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Finite element analysis of the cervical spine and soft tissue of the neck at different flexion angles

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Abstract

Aim: This study aims to investigate the impact of von Mises stress distribution on the cervical spine and soft tissue of the neck at different flexion angles of 0°, 15°, 30°, 45°, and 60°.

Materials and Methods: Finite element analysis of the neck's cervical spine and soft tissue was performed separately in Ansys Discovery Live software, a possible approach for simulating the mechanical behavior of the neck. Three-dimensional (3D) models were created in 3D Max software and static structural analyses of soft tissues were performed in ANSYS by using the Finite Element Method. The maximum stress distributions of the cervical spine in cervical vertebra bodies at different flexion angles were analyzed at the lowest and highest stress values of 0° and 30°, respectively. For the intervertebral contact surfaces, the lowest and highest stress values were determined at 0° and 45°, respectively.

Results: The value of stress showed a linear increase with increasing flexion angles in the soft tissue of the neck. The observation that the stress values obtained at different flexion angles were arbitrarily in either positive or negative directions when compared to the upright posture suggests that the effect of neck flexion on stress distribution in the cervical spine is complex and multifactorial. The change in stress values in the soft tissue of the neck was always positive and linear with increasing flexion angles.

Conclusion: People who work with technological devices are prone to a musculoskeletal disorder associated with forward flexion of the neck, and individuals are encouraged to adopt a neck flexion angle between 0° and 15°. This finding could help guide the development of strategies to reduce the risk of neck injury or damage in different postures.

Introduction

Neck pain (NP) is a prevalent musculoskeletal disorder, especially in industrialized countries, and it is a condition prone to chronicity, leading to substantial medical and social costs [1]. NP can arise from any structures in the neck, and there are many potential causes of NP. Mechanical disturbances are the most common cause of nonspecific NP [2]. The use of computers [3] and smartphones [4,5] has become increasingly prevalent in recent years, which has led to a rise in complaints of NP. This is because prolonged use of these devices can cause some anatomical disorders [6] and place significant strain on the neck. Forward head posture, also known as turtle neck posture or anterior head carriage, is a musculoskeletal disorder caused by adopting an inappropriate posture, such as sitting for long hours at a computer with the monitor located below the eyesight level. This can result in the anterior curve in the lower cervical vertebrae and the posterior curve in the upper thoracic vertebrae becoming exaggeratedly large [7-10].

Prolonged forward head posture has been identified as a cause of various musculoskeletal disorders, including upper crossed syndrome, which can lead to reduced lordosis (or backward curve) of the lower cervical vertebrae and increased kyphosis (or forward curve) of the upper thoracic vertebrae [7, 8]. As such, a posture also contracts muscular fibers around atlantooccipital articulation (*articularis atlantooccipitalis*) and overstretches the muscles around joints. It was also reported to possibly give rise to chronic NP [11].

The use of computational methods and simulation software has provided an important advantage in understanding the stress and strain on the cervical spine and soft neck tissue. The finite element method (FEM) is a powerful computational technique that can be used to quantify the degree of strain and stress in the spinal components

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and other internal or external responses given to mechanical loading by these components [12, 13]. The FEM is a numerical technique used to perform engineering analyses on computerized models of real-life structures. The structure is divided into finite parts or elements, and mathematical equations are used to estimate the behavior of each element under different loading conditions. The elements can be one-dimensional, two-dimensional, or three-dimensional, and they represent different shapes in the structure. One-dimensional elements are used to represent a line or beam, two-dimensional elements are used to represent a surface or plane, and three-dimensional elements are used to represent a solid or volume component [14]. Several studies have been conducted with the FEM method for the cervical spine or soft tissue [15-20], and a relatively small number of studies analyzing the stress at various neck flexion angles are available. This study investigated the von Mises stress distribution of the cervical spine and soft neck tissue at different flexion angles. The most suitable flexion angle was determined by comparing the stress distribution values using FEM.

Materials and Methods

Finite element method (FEM)

The human body and its internal structure have a complex and intricate geometry that is difficult to accurately represent in realistic models. Therefore, bone and tissue structures are mostly modeled by scanning [15]. Briefly, this method involves the creation of a surface model from a 3D scan of the biological structure and then converting this model into a solid model. Additionally, isometric images of the structure from different right angles can be used to model complex structures. These visuals can be imported into design software, such as ZBrush, Maya, 3DS Max, and SolidWorks, to which projections and modeling processes are carried out. For numerical analysis, the 3D head and skeleton models for the human body and soft tissue of the neck, which were taken from an open web source (https://3dmdb.com/, Access date: 10.08.2020.), were bent at 0°, 15°, 30°, 45°, and 60° flexion angles determined based on literature survey.

