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STATIC EQUILIBRIUM OF THE CERVICAL SPINE

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Abstract: The paper presents a study regarding the static equilibrium of normal human cervical spine at the level of C7 vertebra. In order to reveal the equilibrium conditions, three positions of the head and neck were assessed: vertical, horizontal and inclined forward at 45 deg. The anthropometric dimensions of the model were established from measurements on CT images of a 35 years old subject. The weights of the head and neck were approximated as percentages of the whole body weight. Establishing some simplifications regarding the load-bearing conditions at C7 level, reaction forces were calculated. The results lead us to concluding data about the reaction forces behaviour in certain positions of the head and neck.

1. INTRODUCTION

Neck pain or other symptoms caused by a cervical spine disorder are a very common problem for many persons, adults or children. The cervical spine is composed of many different anatomic structures, such as bones, joints, muscles, and ligaments. These parts of the cervical spine are normally well balanced and able to contribute to the movements of the spine, and the whole body. Thus, when a disorder appears in certain parts of the cervical spine, it becomes a source of pain and discomfort. The static equilibrium of the normal cervical spine is important to analyze the posture and static equilibrium of some disorders such as lordotic and cifotic cervical spine curvatures, in different positions.

The spine is a three-dimensional mechanical structure that transmits loads, allows motion and protects the spinal cord from damage. The spinal column consists of cervical vertebrae, C1 to C7, thoracic vertebrae, T1 to T12, lumbar vertebrae, L1 to L5, the sacrum and intervertebral discs [3].

Human neck is a mobile structure, being capable of rotations in all three anatomical planes. The range of motion of cervical spine is generated by the anatomical particularities of the vertebrae, muscles, joints and ligaments together.

In this paper an equilibrium study of the cervical spine in sagittal plane is described. Determination of the anatomical connection of the individual gravity is thus of primary importance for the evaluation of equilibrium in sagittal plane [6]. Also, the muscular activity of the neck is a major issue in maintaining the equilibrium of the head and neck assembly in certain positions.

There are several attempts in determining the muscular forces acting on the neck structure for maintaining the orthostatic equilibrium position. One of those uses a CT reconstruction of the bone structure and a simulation based on the model populated with muscle groups. This study provided the muscular pattern and loads within the C4–C5 vertebrae. The results in this case are coherent with EMG results earlier (Svensson 2004) developed [1].

The present study uses classical mechanics and some simplifications to determine the muscular forces and the reactions in intervertebral disc and joint facets. The body segment masses used in calculus, positioning of the reaction forces and force distribution in the muscle tissues were adopted from literature [2], [4], [5], [7], [8], [9].

2. STUDY OF STATIC EQUILIBRIUM

In this paper, the equilibrium of the cervical spine was studied in sagittal plane only. In order to reveal the changing in action and reaction forces three static positions were studied: orthostatic posture of the spine, horizontal position of the head and neck, and inclined forward at 45 deg.

In order to write the equilibrium equations several assumptions were established. The conditions refer to the mass of the various body segments, angular and linear dimensions between vertical line of the body and various spinal elements and centre of gravity, measured in sagittal plane. The masses were approximated as percentages of the whole body mass of a 80 kg person, the values being those presented in figure 1. The weight of the head and neck is about 8% from whole body weight of any normal person.

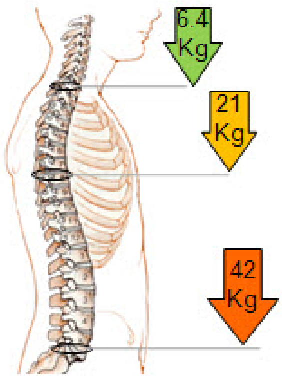

Figure 1 Weight distribution for a 85 kg person

The anthropometrical dimensions taken into consideration in writing the equilibrium equations were extracted from the CT topogram of the same subject (figure 2). Here were identified the mass and geometric elements:

- Centre of gravity of the head was found at the intersection of two anatomical reference lines: Frankfort horizontal line - an imaginary line that projects from the median line of the occipital bone and upper rim of the external auditory canal–the auricular point, to the lower rim of the orbit–the infraorbital point [10] - and External auditory meati axis;
- Center of gravity of the cervical segment founded on the C4 vertebral body;
- Direction of the facet joint reaction force defines an angle α_2 with respect to the vertical direction;
- Muscle force direction defines an angle α_1 with respect to the vertical direction;
- Reaction force acting on intervertebral disc C7-T1 and the vertical direction defines an angle α_3.

