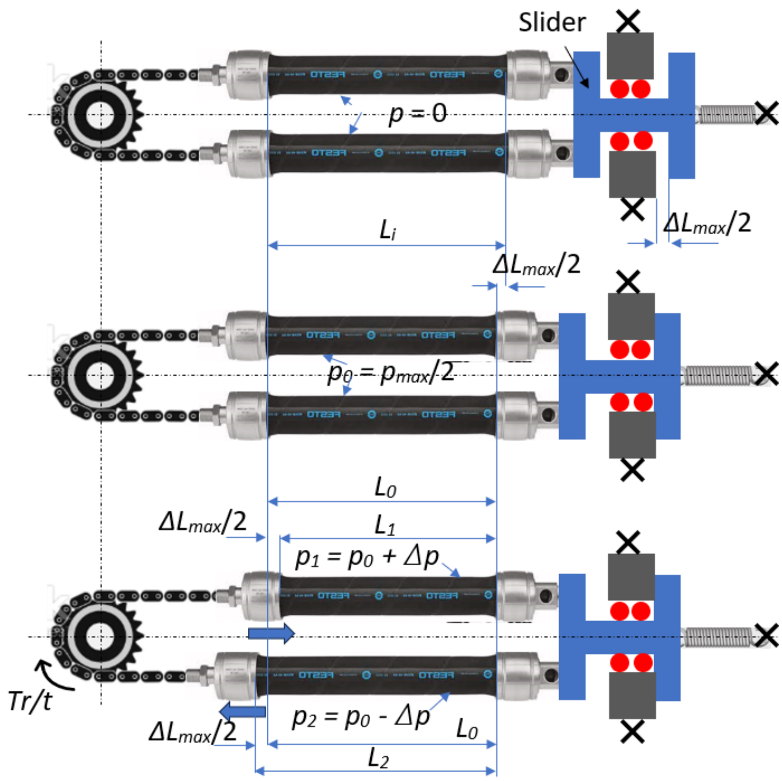

Figure 7. Working principle on the torsion motor in the transverse plane.

In the third phase, in order to rotate the chain wheel and, implicitly, the neck joint mobilization frame by an angle θ, the two muscles are charged with air alternatingly. Thus, while one of the muscles is charged with a pressure of $p_1 = p_0 + \Delta p$ and contracts, the second muscle relaxes until reaching a pressure of $p_2 = p_0 - \Delta p$. Consequently, the lengths of the pneumatic muscles become $L_1 = L_0 - \Delta L$ and $L_2 = L_0 + \Delta L$, respectively.

In order to rotate the chain wheel in the opposite direction, the two muscles will be charged as follows: the first muscle relaxes under a pressure of $p_1 = p_0 - \Delta p$ and the second muscle contracts under the action of a pressure of $p_2 = p_0 + \Delta p$.

The maximum necessary rotation angle in the transverse plane is $\theta_{max} = \pm 80° = \pm 4\pi/9$ rad. For this value, the Gall chain wheel radius of $R_p = 21.08$ mm was calculated.

4. Static Analysis of the Torsion Motor

The static behavior of the motor is studied by means of determining the forces it is subjected to. The relationships used for this purpose consider the constructive parameters of the muscles and their feed pressures. The forces developed by the Festo pneumatic muscles can be determined by means of the equations below, sourced from [21,22]:

$$F = p \cdot \frac{\pi}{4} \cdot d^2 \cdot \left[a \cdot (1 - c \cdot \varepsilon)^2 - b \right] \tag{3}$$

where

$$a = \frac{3}{(\tan \alpha_{min})^2} \tag{4}$$

$$b = \frac{1}{(\sin \alpha_{min})^2} \tag{5}$$

Further, p is the feed pressure of the pneumatic muscle, d is its interior diameter, α is the braiding angle of the threads forming the muscle's protective envelope (Figure 8) and c is a coefficient that accounts for the fact that the radially deformed muscle does not have a perfectly cylindrical shape and the pressure is not transmitted integrally in its envelope [22]. For the DMSP-10-300N muscle, a value of c = 1.6 is adopted.

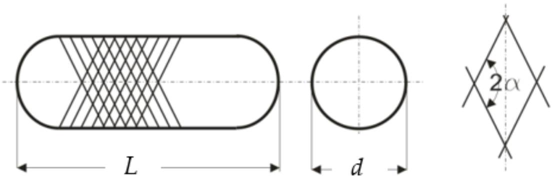

Figure 8. Braiding of the muscle's protective envelope.