The model selection was made by considering different models with similar dimensions. The dimensions of the 3D head model are approximately 255 mm, 240 mm, and 175 mm whereas the dimensions of the skeleton model are approximately 260 mm, 240 mm, and 178 mm.

Later, the mesh structures of these models were reconstructed and transformed into solid models. Static structural analysis was applied to models with defined boundary conditions in Ansys discovery live software, and the resulting stress values were determined. In the analysis, material properties were described as uniform for the soft tissue of the neck and cervical spine, and the real biological system was handled with a more straightforward approach.

Creation of 3D models

Ready-made human soft tissue of the neck and skeleton (cervical spine) models were analyzed separately from an open web source for numerical analysis. The models were imported into the 3DS Max software, where they were automatically converted to ". max" file format. The freedom points, the joints, in other words, of the human soft tissue models, were defined with the skin command in 3DS Max software. With the help of this software, the desired moves and positions, such as lifting a hand or foot or turning the

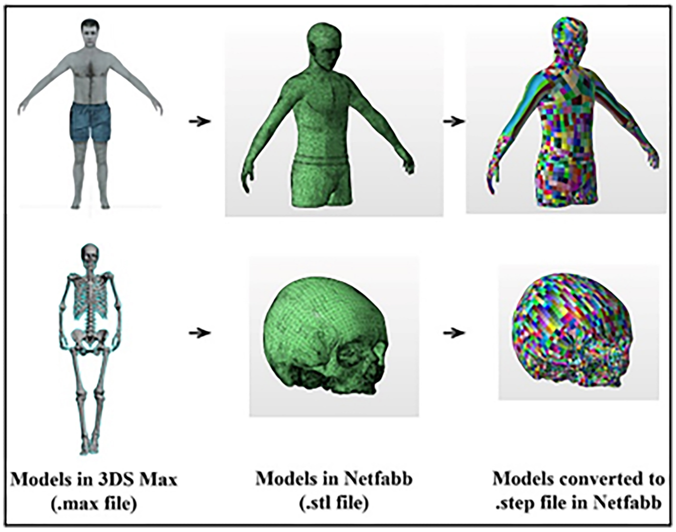

Figure 1. 3D models and conversion process of the neck and skeleton soft tissue.

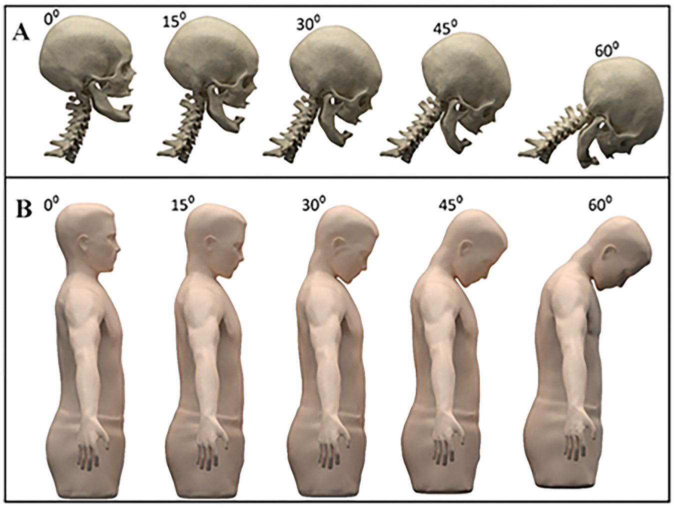

Figure 2. Rendered images of 3D solid models bent at different flexion angles of (A) head skeletal structure and cervical spine and (B) soft neck tissue.

