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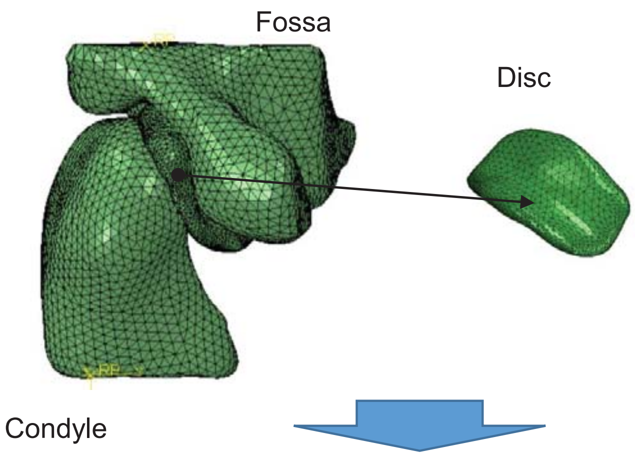
Graphical Abstract

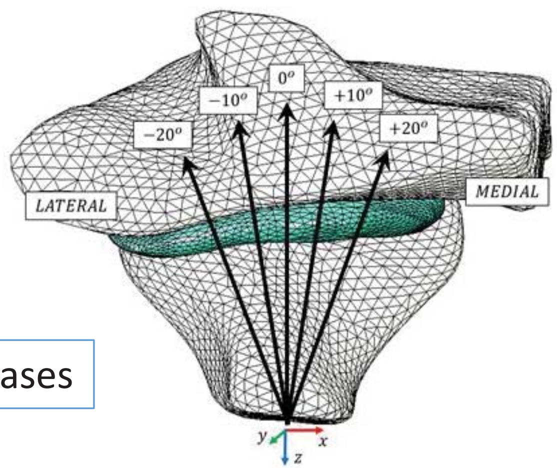
Effects of loading direction in clenching on stress distribution in the temporomandibular joint

3D TMJ FE Model



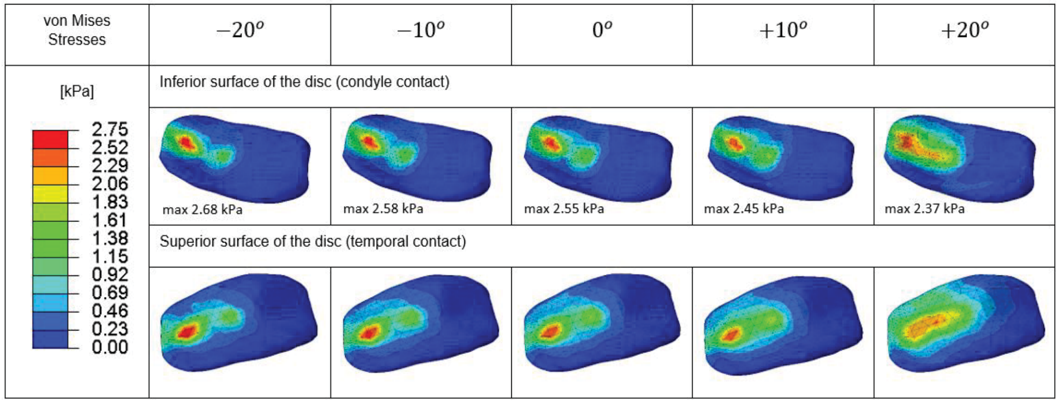
Viscoelastic properties for the disc

$$E(t) = E_0\left[1 - \sum_{i=1}^{n_t} e_i\left(1 - \exp\left(-\frac{t}{\tau_i}\right)\right)\right]$$



Lateral loading cases

Results: von Mises Stresses



Highlights

- Medio-lateral clenching movement under relaxation conditions is studied
- TMJ three-dimensional model is presented and analysed.
- Full viscoelastic model for TMJ disc simulation was implemented.
- TMJ stress distribution is influenced by loading directions
- Lateral region was encountered to presents higher stresses.