2.1. HORIZONTAL EQUILIBRIUM

In order to study the static equilibrium of the cervical segment at the C7 level, we considered the head and neck aligned with the horizontal direction. This position can be achieved when a subject is lying on a horizontal surface, with the face down.

In the considered posture, forces which are responsible for the equilibrium state are F_1, F_2 and F_3, having unknown values (figure 3). The F_1 force represents the posterior muscle force, F_2 is the reaction force acting on the inferior joint facet of the vertebral arch, and F_3 is the reaction force acting on the vertebral disc C7-T1. Two of these forces (reaction force on the inferior joint facet and the reaction force on the vertebral disc) are internal forces, while the posterior muscle develops an active force.

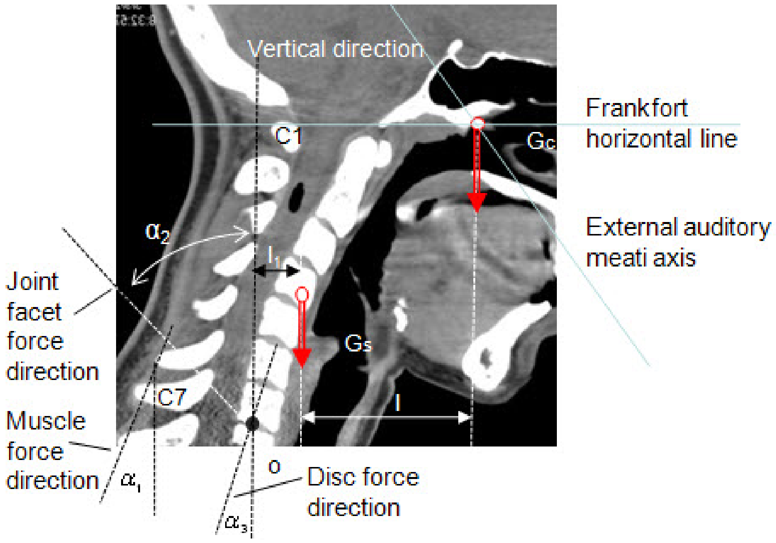

Figure 2 Centres of gravities, linear and angular dimensions measured on CT image

The directions and the application points of these forces are known from the measurements realized on the CT topogram of the subject.
Another external forces involved in static equilibrium are the own weights of the head G_c and cervical segment G_s. The values of these forces were established as we mentioned in the beginning of the section 2.
Both internal and external forces acting at the C7 vertebral level are presented in figure 3.
A reference coordinate system was attached to the C7 vertebra~~e~~, having the origin placed on the instantaneous centre of rotation (CIR) of the vertebra. The numerical values of the mass and anthropometric dimensions are presented in table 1, where m_c and m_s represents the head and cervical segment masses.

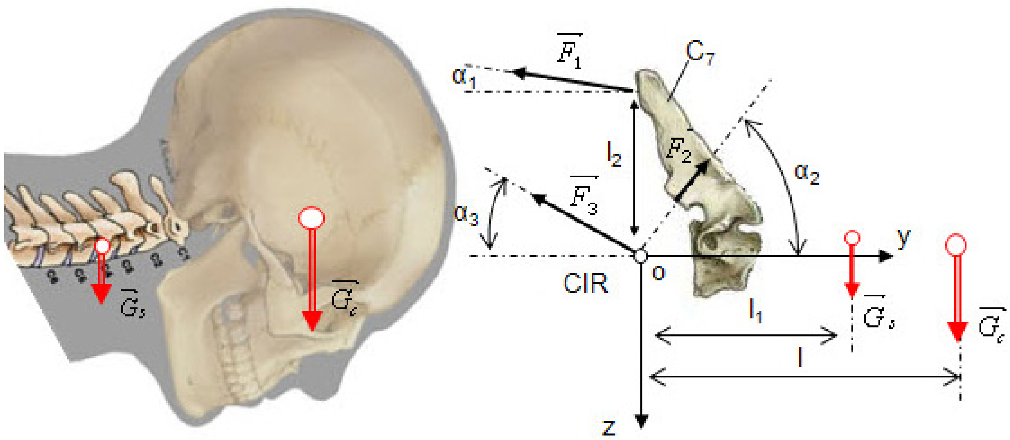

Figure 3 Static equilibrium of the head and neck in horizontal position

m_c [kg]	m_s [kg]	α_1 [°]	α_2 [°]	α_3 [°]	l [mm]	l_1[mm]	l_2[mm]
5	1.4	15	45	30	250	80	40

