Original Article

INVESTIGATION OF STRESSES DEVELOPED IN NATURAL AND IMPLANTED HUMAN CERVICAL SPINE BY FINITE ELEMENT METHOD

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Abstract:
Background: For design of suitable spinal implants, computational investigation of stresses developed within spine as a result of implantation is very important. Hence, the present study has been carried out for computation of stresses developed within Cervical Spine area during various neck motions using Finite Element method, for natural spine as well as for spines with implantation of both types viz Fusion Surgery and Total Disc Replacement. Methods: Computerized Tomography (CT) scan data of Indian people have been collected from hospitals. Important properties viz Elastic Modulus (E) and Density (ρ) of bones have been extracted from CT scan data for development of models for stress analysis. Bones with varying 'E' and 'ρ' values have been classified in five different categories. Under applied moments of 0.6 N-m, 1.2 N-m, 1.8 N-m and 2.4 N-m stress patterns have been computed for all six possible motions in (a) Natural Cervical Spine (b) Cervical Spine with Fusion Surgery (FS) and (c) Cervical Spine with Total Disc Replacement (TDR). Results: Stresses in all regions for natural spine have been found to be lowest compared to spines with FS and TDR. Stresses generated within spines with TDR are in between of those with FS and natural spine for some regions whereas for other adjacent regions stresses generated for spines with TDR are highest. Stress values declined steadily with respect to increase in bone strength for cervical spines with FS. Conclusion: Stresses developed are lower with TDR than with FS in all regions except in close vicinity of implanted artificial disc.

Key words: Cervical Spine, Vertebra, Inter-vertebral Disc, Bone Density, Implantation, Neck Motions, Von Mises Stress

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INTRODUCTION

While transmitting weight of the upper body to the pelvis, human spine is subjected to internal forces or reactions which generally exceed many times the entire body weight of the person. For this reason, often spinal problems like injuries and disc degenerations occur. When they become acute, the only possible biomechanical remedy is surgical intervention with implantation. In conventional surgical procedure known as Arthrodesis or Fusion Surgery (FS), upper and lower adjacent vertebrae of the degenerated region are joined with plates and screws. Thus motion of damaged or defective vertebral portion is eliminated and further manifestation of wear is prevented. The most common form of FS is Anterior Cervical Plate Fixation, as shown in Figure 1.

Figure 1: Anterior Cervical Plate Fixation (ACPF)

Figure 2: Total Disc Replacement (TDR)

In other cases, where this kind of surgical intervention is not possible because of unavailability of bone mass from anterior side, another method, known as Posterior Lateral Mass Screw Fixation, is employed. A further improved version of FS, introduced a few years back, is known as Transpedicular Screw Fixation. This method does not involve any plates and pedicles of adjacent vertebrae are held together with screws only. The more advanced kind of surgery known as Arthroplasty or Total Disc Replacement (TDR), involves replacement of damaged inter-vertebral disc(s) by implantation of artificial discs, as shown in Figure 2. However, this is a newer concept and is still in developmental stage. But for all these methods of surgery, investigation of stresses developed at regions of implantation, before and after the surgery, is of primary importance. Also variations of stresses with regard to changes in bone properties represent another important factor. So, in this present study, computational investigation of stresses developed at C5-C6 level within Cervical Spine area for all possible neck movements has been done for a Natural Spine (without any implantation), a Spine after FS and a Spine after TDR. The results have been compared with graphical plots. Variation in the stress values with respect to changes in bone properties also has been investigated.