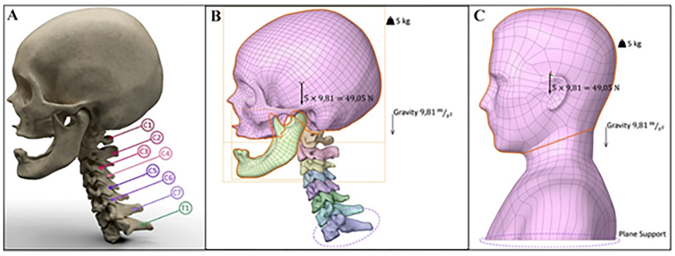

Figure 3. (A) Head skeletal structure and cervical spine, the center of gravity and boundary conditions of the (B) meshed head skeletal structure and cervical spine, and (C) meshed soft tissue of the neck model.

head, can be applied to the models. The soft tissue of neck analysis was performed directly on the human model by defining only muscle properties, ignoring the dermis layer as it is very thin, and its impact is negligible.

In 3DS Max software, existing overlapping or defective mesh structures were corrected, and models at each flexion angle were exported in (.stl) format. The critical point in this step is that the (.stl) file format should be converted to solid models for numerical analysis. In particular, the surfaces obtained by 3D scanning of a real structure are built as surface models, which then have to be converted into Computer-Aided Design (CAD) models. Otherwise, even if the models are transferred to numerical analysis, they would be recognized as point clouds and, therefore, could not be processed for analysis. For this reason, model files exported in (.stl) format were imported into Autodesk Netfabb software, wherein the last defective mesh surfaces of the models were recreated and converted into a CAD-Solid model and finally were exported in (.step) file format. The same procedure was followed for the head skeletal structure and cervical spine. In 3DS Max software, the structures considered in the analysis, such as the skull, mandible, cervical vertebrae (C1, C2, C3, C4, C5, C6, C7), and first thoracic vertebra (T1), were detached from the skeletal model as separate parts. The head skeleton models for each flexion angle were first exported in (.stl) file format. The same procedure was applied in the human soft tissue model to create solid skeleton models. 3D models and the conversion process of the soft tissue of the neck and skeleton used in the analysis can be seen in Figure 1.

The head skeletal structures and soft tissue of the neck were bent at the determined flexion angles by considering each cervical vertebra separately in 3DS Max software. Figure 2 shows the rendered images of 3D solid models of (A) the head skeletal structure and cervical spine and (B) the soft tissue of the neck as bent in 3DS Max software at different flexion angles of 0°, 15°, 30°, 45° and 60°.

Numerical static structural analyses of the cervical spine structure and soft tissue of the neck

The stress analysis applied to human soft tissue and cervical spine models was performed separately in Ansys Discovery Live software. Each skeleton model converted into a CAD model was transferred to Ansys Discovery Live software, and the skull and mandible were grouped as a single part. The mass of the head model was defined as 5 kg [21], and gravitational acceleration was applied as 9.81 m/s^2. For the boundary condition, the first thoracic vertebra (T1), selected at all surfaces, was defined as fixed support, and the intervertebral contact type, by default, was described as bonded.

Maximum stress values on the surface and in the body were taken from the intervertebral contact surface and cervical vertebral body, respectively. In addition, maximum stress points and stress distributions are obtained as images. Here, the respective stresses were determined as per the von Mises criterion. Rendered images of 3D solid models of the head skeletal structure and cervical spine with cervical vertebrae (C1, C2, C3, C4, C5, C6, C7) and first thoracic vertebra (T1) are given in Figure 3 (A). The analysis design, the center of gravity, and boundary conditions of the meshes of the head skeletal structure and cervical spine and meshed of the soft tissue of neck models are shown in Figure 3 (B and C).

Before starting the analysis, human soft tissue CAD models were imported into Ansys Space Claim, where the part of the human body model below the head was removed, and the head was split from the cervical region. At this stage, each human soft tissue model consisted of two parts: head and chest. This means that the relevant weight could be defined only to the head. Human soft tissue models sliced and split in Ansys Space Claim were also imported into Ansys Discovery Live, where a mass of 5 kg was defined to the head similarly, and the gravitational acceleration value was also set as 9.81 m/s^2. The head and neck were automatically bonded to each other.

To prevent the stress from concentrating on the lower part and causing errors in the evaluation, the lower part of the chest was defined as plane support. Finally, mesh surfaces on the anterior and posterior sides of the soft tissue of the neck were selected, and "maximum stress on surface" values were taken from there. Likewise, maximum stress points and stress distribution were obtained from simulation visuals.

Material properties were defined assuming that they were homogeneous single structures. For mesh generation, the automatic mesh geometry and mesh number recommended by the software were used.

Material properties as defined for bone and soft tissue are given in Table 1 [20, 22-25].