The braiding angle α of the threads is determined by the equation provided in [23]:

$$F = p \cdot \frac{\pi}{4} \cdot d^2 \cdot \left[\frac{3 \cdot (\cos \alpha)^2 - 1}{1 - (\cos \alpha)^2} \right] \quad (6)$$

The angles α_{max} and α_{min}, respectively, are obtained when the force developed by the muscles is 0 and 475.8 N (at p = 6 bar), respectively. This value is provided by MuscleSim v. 2.0.1.5 software for a DMSP-10-300N muscle. Thus:

$$F = 0 \rightarrow \alpha_{max} = arcos(0.577) = 54.7^\circ \quad (7)$$

$$F = 475.8 \text{ N} \rightarrow \alpha_{min} = arcos(0.847) = 23^\circ \quad (8)$$

For this value of α_{min}, the coefficients a and b are a = 16.65 and b = 6.55. Under these conditions Equation (3) becomes

$$F = p \cdot \frac{\pi \cdot d^2}{4} \cdot \left[16.65 \cdot (1 - 1.6 \cdot \varepsilon)^2 - 6.55 \right] \quad (9)$$

Due to their antagonistic motions, the pneumatic muscles cause a torque on the axle of the chain wheel, calculated by the equation below:

$$T_t = R_p \cdot (F_1 - F_2) \quad (10)$$

The forces developed by the two muscles are F_1 and F_2, respectively. By replacing the formulas of the two forces in the equation above, the relationship for the rotation torque in one direction of the transverse plane of the neck joint mobilization frame is obtained:

$$T_t = R_p \cdot \pi \cdot \frac{d^2}{4} \left\{ p_1 \cdot \left[16.65 \cdot (1 - 1.6 \cdot \varepsilon_1)^2 - 6.55 \right] - p_2 \cdot \left[16.65 \cdot (1 - 1.6 \cdot \varepsilon_2)^2 - 6.55 \right] \right\} \quad (11)$$

where the specific axial deformations of the two muscles are

$$\varepsilon_1 = \varepsilon_0 + \frac{R_p \cdot \theta}{L_i} = 0.1 + \frac{21.08 \cdot \theta}{300} = 0.1 + 0.07 \cdot \theta \quad (12)$$

$$\varepsilon_2 = \varepsilon_0 - \frac{R_p \cdot \theta}{L_i} = 0.1 - \frac{21.08 \cdot \theta}{300} = 0.1 - 0.07 \cdot \theta \quad (13)$$

Upon processing Equation (11) and by neglecting the terms of ε^2 type,

$$T_t = 7.87 \cdot (p_1 - p_2) - 6.15 \cdot (p_1 + p_2) \cdot \theta \quad (14)$$

By means of Equation (14) and Figure 9, the torque in the transverse plane can be calculated for different angles of interest (±80° = ±4π/9 rad and 0°, respectively).

$$T_t\left(-\frac{4\pi}{9}\right) = \left[7.87 \cdot (6 - 0) - 6.15 \cdot (6 + 0) \cdot \left(-\frac{4\pi}{9}\right)\right] \cdot 10^{-1} = 9.87 \text{ N} \cdot \text{m}$$

$$T_t(0) = [7.87\cdot(3-3) - 6.15\cdot(3+3)\cdot(0)]\cdot 10^{-1} = 0\ \text{N}\cdot\text{m}$$

$$|T_t\left(\frac{4\pi}{9}\right)| = |\left[7.87\cdot(0-6) - 6.15\cdot(0+6)\cdot\left(\frac{4\pi}{9}\right)\right]\cdot 10^{-1}| = 9.87\ \text{N}\cdot\text{m}$$

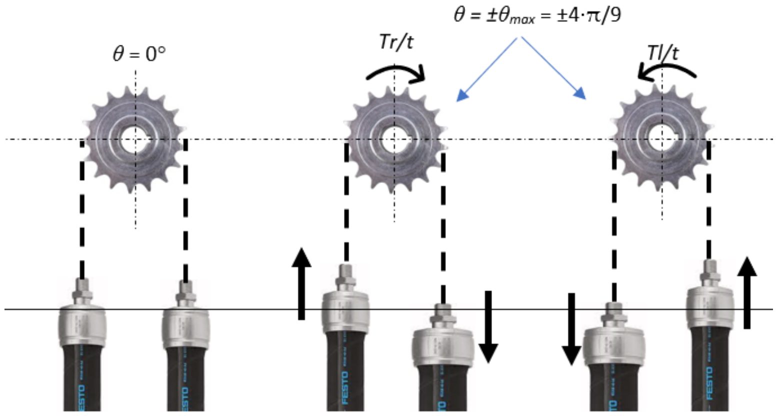

Figure 9. Chain wheel rotation in the transverse plane.