BRIEF SURVEY OF LITERATURE

After introduction of Finite Element method in 1956, it was mainly employed for structural analysis. Liu and Ray[1] in 1973 first used this technique to understand the behavior of human spine. Since then many researchers worked on finite element application to the human lumbar spine area. But to analyze the biomechanics of human cervical spine, comparatively lesser research work has been reported. Hosey and Liu's[2] finite element model of head and neck, in 1980, did not include cervical posterior components and geometrical features such as orientation of the discs from anterior to the posterior and the uncinate processes. Later on, finite element models with much more detailed features have been formulated by Saito et al[3], Kleinberger[4], Bozic et al[5], Teo et al[6], Yoganandan et al[7,8] and many others during the last decade of twentieth century. Later, Kopperdahl et al[9] in 2002 conducted a study to investigate the Quantitative Computed Tomography (QCT) Density–Mechanical property regressions for trabecular bone for use in biomechanical modeling of the human spine. QCT density showed a strong positive correlation with modulus (n = 76) and yield stress (r2 = 0.90–0.95, n = 53, p < 0,001). Also, a weak positive linear correlation was found with yield strain (r2 = 0.58, n = 53, p = 0.07). Zhang QH et al[10] in 2005 processed the digitized geometrical data of the embalmed skull and vertebrae (C0-C7) of a 68-year old male cadaver to develop a comprehensive, geometrically accurate, nonlinear C0-C7 finite element model. The biomechanical response of human neck under physiological static loadings, near vertex drop impact and rear-end impact (whiplash) conditions were investigated and compared with published experimental results. Under static loading conditions, the predicted moment-rotation relationships of each motion segment under moments in mid-sagittal plane and horizontal plane agreed well with experimental data. Jang Taek Hyun et al[11] in 2008 created a finite element model of cervical spine column and validated it with the experimental data. The probability of injury of the disc, under dynamic loading, was investigated at various disc degeneration levels under dynamic loads. The result showed that the probability of injury was drastically increased with the disc degeneration levels. Kallemeyn Nicole A. et al[12] in 2008 created a finite element model of patient-specific Functional Spinal Unit (FSU) of Cervical Spine and validated it by comparison to data presented in the literature. They reported improved mesh development methods on existing multi-block meshing methods to create hexahedral cervical spine finite element models on a patient-specific basis and found that it could account for variations in anatomy and also could provide insight for planning of surgical treatment. Bahramshahi N. et al[13] in 2010 developed and validated a three-dimensional finite element model of cervical spine (C3-C5). They used Hypermesh and MSC. Marc software for the purpose. The modeling was done by using 20-noded hexagonal elements. It included inter-vertebral disc, cortical bone, cancellous bone, endplates, and ligaments. The structure and dimensions of each spinal component were compared with experimentally measured values. The finite element simulation was conducted to investigate compression, flexion\extension and right\left lateral bending modes. The simulation results were validated and compared closely with the published experimental data and the existing finite element models. The results showed greater flexibility in flexion and lesser flexibility in extension, in general. Zafarparandeh Iman et al[14] in 2013 investigated the effect of asymmetry on finite element model of cervical spine. They used the finite element model to get basic insights into workings of the cervical spine system and by using which they investigated the clinical instability of it and also attempted to establish the diagnostic guidelines.

METHODS

In the present study, finite element method has been used for analysis of natural as well as implanted Cervical Spine, as described below:

Computational analysis with natural model

Step 1: Development of natural (Intact) cervical spine model

To generate a model of cervical spine (C0-T1) from Computerized Tomography (CT) scan data, collected from hospital in DICOM format, firstly contours were generated from the CT scan data using a threshold value of 600 Hounsfield Unit (HU). These contours were then filtered (to eliminate artifacts and other unwanted matters) and stacked up using the image processing software named MIMICS (Materializes Interactive Medical Image Control System) to create the cervical spine (C0-T1) model as shown in Figure 3. This model was then exported to ANSYS, the finite element software package, after assignment of material properties.

Step 2: Assignment of Material Properties

Since bone is a living tissue, so its properties vary along its length and breadth. Such variation is reflected by the values of Hounsfiled Units (HU) in the CT scan images. By proper selection of threshold values of HU, bones with varied properties (E and ρ) could be extracted. Further, based on the ranges of values of E and ρ, bones have been classified into five categories as described below:

Normal Bone (NB): ‘E’ ranging from 11 to 20 GPa and ‘ρ’ from 1600 to 1900 Kg/m3
Weak Bone (WB): with ‘E’ and ‘ρ’ values approximately 90% of Normal Bone
Very Weak Bone (VWB): with ‘E’ and ‘ρ’ values approximately 70% of Normal Bone
Strong Bone (SB): with ‘E’ and ‘ρ’ values approximately 110% of Normal Bone
Very Strong Bone (VSB): with ‘E’ and ‘ρ’ values approximately 130% of Normal Bone