Effects of loading direction in prolonged clenching on stress distribution in the temporomandibular joint

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Abstract

Parafunctional habits, such as bruxism and prolonged clenching, have been associated with dysfunctional hyperactivity of the masticatory muscles, including the lateral pterygoid muscle. The resultant loading to the temporomandibular joint (TMJ) is subject to the degradation of bone, cartilage and disc in the TMJ. In this study, we examined the effect of clenching direction on the stress distribution in the TMJ. In this line, we hypothesised that asymmetrical clenching involved in parafunction might result in increased stresses on the TMJ disc as well as on the condylar and temporal articular surfaces.

The distribution of stress for various directional loadings was analysed using a three-dimensional finite element model of the TMJ, with viscoelastic properties for the disc. The numerical results revealed that load direction influenced the amount and distribution of stresses on the disc surfaces. In particular, the lateral region of the disc suffered higher stress values. Moreover, the results showed a significant stress relaxation in the disc that revealed its capacity for stress energy dissipation.

From the present study, it can be established that during prolonged clenching, the higher stresses are concentrated in the lateral region, which could imply that TMJ disorders related to damage or wear in the disc and the condylar cartilage, overall, occur when lateral dysfunctional displacements are present.

Keywords

Temporomandibular joint, parafunction, prolonged clenching, finite element analysis, viscoelastic behaviour, stress analysis.

1. Introduction

The temporomandibular joint (TMJ) is likely to withstand various loads during mastication owing to its mechanisms of stress absorption, distribution, and energy dissipation (Tanaka and Eijden, 2003). The TMJ disc, located between the mandibular condyle and temporal bone, as well as the articular condylar cartilages (Lamela et al., 2013), provides a large load-bearing capacity over the entire motion range of the human jaw joint (Koolstra and Tanaka, 2009) and prevents peak loads (Barrientos et al., 2016; Fernández et al., 2013; Hu et al., 2003). The cancellous bone of the mandibular condyle can additionally stand compressive and tensile deformations during loading of the TMJ with a minimum amount of bone mass because of its plate-like trabeculae structure (Giesen et al., 2001; van Ruijven et al., 2002).

Parafunctional habits, such as bruxism and prolonged clenching, have been associated with dysfunctional loading to the TMJ (Abe et al., 2013; Pérez del Palomar and Doblaré, 2006). It has been reported that patients with parafunction in the form of clenching reveal a higher condylar asymmetry than those with no disorders (Bodner and Miller, 1998). Furthermore, parafunctional hyperactivity of the lateral pterygoid muscle has been reported to lead to masticatory muscle pain (Hiraba et al., 2000; Uchida et al., 2001). Tanaka et al., (2007) additionally investigated the effect of hyperactivity of the lateral pterygoid muscle on the disc during prolonged clenching using a finite element model of the TMJ. However, these studies have been solely focused on lateral pterygoid muscle activity, and limited information is available regarding the effect of clenching direction on the stress distribution, which can lead to degenerative joint changes such as osteoarthrosis. Moreover, Gallo et al., (2000) suggest that, during mastication, fatigue failure of the disc could be caused by dynamic shear stress induced by grinding jaw movement. Therefore, asymmetrical clenching involved, i.e. in bruxism, can cause changes in the TMJ loading direction.

To help predict the stress distribution in the TMJ and to examine the possible effects of the loading direction in clenching on the stress distribution in the TMJ, a finite element (FE) model of the TMJ was assembled. The model was based on both computed tomography (CT) and magnetic resonance imaging (MRI) from one healthy subject. In this study, the distributions of stresses were analysed with various directional loadings on the TMJ disc. Therefore, we hypothesised that asymmetrical clenching involved in parafunction might result in increased stresses on the TMJ disc as well as on the condylar and temporal articular surfaces.

2. Materials and Methods

2.1 Reconstruction of three-dimensional TMJ model

An asymptomatic female patient (28 years old) without TMJ disorders was selected for three-dimensional (3D) reconstruction. 3D CT and MRI were taken for orthodontic treatment at Hospital Universitario Central de Asturias following all protocols from their Ethical Committee.

The contours of the right temporal bone and the mandibular condyle were obtained from the 3D scans, while the TMJ disc was constructed based on the MRI images.