Results

Von Mises stress distribution results of cervical spine

In Ansys Discovery Live software, von Mises stress distribution in the cervical spine at 0°, 15°, 30°, 45°, and 60° flexion angles was performed, and maximum stress points were determined (Figure 4).

The maximum stress values of the vertebral bodies and intervertebral contact surfaces of the cervical spine were obtained. As shown in Figure 5 and Figure 6, the lowest stresses were in C6 and C7 at 0° (upright position), whereas the highest stress at 30° was in C5, C6, and C7 vertebrae on vertebral bodies. Notably, among the 7 cervical vertebrae (C1 to C7) and one thoracic vertebra, T1, C6, and C7 were the most stressed vertebrae at almost all flexion angles. At 60°, stress is distributed to all vertebrae, and the T1 vertebra was the least affected at all flexion angles.

The intervertebral contact surfaces of the cervical spine and first thoracic vertebra were taken as the upper contact surfaces for each vertebra. As shown in Figure 5, the maximum von Mises stress values on the intervertebral contact surfaces were lowest on C7 at 0° and highest on C3 at 45°. Compared to 0° (upright position), stress values were greater at all flexion angles, which is attributed to the fact that the moment effect, hence the weight felt in the lower vertebrae (C6 and C7) in particular, increases as the center of gravity of the head shifts forward. While the C7 vertebral contact surface had maximum stress values at 0°, 15°, and 30°, the greatest stress occurred on the C3 vertebra at 45°. As with the cervical vertebral body,

Table 1. Material properties used for bone and soft tissue.

Entity	Poisson ratio	Young modulus (MPa)	Density (kg/m^3)
Bone	0.38	12000	1.800
Soft tissue (muscle)	0.45	4	1.000

Table 2. The analysis results of maximum von Mises stress on cervical vertebrae (C1 to C7) and first thoracic vertebra (T1).

Cervical	0^0		15^0		30^0		45^0		60^0	
Vertebra	Body	Surface	Body	Surface	Body	Surface	Body	Surface	Body	Surface
C1	0.5058	0.1272	0.9314	0.5808	1.9107	0.6193	2.3103	0.6200	3.3201	2.9098
C2	1.0148	0.2519	1.4011	1.1537	2.0094	1.3946	0.6200	2.8216	3.3081	3.3081
C3	0.9381	0.1695	1.7237	1.2644	2.7807	1.6954	6.2375	6.2375	3.3201	1.7275
C4	1.2326	0.0706	2.4862	0.4258	5.1748	0.4786	6.2375	0.4815	3.3201	1.1516
C5	1.9408	0.1781	3.7624	0.4309	6.4712	0.8104	6.2375	1.3866	3.3201	1.5625
C6	2.8083	0.5042	5.7226	1.4602	6.4712	1.8671	6.2375	2.6943	3.3201	2.8039
C7	2.8083	1.1420	5.7226	3.1058	6.4712	2.6839	6.2375	4.5535	3.0498	3.0498
T1	0.3020	0.1484	0.6061	0.1684	1.1007	0.4837	0.8042	0.3291	1.0146	0.5060
Max	2.8083		5.7226		6.4712		6.2375		3.3201	

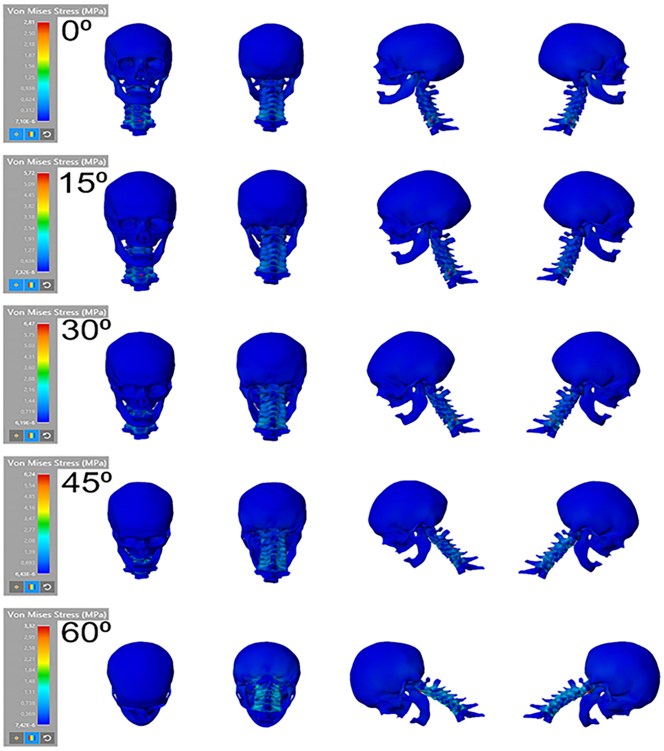

Figure 4. Stress distribution and maximum stress points (circled in red) in the cervical vertebral body and intervertebral contact surface at 0°, 15°, 30°, 45°, and 60° flexion angles.