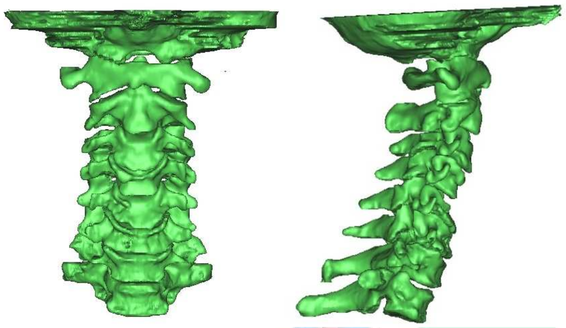


Figure 3: 3D Model of Cervical Spine in MIMICS

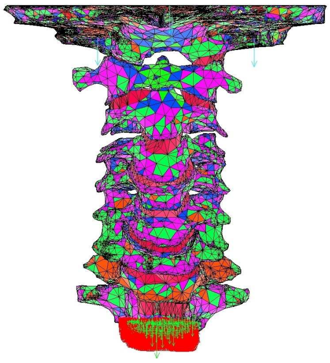
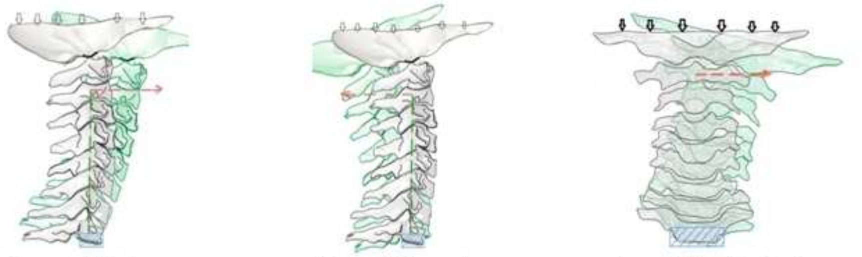


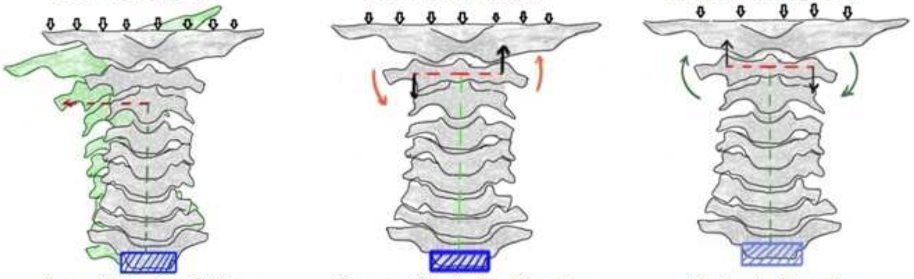
Figure 4: Finite element model of natural Cervical Spine with assigned Material Properties

Step 3: Selection of Element Type and Mesh Generation

Tetrahedral solid element (SOLID 92) was selected for discretization process. Mesh was generated from the volume file keeping the element size fixed at 5. Nodes and elements were created from the total volume during the mesh generation process. Both nodes and elements were written in a file for automatic assignment of material properties in MIMICS. After proper material assignment (as shown in Figure 4) the file was exported to ANSYS for analysis purpose.



Forward Flexion Forward Extension Lateral Bending Left



Lateral Bending Right Counter Clockwise Rotation Clockwise Rotation

Figure 5: All six possible movements of Cervical Spine

Step 4: Loading and Boundary Condition

Within ANSYS environment, all six possible neck movements, as shown in Figure 5, have been simulated on the five finite element models with material properties representing Very Weak Bone, Weak Bone, Normal Bone, Strong Bone and Very Strong Bone.

The most inferior nodes of the T1 vertebra were fixed in all directions. Models have been subjected to moments of 0.6 N-m, 1.2 N-m, 1.8 N-m and 2.4 N-m separately. The moments have been obtained by applying horizontal force of 5 N, 10 N, 15 N and 20 N one after another along X or Y axis (as the case may be) at a height of 120 mm from the fixed bottom end (i.e. at C2 level). The load of head has been taken to be 50 N (as obtained from literature[15]) and has been applied vertically downwards at the skull region in a distributed manner.