Table 1 Masses, linear and angular dimensions involved in horizontal position of the head and neck

The equilibrium equations are:

$$\begin{cases} \sum F_y = 0 \\ \sum F_z = 0 \Rightarrow \\ \sum M_o = 0 \end{cases} \quad (1)$$

By projecting these equations on the system's axes we obtain the following system:

$$\begin{cases} F_2 \cdot \cos\alpha_2 - F_1 \cdot \cos\alpha_1 - F_3 \cdot \cos\alpha_3 = 0 \\ G_c + G_s - F_1 \cdot \sin\alpha_1 - F_2 \cdot \sin\alpha_2 - F_3 \cdot \sin\alpha_3 = 0 \\ l_1 \cdot G_s - F_1 \cdot \cos\alpha_1 \cdot l_2 + l \cdot G_c = 0 \end{cases} \tag{2}$$

Solving the system (2) we obtained:

$$F_1 = \frac{G_s \cdot l_1 + G_c \cdot l}{l_2 \cdot \cos\alpha_1} = 346N \tag{3}$$

$$F_2 = \frac{(G_s + G_c) \cdot \cos\alpha_3 + F_1 \cdot \sin(\alpha_3 - \alpha_1)}{\sin(\alpha_2 + \alpha_3)} = 149N \tag{4}$$

$$F_3 = \frac{F_2 \cdot \cos\alpha_2 - F_1 \cdot \cos\alpha_1}{\cos\alpha_3} = -264N \tag{5}$$

By analyzing the force values, we can observe that the muscular force F_1 required for maintaining the equilibrium state is very high, approximate 5.4 times higher than the static weight forces of the head and neck.

Taking into account a simplifying hypothesis where 1 cm^2 of muscular physiological cross section can develop an average force of 10 N means that for developing ~~a~~ such an amount of force (346 N), a 34,8 cm^2 of muscle cross section have to be involved in action. For a circular section of muscle that means a diameter of 6.5 cm. Of course, the resulted value is corresponding to a group of cervical posterior muscles rather than a single muscle structure.

An important aspect is that the posterior muscle of the neck is not inserted on the C7 level only, but distributed on each vertebra. The distribution of the muscle force is proportional to the size of the vertebral bodies and the own weights which have to be animate. Therefore, the muscular force inserted on a vertebra for maintaining the equilibrium state at the horizontal level is far lower than the resulted value.

Also, the other two forces (reaction of intervertebral disc and reaction of joint facet) have to be distributed at each vertebral level taking into account the vertebral dimensions and the mass distribution along the cervical spine.

2.2. VERTICAL (ORTHOSTATIC) EQUILIBRIUM

Using masses and anthropometrical data achieved in the same way as for the horizontal equilibrium, the vertical equilibrium conditions were applied to a C7 vertebra. The differences in anthropometrical data (table 2) are found in the linear values only because there is no rotation between vertebrae in these two positions. The simplified model used for writing the equilibrium equations in presented in the figure 4.

m_c [kg]	m_s [kg]	α_1 [^{o}]	α_2 [^{o}]	α_3 [^{o}]	l[mm]	l_1[mm]	l_2[mm]
5	1.4	15	45	30	70	25	40

Table 2 Masses, linear and angular dimensions involved in vertical position of the head and neck

By writing the equilibrium equations in this case, the following system has resulted:

$$\begin{cases} -F_1 \cdot \sin\alpha_1 - F_2 \cdot \sin\alpha_2 - F_3 \cdot \sin\alpha_3 = 0 \\ -G_c - G_s - F_1 \cdot \cos\alpha_1 + F_2 \cdot \cos\alpha_2 - F_3 \cdot \cos\alpha_3 = 0 \Rightarrow \\ -F_1 \cdot \cos\alpha_1 \cdot l_2 + G_s \cdot l_1 + G_c \cdot l = 0 \end{cases} \tag{6}$$