In order to obtain the torque in [N·m], a multiplying factor of 10^{-1} was introduced in the relationship above. This is necessary because the pressure is expressed in [bar (daN/cm^2)] and the numerical coefficients are expressed in [cm^3]. The results are very close to the requirements, that is, achieving a torque of 10 N·m. This shows that by the forces they develop, the two selected muscles are capable of meeting the assumed requirement.

The position of the equilibrium (resting position) of the chain wheel axle is obtained for zero torque, that is, for T_t = 0.

$$\theta_{ech} = \frac{7.87\cdot(p_1 - p_2)}{6.15\cdot(p_1 + p_2)} = 1.28\cdot\frac{p_1 - p_2}{p_1 + p_2} \quad (15)$$

Table 2 shows the angles at equilibrium of the chain wheel axle for several (p_1; p_2) sets of values, with p_1 and p_2 varying antagonistically between 0 and 6 bar:

Table 2. Values at equilibrium of angle θ.

p_1 [bar]	0	1	2	3	4	5	6
p_2 [bar]	6	5	4	3	2	1	0
θ_{ech} [rad]	−1.28	−0.853	−0.426	0	0.426	0.853	1.28
θ_{ech} [°]	−73.37	−48.91	−24.45	0	24.45	48.91	73.37

The data in the table above show that the mobile assembly of the rehabilitation device rotates in one or the other direction by an angle of θ_{max} = ±73.37°. The difference in relation to the imposed requirement of ±80° is determined by the simplifying hypotheses that were considered in the calculations above.

Regarded as a system, the torsion motor, consisting of the two pneumatic muscles, is of MIMO (Multiple Input–Multiple Output) type. The input quantities are the pressures p_1 and p_2 and the outputs are the torque T, the rotation angle θ and the torsional rigidity k. The output quantity of maximum interest for the actuation of the rehabilitation equipment in the transverse plane is angle θ. In order to maximize the precision of the rotation, the system has to be transformed from a MIMO into a SISO (Single Input–Single Output) type one. The input quantity of the SISO system is the variable Δp, namely the pressure that is added to and respectively extracted from the two pneumatic muscles when the chain wheel rotates in one or the other direction.

In order to initiate rotation in the transverse plane, after pre-charging both muscles with air at a pressure of p_0 = p_{max}/2 = 3 bar, one muscle is fed an additional pressure of Δp

(Δp = 0 to 3 bar), while the same amount of pressure, Δp, is discharged from the other one. Thus, the pressures in the two muscles become

$$p_1 = p_0 + \Delta p \tag{16}$$

$$p_2 = p_0 - \Delta p \tag{17}$$

and, consequently, Equation (14) is

$$T_t = 7.87 \cdot (p_0 + \Delta p - p_0 + \Delta p) - 6.15 \cdot (p_0 + \Delta p + p_0 - \Delta p) \cdot \theta \tag{18}$$

$$T_t = 2 \cdot 7.87 \cdot \Delta p - 2 \cdot 6.15 \cdot p_0 \cdot \theta \tag{19}$$

Equation (20) describes the position of angular equilibrium attained when T_t = 0:

$$\theta_{ech} = \frac{7.87 \cdot \Delta p}{6.15 \cdot p_0} = \frac{7.87 \cdot \Delta p}{6.15 \cdot 3} = 0.426 \cdot \Delta p \tag{20}$$

The variation in the equilibrium angle of the joint versus the variable Δp is shown in Figure 10.

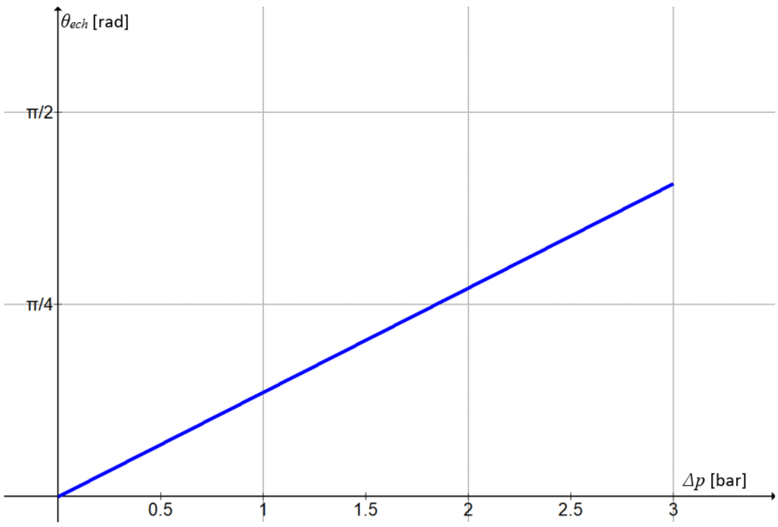

Figure 10. Variation in angle θ_{ech} versus Δp.