Computational analysis with implanted model

As shown in Figure 6, the damaged or degenerated disc has been dissected, the dissected volumes were re-meshed and material properties were reassigned. Then the procedures were the same as the natural model. Assembly of bone and two different implants viz Plate and Screws for FS and Ball & Socket type Artificial Inter-vertebral Disc for TDR, were performed within Pro-E, a commercially available CAD package. The attachment sites were again re-meshed and merged in ANSYS which ensured that there was no relative motion between the implant and the vertebral endplates. The application of loads and boundary conditions has been the same as for the natural model.

RESULTS AND DISCUSSIONS

For investigation of stresses generated in the vicinity of implantation, the whole area has been divided into six distinct regions of interest, as shown in Figure 7. The stress patterns obtained at these six regions for Natural Cervical Spine (NATURAL), Cervical Spine with Fusion Surgery (FS) and Cervical Spine with Total Disc Replacement (TDR) are shown graphically. Computation of maximum Von Mises Stress has been done for all five bone conditions viz VWB, WB, NB, SB and VSB. Also, such stresses have been computed at the six regions of interest for both Natural and Implanted Spine (FS and TDR) undergoing all six possible neck movements viz Forward Flexion (FF), Forward Extension (FE), Lateral Bending on Left (LBL), Lateral Bending on Right (LBR), Counter Clockwise Rotation (CCR) and Clockwise Rotation (CR) under a constant vertical load of 50 N (representing the Head) and moments of 0.6 N-m, 1.2 N-m, 1.8 N-m and 2.4 N-m respectively (in the direction of movement). Since the stresses obtained by increasing applied moments show predictive pattern, so only the stresses computed for the highest load i.e. 2.4 N-m have been shown in Figure 8–13. Also, stresses developed due to the movements LBL and LBR have been found to be almost same. Similar is the situation for CCR and CR. Hence stresses for only four (4) neck movements i.e. Forward Flexion (FF), Forward Extension (FE), Lateral Bending (LB) and Neck Rotation (NR) have been shown.

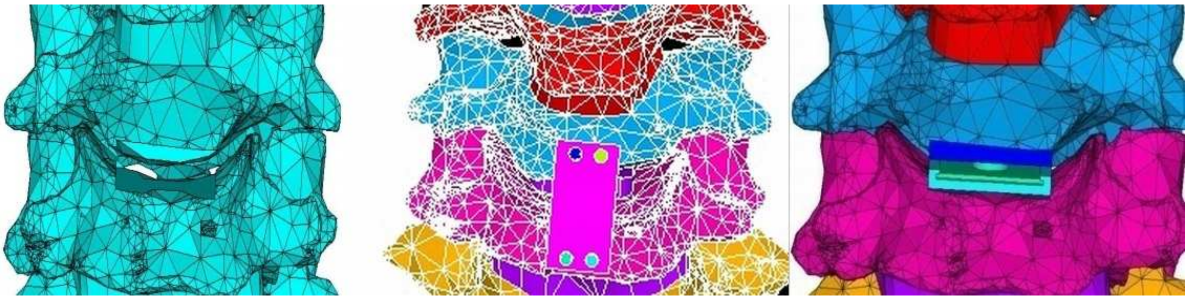


Figure 6: (a) Finite element model of surgically removed bone (b) Finite element model of plate and screw implant (c) Finite element model of artificial disc implant

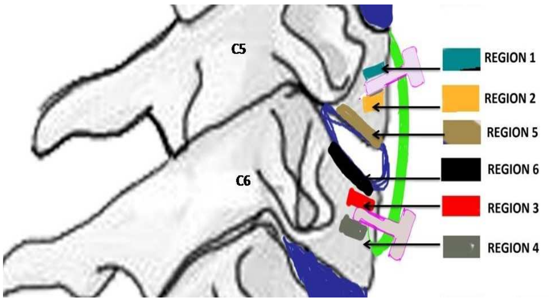
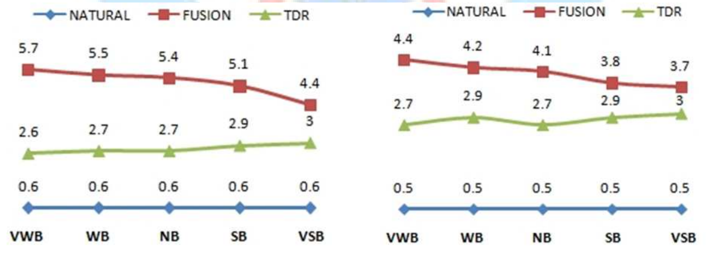