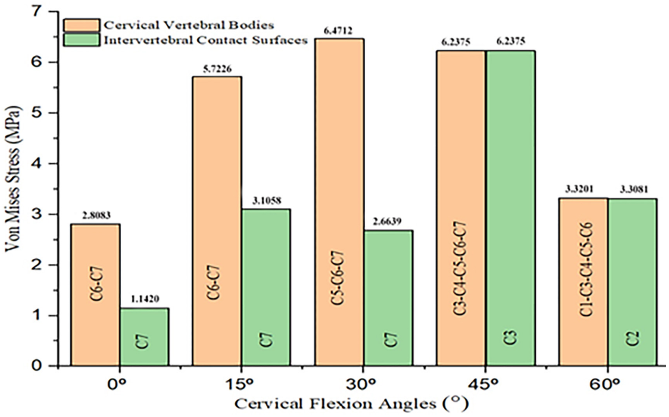

Figure 5. The maximum stress values of most stressed cervical vertebral bodies.

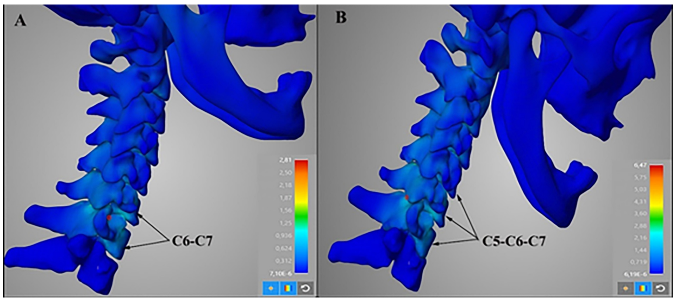

Figure 6. The maximum stress distribution in the cervical vertebral bodies at (A) 0° and (B) 30°.

the T1 vertebra had the lowest stress on the intervertebral contact surfaces at all flexion angles.

The detailed results of the analysis of all cervical vertebrae (C1 to C7) and the first thoracic vertebra (T1) with the von Mises stress values for the vertebral body and intervertebral contact surface at different flexion angles and the maximum stress value at each angle are given in Table 2.

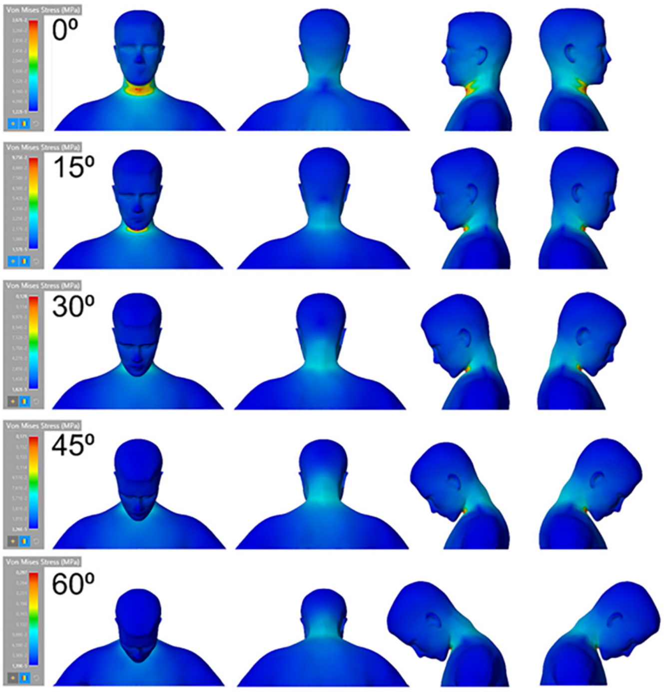

Figure 7. Stress distribution and maximum stress points (shown in red) at 0°, 15°, 30°, 45°, and 60° of cervical flexion on the anterior and posterior sides of the neck soft tissue.