Starting from Equation (14), the torsional rigidity of the joint that rotates the chain wheel is defined as

$$k = \frac{dT_t}{d\theta} = -6.15 \cdot (p_1 + p_2) \tag{21}$$

The maximum value of the torsional rigidity is obtained from Equation (19):

$$k_{max} = \frac{dT_t}{d\theta} = -2 \cdot 6.15 \cdot p_0 \cdot 10^{-1} = -3.69 \ [\text{N} \cdot \text{m/rad}] \tag{22}$$

Figure 11 presents the variation in the torsional rigidity versus the sum of pressures (p_1 + p_2). It can be noted that a high torsional rigidity is obtained for high feed pressures of the two pneumatic muscles. A high rigidity determines an increase in positioning precision.

The inverse of torsional rigidity is the torsional compliance. This is a motor's capacity for allowing deviations from the position of equilibrium when the actuated system is subjected to disturbance by exterior forces. Pneumatic muscles benefit from adjustable compliance and thus ensure the adaptability of the actuated system to the actual working situation that may differ from the initially envisaged one [24]. The relationship for calculating torsional compliance is

$$C = k^{-1} = \left(\frac{dT_t}{d\theta}\right)^{-1} = -\frac{1}{6.15 \cdot (p_1 + p_2)} \tag{23}$$

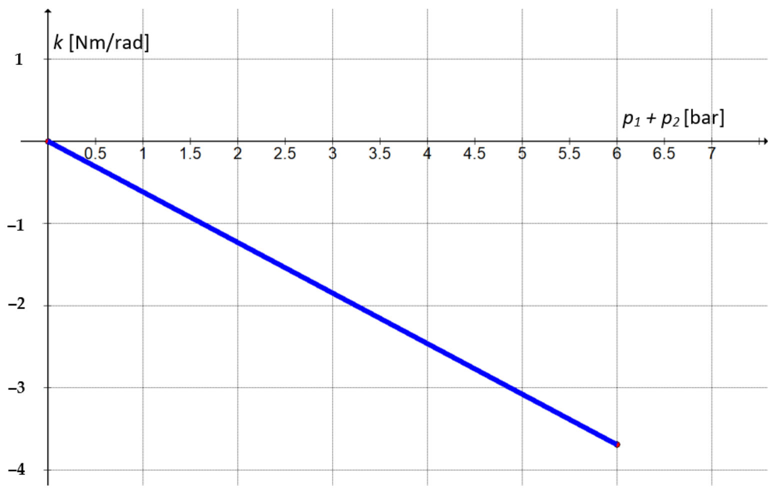

Figure 11. Modification of torsional rigidity by varying the sum of feed pressures.

Figure 12 shows the variation in torsional compliance versus the sum of the feed pressures of the two pneumatic muscles.

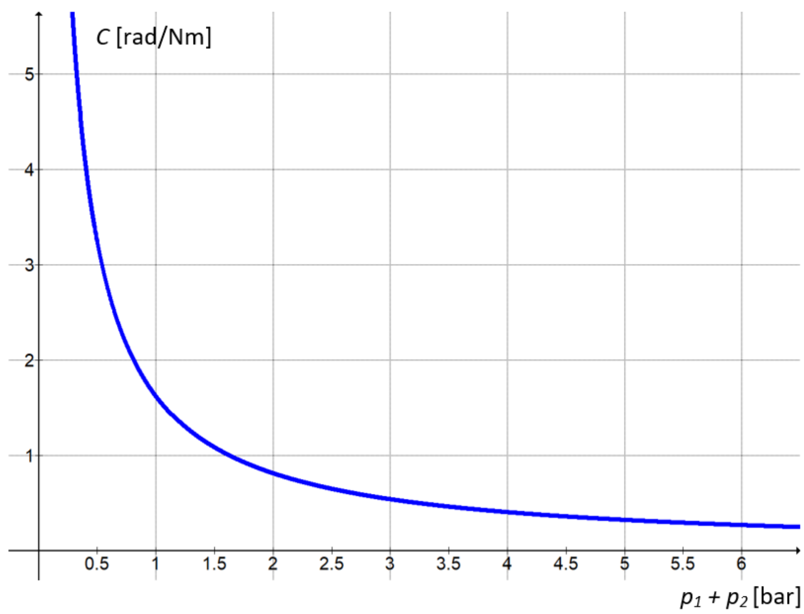

Figure 12. Variation in torsional compliance versus the sum of feed pressures.