DICOM files were processed using MIMICS software (Materialize, Leuven, Belgium), producing stereolithographic (STL) files of the mandibular condyle and temporal bone (glenoid fossa). The articular disc was manually created referring to the MRI data and shaped according to the respective articular surfaces. Surfaces of condyle, fossa and disc were then exported and treated using Rhinoceros software (McNeel&Associate, Seattle, WA, USA). The disc was converted to a solid using the same software. Finally, surfaces of bones and disc were meshed using Hypermesh (Hyperworks, Altair Engineering, Michigan, USA). As a result, the condyle was meshed as a shell with 3084 triangular elements (R3D3). The temporal bone was meshed as a shell with 4535 triangular elements (R3D3). The disc was meshed as a solid with 11560 tetrahedral elements (C3D4). Meshes were exported to Abaqus CAE (Simulia, Dassault Systemes, Rhode Island, USA), where the FE was calculated.

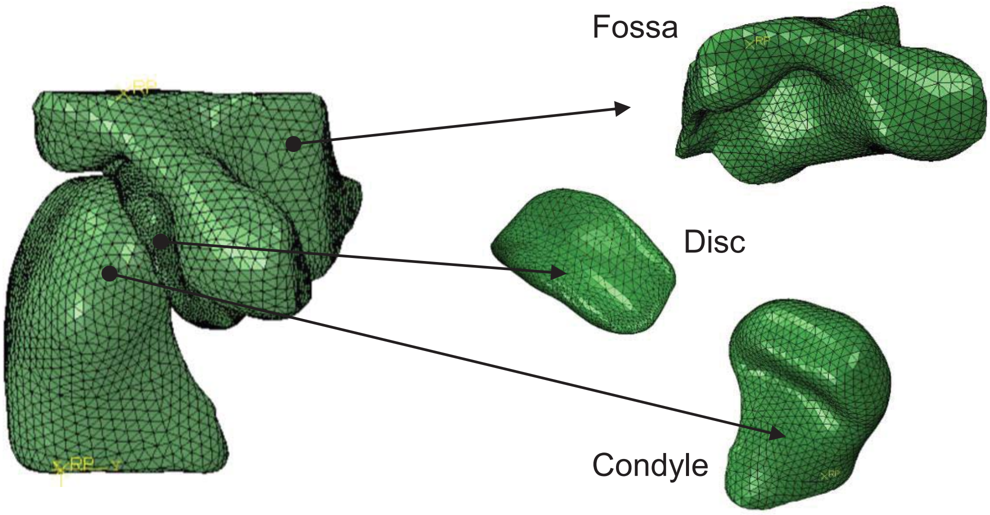

Figure 1. Detail of the TMJ meshed parts.

2.2 Finite element model definition

Abaqus CAE was used to implement the FE model of the TMJ. Once the meshed parts (fossa, condyle and disc) were imported and assembled in Abaqus, the mechanical behaviour was defined for each part.

The condyle and fossa were modelled as discrete rigid solids. This assumption was made due to the higher stiffness ratio between bone and cartilage and between bone and disc as well as taking into consideration that the main objective was to estimate the stresses in the disc. On the other hand, the disc was modelled as a deformable solid, that is, was able to deform and move along the articular surfaces. Finally, two uniform-thickness layers covering the condylar (1.15 mm) and temporal (0.41 mm) bone articular surfaces were created to model the respective articular cartilages.

For the mechanical behaviour of the materials, firstly, a linear viscoelastic model was used for the disc. The viscoelastic model was implemented using a generalised Maxwell model by means of an optimised Prony series:

$$\mathrm{E(t)} = \mathrm{E}_0\left[1-\sum_{\mathrm{i}=1}^{\mathrm{n_t}}\mathrm{e_i}\left(1-\exp\left(-\frac{\mathrm{t}}{\tau_\mathrm{i}}\right)\right)\right], \quad (1)$$

where E_0 is the instantaneous modulus of the material, n_t the number of Maxwell terms and $(\mathrm{e_i}, \tau_\mathrm{i})$ the Prony coefficients. The parameters of the viscoelastic model are included in Table 1 (Barrientos et al., 2018). Secondly, a linear elastic mechanical behaviour was considered for the cartilages (Singh and Detamore, 2008; Tanaka et al., 2014). The values of the Young's modulus and Poisson ratio for each cartilage and the disc are presented in Table 1.