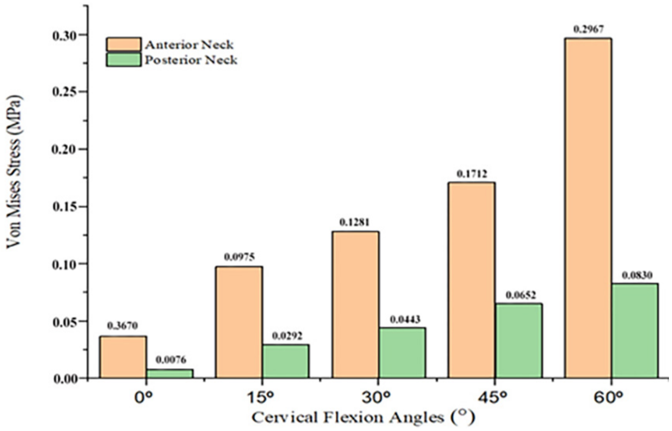

Figure 8. Stress distribution values at 0°, 15°, 30°, 45°, and 60° of cervical flexion on the anterior and posterior sides of the neck soft tissue.

Von Mises stress distribution results of the soft tissue of the neck

The stress distribution obtained for the neck soft tissue model and the maximum stress points are given in Figure 7. The von Mises stress values in the anterior and posterior sides of the soft tissue of the neck at cervical flexion angles of 0°, 15°, 30°, 45°, and 60° were determined separately (Figure 8).

The von Mises stress distribution in the soft tissues on the anterior and posterior sides of the neck showed a gradual increase with increasing flexion angles. The lowest stress was, as expected, at 0°. At 15, 30, 45, and 60, the von Mises stress values in the anterior side increased by approximately 2.65, 3.49, 4.66, and 8.08 times, respectively, compared to 0°. Likewise, the von Mises stresses in the posterior side at 15°, 30°, 45°, and 60° were 3.84, 5.82, 8.57, and 10.92 times greater, respectively. Comparing the anterior and posterior sides, stress values were higher on the anterior side by 4.82, 3.33, 2.89, 2.62, and 3.57 times at 15°, 30°, 45°, and 60°, respectively.

Discussion

This study aimed to determine, with the help of FEM, the von Mises stress distribution in the cervical spine and neck soft tissue induced by forward flexion of the head at different flexion angles of 0°, 15°, 30°, 45°, and 60°.

Many biomechanical studies have investigated the cervical region through FEM analysis [12, 16-20]. However, no comprehensive studies have numerically analyzed the stress distribution in the spine and soft tissue at different flexion angles in the cervical region. Our previous study examined the von Mises stress distribution in the soft tissue in the lumbosacral area at different flexion angles when sitting at a desktop computer using the FEM. For the least stress to occur in the soft tissues on both the anterior and posterior sides of the lumbosacral region, the ideal flexion angle of the spine was determined to be 0 degrees (upright posture) to 15 degrees [26]. It was found in another study focused on the neck region using FEM that neck tension increased with decreasing cervical lordosis. The active range of motion in the upright cervical spine decreased by 24-33%, and strain increased by 5-95% [12].

Computer-based theoretical studies are important because it is difficult to directly determine the stress on the neck with the flexion of the head. In this context, the cervical region consisted of vertebrae and soft tissues. However, in the real biological system, in addition to the cervical vertebra and soft tissue of the neck, the effects of other structures such as discs, ligaments, arteries, veins, and nervous system, as well as the structural differences unique to the individuals, are also important parameters.

According to the stress distribution analysis results for the cervical vertebral bodies, the maximum stress created by the head's weight during upright posture (0°) was in the C6 and C7 vertebrae. Similarly, the maximum stresses were in the C6-C7 vertebrae at 0° and 15° and in the C5-C6-C7 vertebrae at 30°.

The stress is distributed equally in the middle and lower cervical vertebrae at 45° and in almost all vertebrae (except T1) at 60° flexion angles. It is predicted that the stress between vertebrae increases with forward head flexion. While 30° and 45° flexion angles are not entirely convenient for vertebrae, 60° flexion harms all vertebrae. Therefore, if cervical flexion is above 15° for a long time, the cervical spine structure will be negatively affected. In other words, the stress in the cervical spine increases with flexion angle, leading to further degeneration of the vertebrae and may predispose to cervical osteoarthritis.