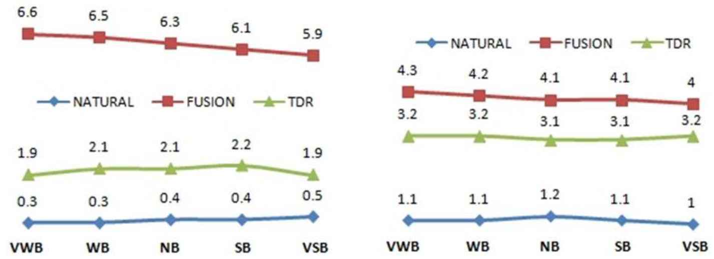
Figure 7: Position of six regions of interest

From these graphs; it is possible to get some idea about how the maximum Von Mises stresses vary with bone conditions for a particular type of neck movement. Also, comparative estimate can be obtained regarding the stresses generated within the six regions of interest in a Natural Cervical Spine vis-à-vis Implanted Cervical Spine (both for FS and TDR) under the same load. Finally, comparison of stresses generated at same region under the same applied load but for different neck movements is also possible. A close look at the graphs reveals that stresses generated in region 1 of cervical spine with TDR is much less than that with FS for all four neck movements. The difference in stresses is much more for lateral bending (LB) movement. Also, it is found that while there is a steady decline in stress values (for all four neck movements) with respect to increase in bone strength (density and elasticity) for cervical spines with FS, but for those with TDR, no such steady pattern is observed. For region 2, same declining stress pattern is found for FS but it can be seen that the reduction of stress values for TDR in comparison to FS is much more enhanced. Same pattern is observed for region 3 and 4. But for region 5 and 6, it is found that stresses generated for TDR are higher than those for FS. In general, it can be mentioned that the stresses in all regions for natural spine are lowest compared to spines with FS and TDR and also the values are almost steady with respect to change in bone strength, for all four type of neck movements. The stresses generated within spines with TDR are somewhere in between of those with FS and natural spine for first four regions (region 1,2,3 and 4) whereas for the next two regions (region 5 & 6) the stresses generated for spines with TDR are highest among all three. The reason for this increase can be attributed to the close vicinity of region 5 & 6 with the artificially implanted disc.



Max. Von Mises Stress (MPa) in Region 1 for FF

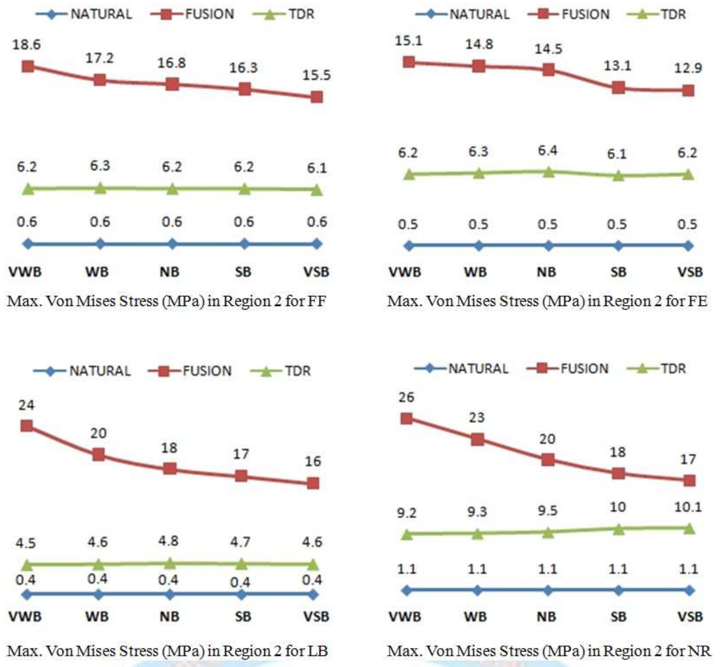
Max. Von Mises Stress (MPa) in Region 1 for FE