Model Part	E [MPa]	ν
Condylar cartilage	0.8	0.3
Temporal cartilage	1.5	0.3

Disc	0.18	0.4
Disc (viscoelasticity)	τ_i [s]	e_i
Prony term 1	0.0384	0.5733
Prony term 2	0.4925	0.1223
Prony term 3	6.3499	0.0818
Prony term 4	106.4815	0.0926

Table 1. Material properties for the cartilages (from Tanaka et al., 2014) and disc (from Barrientos et al., 2018).

In regard to the boundary and loading conditions, the movement of the temporal bone was restricted for all degrees of freedom at its superior region, while the condyle was fixed in rotation, allowing only displacements. To control the movement of the condyle during simulations, a reference point was defined. The necessary displacements to achieve a 10% strain in the disc for each configuration were estimated (see Table 2) in order to simulate the different directional loadings of clenching (see Figure 2).

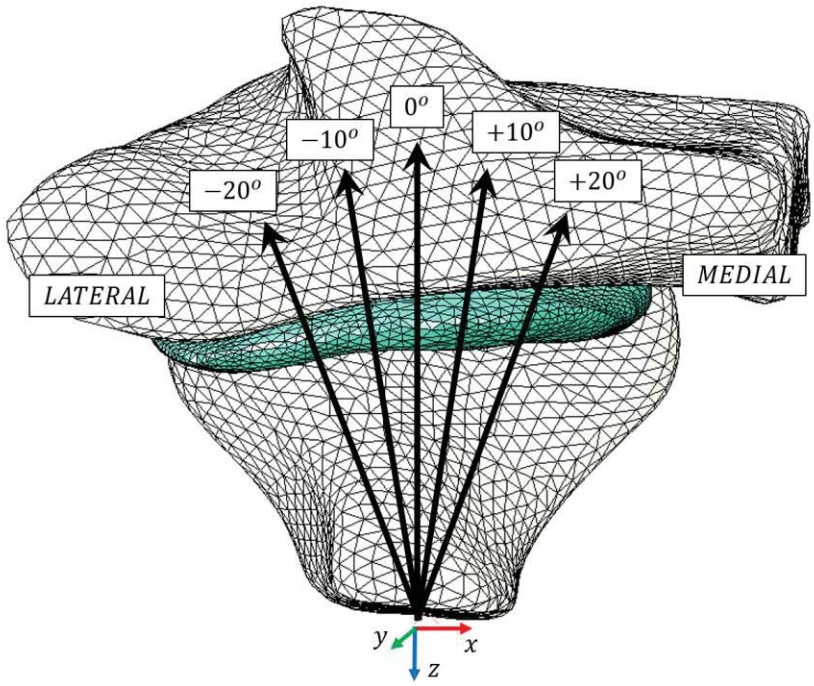

Figure 2. Illustration of the condylar directional loading applied in the TMJ simulation.

Between the articular cartilages and disc, surface-to-surface contacts were used, where a tangential rough behaviour and a normal behaviour with hard contact were used (Barrientos et al., 2016).

2.3 Simulations

The simulations of prolonged clenching were made in different steps, described as the loading conditions illustrated in Figure 3.

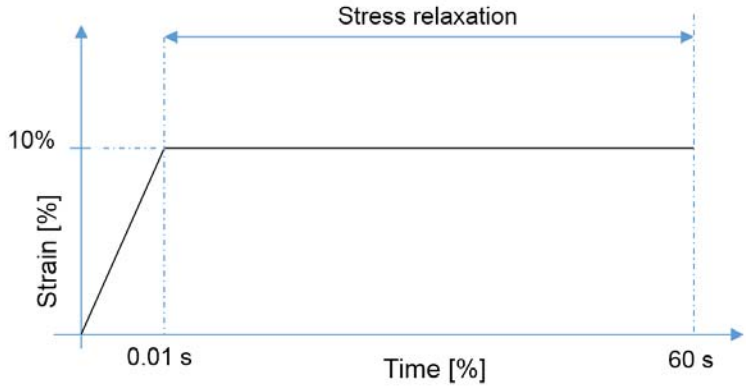

Figure 3. Loading conditions for simulation of prolonged clenching.