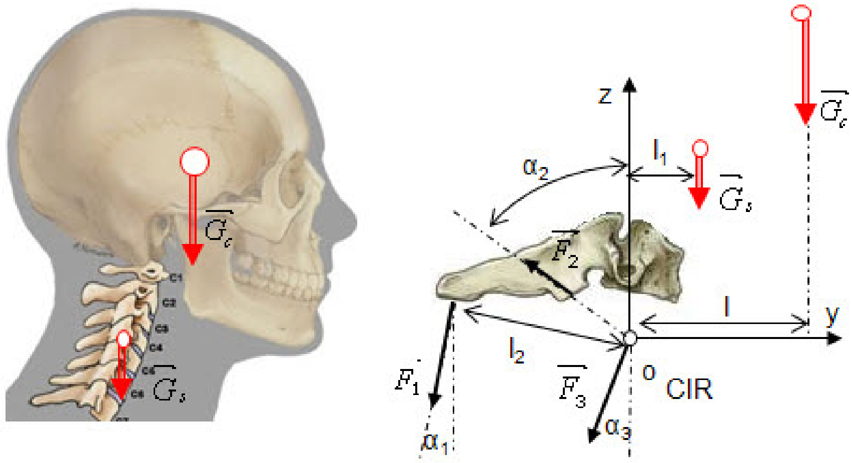

Figure 4 Static equilibrium of the head and neck in orthostatic position

Solving the system (6) we obtained:

$$F_1 = \frac{G_s \cdot l_1 + G_c \cdot l}{l_2 \cdot \cos\alpha_1} = 98N \tag{7}$$

$$F_2 = \frac{(G_c + G_s)\cdot \sin\alpha_3 + F_1 \cdot \sin(\alpha_3 - \alpha_1)}{\sin(\alpha_3 + \alpha_2)} = 59N \tag{8}$$

$$F_3 = \frac{-F_1 \cdot \sin\alpha_1 - F_2 \cdot \sin\alpha_2}{\sin\alpha_3} = -134N \tag{9}$$

By comparing the values of the forces resulted in this case with the values obtained for the horizontal equilibrium, we can observe a diminution of the last results. The muscular force F_1 is highly reduced (3.5 times) in value due to the vertical alignment of the vertebrae in this case. This alignment allows the vertebral bodies to sustain the weight of the head, and to transmit this weight to the lower spine segments.
In the same way, the equilibrium conditions were writing for the inclined position of the head (forward, 45 deg). After solving the system we achieved the following force values: F_1= 314 N, F_2= 147 N, F_3= -282 N, were the forces abbreviation has the same meaning. The values in this case were compared with the force values from the previous cases.

3. CONCLUSIONS

In order to estimate a tendency of variation of the action and reaction forces at the C7 vertebral level, the forces calculated in three cases were analyzed and represented on the same load-position graphic (figure 5).
The variations of the muscular and joint facet forces present a fast ascendant tendency from the orthostatic position of the neck to the inclined position, and a mild ascendant tendency from this position to horizontal. On the other hand, the reaction force on the disc exhibit maximum values in the inclined position of the head. This can be explained by the good pressure distribution on the disc in the orthostatic posture and the relative relaxation of the disc in the horizontal position.

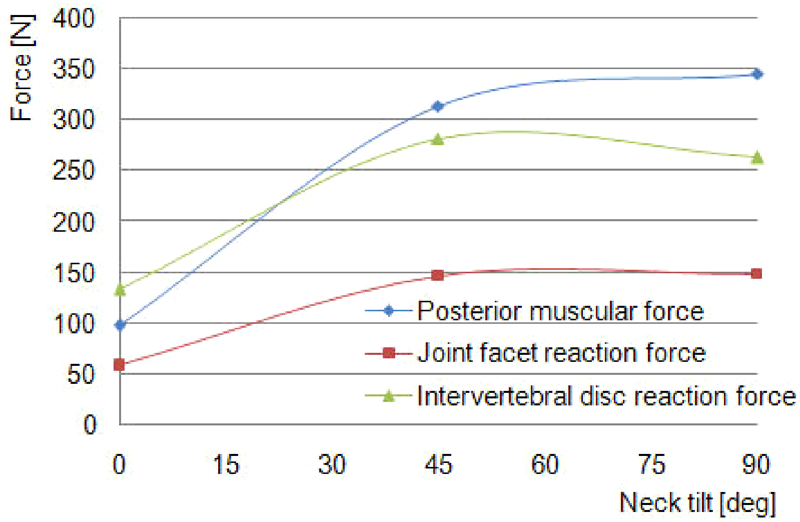

Figure 5 Theoretical variation of the forces as function of the head and neck position

The obtained results are valid for sagittal plane approach only. For complex positioning of the head, new components of the muscular forces will appear, in order to maintain the equilibrium state. In these cases, non-symmetrical loadings can appear on the joint facers.

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