Max. Von Mises Stress (MPa) in Region 1 for LB

Max. Von Mises Stress (MPa) in Region 1 for NR

Figure 8: Stresses generated in Region 1 for all four neck movements (FF, FE, LB and NR)



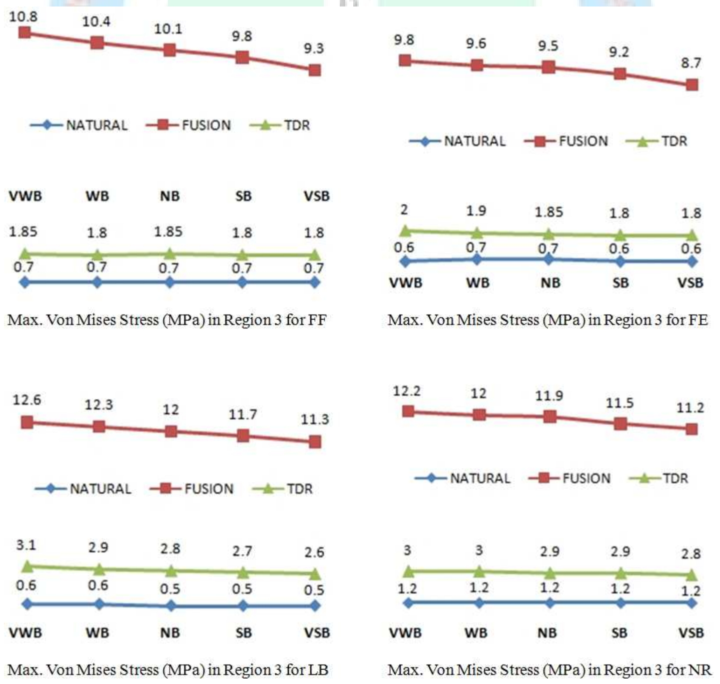
Max. Von Mises Stress (MPa) in Region 2 for FF

Max. Von Mises Stress (MPa) in Region 2 for FE

Max. Von Mises Stress (MPa) in Region 2 for LB

Max. Von Mises Stress (MPa) in Region 2 for NR

Figure 9: Stresses generated in Region 2 for all four neck movements (FF, FE, LB and NR)



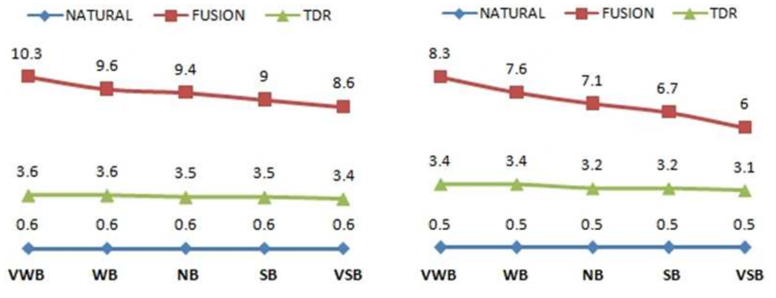
Max. Von Mises Stress (MPa) in Region 3 for FF

Max. Von Mises Stress (MPa) in Region 3 for FE

Max. Von Mises Stress (MPa) in Region 3 for LB

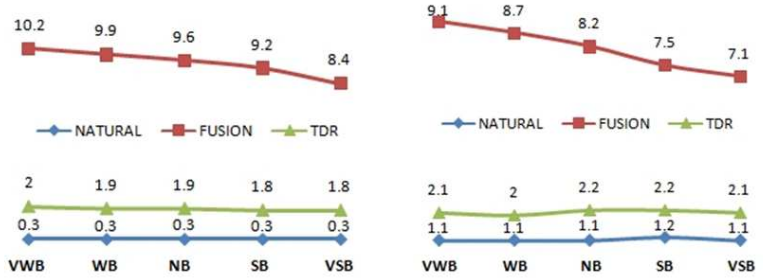
Max. Von Mises Stress (MPa) in Region 3 for NR