Before starting the simulation, there was an initial step to establish the contacts between articular cartilages and the disc. Next, the disc was compressed for 0.01 seconds up to a 10% strain, applying the corresponding displacements for each load case (see Table 2). Furthermore, the strain was maintained for 60 seconds, allowing viscoelastic relaxation of the disc (see Figure 3).

Angle [^{o}]	U_x [mm]	U_y [mm]	U_z [mm]
-20	-0.035	0.096	-0.096
-10	-0.017	0.098	-0.098
0	0	0.1	-0.1
10	0.017	0.098	-0.098
20	0.035	0.096	-0.096

Table 2. Displacement applied to the reference point of the condyle according to the model coordinate system.

Stress analysis was executed by the FE analysis programme Abaqus (Dassault

Systèmes, Paris, France). The von Mises stresses on the inferior and superior disc surfaces were evaluated during a 1-minute clenching period under strain loading conditions (see Figure 3).

3. Results

The stress distributions on the superior and inferior surfaces of the TMJ disc during prolonged clenching under constant strain are shown at two different instances of time: t = 0.01 seconds, which corresponded with the onset of clenching, and t = 60 seconds at the end of the relaxation step.

At the onset of clenching (t =0.01 s), the largest von Mises stresses were located on the inferior and anterior disc surfaces of the lateral area irrespective of the loading direction (Figure 4). Particularly, when the loading was applied in the -20^{o} direction, the largest von Mises stress was on the inferior disc surface (13.5 kPa), and it was concentrated on the lateral area of the disc. Meanwhile, when the loading was applied in 20^{o} direction, the von Mises stress on the inferior and superior disc surfaces was distributed over a wider area, and the stress concentration on the lateral area of the disc was reduced (12.1 kPa). At the end of prolonged clenching (t = 60 s), the von Mises stress was decreased irrespective of the loading direction (Figure 5). The largest von Mises stress, ranging from 2.37 kPa to 2.68 kPa, was located on the inferior and superior disc surfaces of the lateral area. Particularly, when the loading was applied in the 20^{o} direction, the von Mises stress was spread over a wider area on both inferior and superior disc surfaces, and the stress concentration on the lateral area of the TMJ disc was reduced due to the function of stress relaxation and energy dissipation of the TMJ disc. The average relaxation for all the simulated cases was approximately 80% after prolonged clenching.

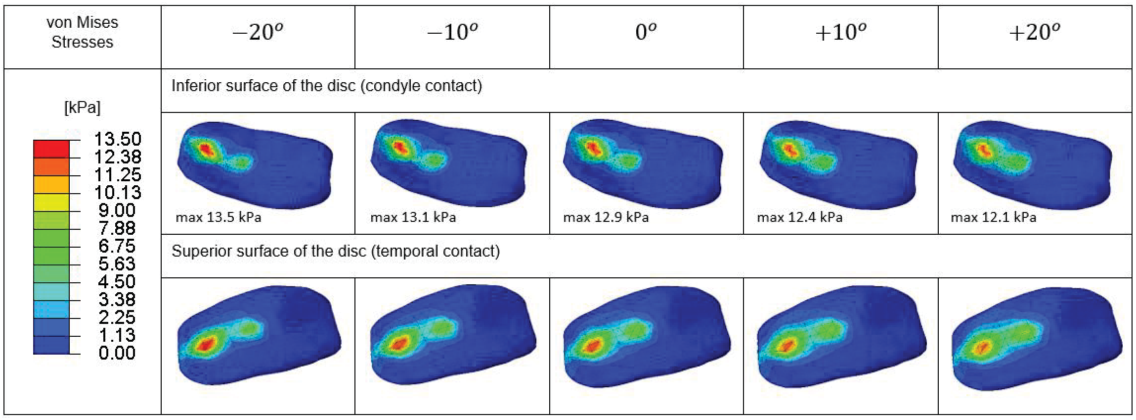

Figure 4. von Mises stresses in the TMJ disc at t = 0.01 s.