The maximum stress value on the intervertebral contact surfaces was in the C7 vertebra at 0°, 15°, and 30° flexions, while it was concentrated in C3 at 45° and C2 at 60° flexions. In other words, when the flexion angle increases from 30° to 60°, the stress is concentrated in the upper cervical intervertebral contact surfaces. Compression stress is thought to greatly impact upright posture, especially on the contact surface of the lower cervical vertebra (C7). Stress is more effective in the upper cervical vertebrae at 30°, 45°, and 60°.

According to the results of the analysis of the neck soft tissue, especially at flexion angles greater than 15°, the stress values increase on both the anterior and posterior sides of the neck. The von Mises stress values in the anterior side of the neck increased approximately 4.66 and 8.08 times at 45° and 60° relative to 0°, respectively. On the posterior side, compared to 0°, the increases at 45° and 60° were 8.57 and 10.92 times greater, respectively. Therefore, the increase in stress in the soft tissue incurred by the increased flexion angle is likely to set the ground for the formation of myalgia and myofascial pain syndrome in this region.

The stress value at 60° reached its highest on the anterior side of the neck and was the most dangerous flexion angle. Comparing the anterior and posterior sides, the stress value was found to be 3.18 times on the anterior side. While the anterior and posterior sides of the model used in the analysis were identical, the muscle concentration of the anterior side is less than that of the posterior side in a true biological system. The NP that occurs when the head is flexed forward is felt in the posterior side of the neck; therefore, it will be more appropriate to focus on this region. Stress values in the posterior side also increase with flexion angle. It should be noted that, as per the results obtained, the stress values show a gradual increase in both the anterior and posterior sides of the neck in parallel to the rise in the flexion angle. The reason is thought to be that the head's center of gravity is closer to the face, whereby the moment effect of the head, when flexed forward, imposes more stress on the neck.

Limitations

This study has a limitation in that it only investigated the stress on the cervical spine and soft tissue at increased flexion angles in the cervical region, assuming that the cervical region consists only of vertebrae and soft tissues. The study's assumption may oversimplify the complexity of the cervical region, and there may be other factors that contribute to the stress on the cervical spine and soft tissues that were not considered in the study. In the real biological system, the cervical region and other regions of the spine are complex structures that include not only the vertebrae and soft tissues but also other structures such as intervertebral discs, ligaments, arteries, veins, and the nervous system. These structures can have considerable effects on the stress and strain of the cervical region and other regions of the spine.

Conclusion

FEM analysis of the cervical spine (cervical vertebra body and intervertebral contact surface) and soft tissue of the neck at different flexion angles was performed in this study. The maximum stress distribution in cervical vertebra bodies at 0°, 15°, 30°, 45°, and 60° flexion angles was analyzed, and the lowest value of stress was 2.8083 MPa at 0°, and the largest value of stress was 2.6639 MPa at 30°. Moreover, the most stressed vertebrae at 0° and 30° were determined to be C6-C7 and C5-C6-C7 vertebrae, respectively. For the intervertebral contact surfaces, the lowest and highest stress values were determined to be at 0° and 45°, and the most stressed vertebrae at these flexion angles were the C7 and C3 vertebrae, respectively. For the soft tissue of the neck, the lowest stress values for both anterior and posterior sides were at 0° and the highest at 60°. The average stress values for the anterior and posterior regions were 0.1460 and 0.0458 MPa. The average stress on the anterior side was 3.18 times higher than that on the posterior side. A number of studies have shown that bent or hunched postures are associated with negative health conditions such as pain, depression, and general stress. Furthermore, the results of the present study revealed potential benefits of maintaining reduced flexion of head and neck while sitting at a desktop computer. Increased flexion of head and neck has been quantitatively shown to increase stress in both vertebrae and soft tissue in the neck. As a matter of fact, maintaining an upright position while sitting at a computer is more beneficial for spinal health. Accordingly, we recommend that the head and neck be in an upright position in the daily life when at a desktop computer and that attention should be paid to avoiding increased stress in the spine, vertebrae as well as the soft tissues in an around the neck, which can be incurred due to improper sitting positions such as bent or hunched positions.

Conflicts of interest

The authors declare that they have no competing interests.

Ethical approval

This study was approved by the Ethics Committee of Atatürk University (Approval number: 15.04.2021/03-28).

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