It can be observed that the values of the torsional compliance decrease as the sum of the feed pressures increases. This suggests that in order to achieve better adaptability to the patient's suffering (the pain threshold), the charging of the two muscles has to be made at low pressures.

5. Discussion

A rehabilitation device for the neck joint has to meet two operational requirements: high positioning precision and high adaptability. In relation to these aspects the rigidity and compliance graphs yield two important conclusions:

1. A high positioning precision that has the certainty of attaining imposed rotation angles can be ensured by charging the two pneumatic muscles at high pressures ($p_1 + p_2 \rightarrow$ 6 bar);

2. A high adaptability of the rehabilitation device to the patient's state requires the lowest possible sum of pressures $p_1 + p_2$.

Meeting the two requirements simultaneously is difficult and calls for a compromise: at the beginning of the rehabilitation exercises the priority is high compliance while, subsequently, attaining precise positioning angles becomes more important.

In terms of the equipment's safety, the structure of the proposed torsion motor allows for applying the optimum rehabilitation motions to the affected segment. Passive joint mobilization entails controlling the applied forces, the amplitudes of motion and the velocities, accelerations, duration, and frequency of the rehabilitation exercises. The possibility of the modification between certain limits of all these quantities allows the adjustment of rehabilitation exercises to the clinical state of the patients and to their pain thresholds. Regarding the risks patients could be exposed to during testing, such risks are negligible to a degree of non-existence, given the reduced values of the motion speed and of the actuation forces. The risks that could occur during the testing phase designed to evaluate and correct equipment performance include the following:

- Technical risks: the risk of an unsuccessful device meaning potential risk for patients due to a non-optimal functioning of the equipment:
    - This risk is eliminated by endowing the equipment with mechanical "stops" positioned to, for example, limit the rotation of the neck support in order to avoid exceeding the pain threshold;
    - All testing will be conducted under the supervision of research team members, who, during the entire duration, interact verbally with the patient and can at any time stop the procedure.
- Professional risks: the proposed research does not involve any significant risk as to the aspect of work safety and no risk as to the aspect of professional diseases. The team of researchers will receive targeted work safety training in order to carry out the proposed research.
- Regarding the risks that patients could be exposed to during testing, such are negligible to a degree of non-existence, given the reduced values of the motion speed and of the actuation forces. All necessary documents for meeting the targeted objective will be devised in accordance with the Ethics Code of Human and Social Scientific Research of the Transilvania University of Brașov (including the approval of the university's Ethics Committee).

The equipment will be tested on patients planning to undertake rehabilitation of the neck joint. The testing will take place within the premises of the university under the supervision of research team members. For participant selection, the research team will liaise with the Faculty of Medicine of Transilvania University of Brasov.

All participants in the testing phase of the study will be given an informative sheet including the following:

- A short description of the aim of the testing phase of the study;
- Why they were selected;
- Emphasis on the voluntary nature of participation;
- The right to leave the testing process at any time;
- The procedure to be applied and the necessary time to be dedicated by the patient;
- Benefits and possible disadvantages of participation in the testing:
    - Emphasis on the possibility of encountering some discomfort—inherent to any rehabilitation procedure—and the fact this will be under control due to the equipment's compliance and the permanent interaction with research team members during the procedure.
- Ensuring confidentiality and anonymity:

    - According to GDPR;
    - According to the modality of storing the data, the period of storage, deletion of data, etc.
- Information about the outcomes of the testing (once testing is completed and data are processed);
- Information about the financing of the testing phase (from the faculty budget);
- Information about the possibility of reimbursement of patient expenditure is applicable.

Upon being informed, all participants will sign an Informed Consent Form.

The financial benefits of the proposed torsion motor are significant, its cost being estimated at up to EUR 1000. In comparison, an electrically actuated, heavily sensorized rehabilitation device costs several thousand euros.

6. Conclusions

This paper put forward a concept of torsion motor actuated by two pneumatic muscles, designed for the actuation of a rehabilitation device of the neck joint. This torsion motor, with an inherently compliant behavior, ensures the adaptability of the rehabilitation equipment to the concrete conditions of the pain tolerance of the individual patient.

The proposed rehabilitation equipment ensures left-to-right rotations of the neck joint in the transverse plane within the angular limits of the healthy body. The small deviations from these values do not affect recovery exercising in any significant manner.

For the proposed pneumatic torsion motor, the working principle was described and its static behavior was analyzed. Its performance was determined and torsional rigidity and compliance were calculated and discussed. Based on the results, recommendations were issued for the optimum operation of the rehabilitation equipment.

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