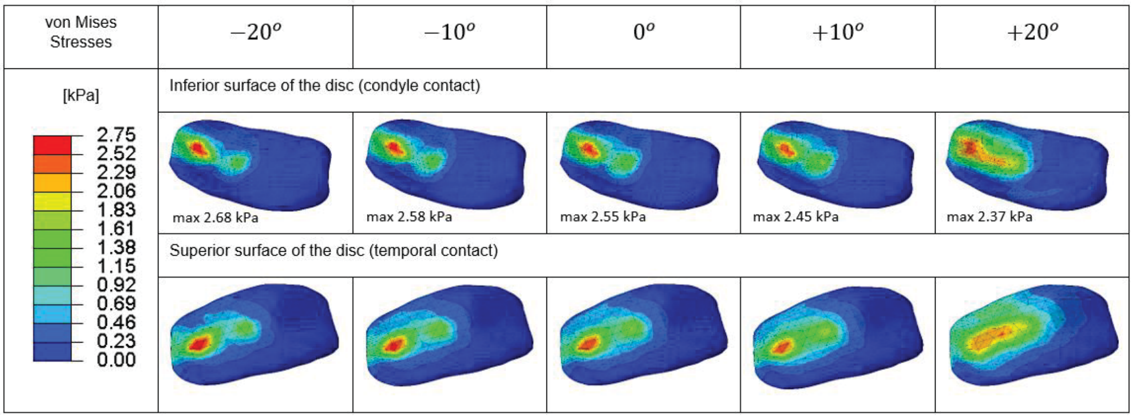

Figure 5. von Mises stresses in the TMJ disc at t = 60 s.

4. Discussion

Parafunctional habits, such as bruxism and prolonged clenching, may produce abnormal compression and shear forces in the TMJ, which can initiate disc displacement and condylar and articular cartilage degenerative changes (Gallo et al., 2006). Dysfunctional hyperactivity of the lateral pterygoid muscle during parafunction has been considered to lead to masticatory muscle pain (Hiraba et al., 2000; Murray et al., 2001). The resultant loading to the TMJ is subject to the degradation of the TMJ components. (Tanaka et al., 2007) have investigated the effect of hyperactivity of the lateral pterygoid muscle on the TMJ disc during prolonged clenching using a 3-dimensional FE model and have indicated that hyperactivity of the lateral pterygoid muscle may be involved in the progression of disc displacement. However, in this analysis, the hyperactivity of the lateral pterygoid muscle was established in the antero-posterior direction. Limited information is available about the effect of prolonged clenching direction in the medio-lateral aspect on the stress distribution in the TMJ. As far as we know, this was the first study in which the effect of loading in medio-lateral direction during clenching was simulated. The asymmetrical clenching was simulated displacing the condyle with different angles.

In the results, the von Mises stresses on the inferior and superior disc surfaces were located on the central and lateral areas at the onset of clenching irrespective of the loading direction. Furthermore, after prolonged clenching, the greater stresses remained on the disc surfaces of the central and lateral areas.
This was in line with previous studies (Beek et al., 2001; Tanaka et al., 2008) and indicated that the lateral displacement during clenching could produce wear and damage in the lateral region of the disc as well as in the condylar cartilage (Hattori-Hara et al., 2014). In addition, previous studies have indicated that stress distributions in the TMJ are speculated from their anatomical and biochemical findings (Kuroda et al., 2009; Öberg et al., 1971; Scapino et al., 2006). In anatomical studies with the human TMJ, Scapino et al., (2006) have demonstrated that marked thinning and perforation of the articular disc is more

frequently found in the central and lateral areas than in the remaining regions, including in asymptomatic TMJ discs. The arthritic changes in various areas of the TMJ disc were fully consistent with the pattern of compressive stress distribution during prolonged clenching elucidated in this study.