Figure 10: Stresses generated in Region 3 for all four neck movements (FF, FE, LB & NR)



Max. Von Mises Stress (MPa) in Region 4 for FF

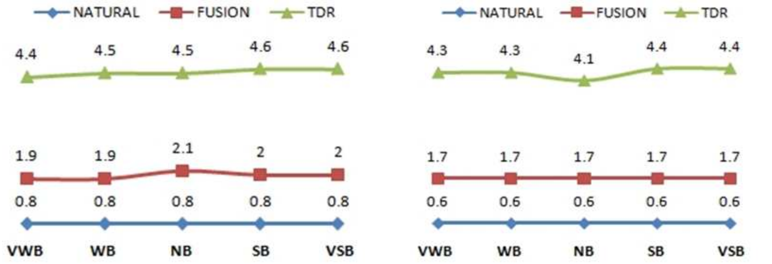
Max. Von Mises Stress (MPa) in Region 4 for FE



Max. Von Mises Stress (MPa) in Region 4 for LB

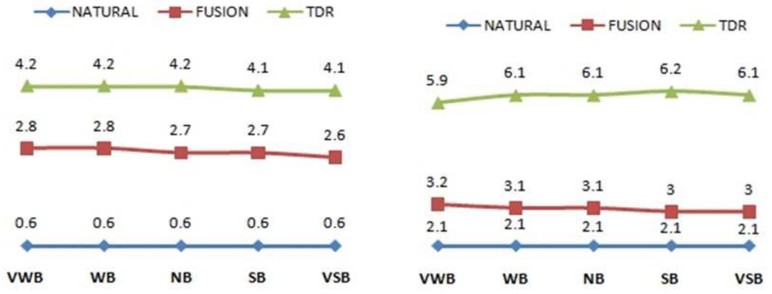
Max. Von Mises Stress (MPa) in Region 4 for NR

Figure 11: Stresses generated in Region 4 for all four neck movements (FF, FE, LB & NR)



Max. Von Mises Stress (MPa) in Region 5 for FF

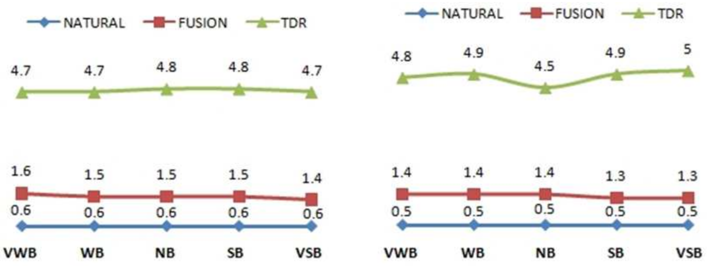
Max. Von Mises Stress (MPa) in Region 5 for FE



Max. Von Mises Stress (MPa) in Region 5 for LB

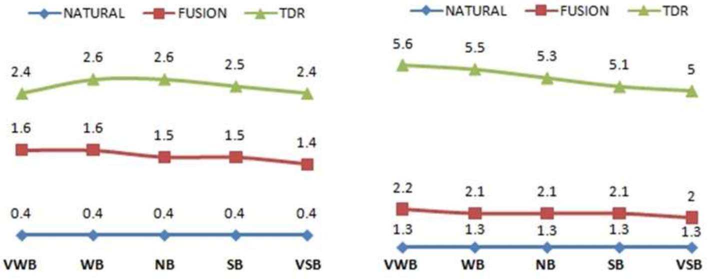
Max. Von Mises Stress (MPa) in Region 5 for NR

Figure 12: Stresses generated in Region 5 for all four neck movements (FF, FE, LB & NR)



Max. Von Mises Stress (MPa) in Region 6 for FF

Max. Von Mises Stress (MPa) in Region 6 for FE



Max. Von Mises Stress (MPa) in Region 6 for LB

Max. Von Mises Stress (MPa) in Region 6 for NR

Figure 13: Stresses generated in Region 6 for all four neck movements (FF, FE, LB & NR)

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