From the load cases in this study, it could be determined that there was a dependency of the stress distribution on the loading direction. At the maximum applied strain (t = 0.01 s), the difference in the von Mises stresses was approximately 11%, achieving the maximum value at -20º and the minimum value at +20º. On the other hand, after relaxation (t = 60 s), the difference was approximately 13%. These results provided arguments for the hypothesis that asymmetrical clenching involved in parafunction would result in increased stresses on TMJ disc surfaces, in quantitative and qualitative aspects. Moreover, Nickel et al., (2009) have studied the influence of tractional forces in the fatigue of TMJ tissues and concluded that translation in the medio-lateral direction could possibly affect degenerative joint changes in the cartilaginous tissues of the TMJ. Fatigue failure and damage of joint tissues may be linked to repeated and prolonged extension and shear (Iatridis and ap Gwynn, 2004; Tanaka and Eijden, 2003). Taken together, shear properties of the TMJ disc in the medio-lateral direction could possibly affect the amount and distribution of stresses during clenching.

This study's results clearly showed a stress relaxation phenomenon during prolonged clenching. This was mainly due to the viscoelastic behaviour of the disc, reported in prior research (Barrientos et al., 2018; Tanaka and Eijden, 2003). The average relaxation ratio in von Mises stresses is approximately 80% (see

Figures 4 and 5). One of our previous studies showed a similar relaxation ratio in TMJ porcine discs (Fernández et al., 2013). On the other hand, stress relaxation has additionally been observed in TMJ discs under shear and tensile loading conditions (Tanaka et al., 2003), and region or sex dependency has been observed as well (Wright et al., 2016). These results imply the significant capacity of the disc for energy dissipation independent of loading direction. The disc shows various mechanisms of energy dissipation as a result of the different phases in its structure: relaxation of the solid matrix, and interstitial fluid flow, within and through the matrix. Without energy dissipation, strain can lead to breakage of the disc and damage of the TMJ (Tanaka et al., 1999).

With respect to this study's analysis, the following remarks can be made:

- As human material was not available, viscoelastic material characteristics for the articular disc were derived from porcine TMJs (Barrientos et al., 2018). The disc material was represented by means of an optimised Prony model (Barrientos et al., 2018). In contrast to hyaline cartilage where biphasic or poroelastic models can be considered as more appropriate (Koolstra and van Eijden, 2005; Pérez del Palomar and Doblaré, 2006), the structures of the TMJ disc consists of fibrocartilage where viscoelastic models such as Kelvin's model are considered to be more adequate for stress analysis (Koolstra et al., 2007), particularly for the analysis of clenching (Allen and Athanasiou, 2006; Detamore and Athanasiou, 2003).
- Tensile and shear properties of the TMJ discs are different from the compressive properties (Detamore and Athanasiou, 2003; Tanaka et al., 2002; Tanaka and Eijden, 2003). The simulation was carried out with a

global viscoelastic material model. This could be seen as a limitation of the study because the anisotropy of the articular disc affects stress distribution (Tanaka et al., 2003; Yuya et al., 2010). However, in the present study's analysis, the disc was mainly subjected to compression; therefore, the simplified material model could be considered as valid.

- The obtained results could be affected by the boundary conditions and contacts used in the model. As a result, the FE model was calibrated with previous test results (Barrientos et al., 2016).
- Condylar and temporal cartilages were included in the FE simulation, being considered to be linear elastic (Singh and Detamore, 2008; Tanaka et al., 2014). This meant that the viscoelastic behaviour of the cartilages (Lamela et al., 2013) was neglected to simplify the model, in order to improve the understanding of the microcircumstancial condition on the TMJ disc.

Conclusions

The present study proves the influence of the medio-lateral loading direction on the stress value and stress distribution of the TMJ disc; achieving the maximum and the minimum stress values at -20º and +20º loading directions, respectively. The higher stress concentrations are encountered in the lateral region for the different loading directions analysed in this work. This fact could imply that TMJ disorders are related to damage or wear in the disc and the condylar cartilage overall when lateral dysfunctional displacement is present.

From the results obtained, there is no significant influence of the loading direction on the viscoelastic disc response. On the other hand, the results reveal how the viscoelastic behaviour of a TMJ disc has a significant role in dissipating energy through stress relaxation, with ratios of approximately 80% in the von Mises stress field.

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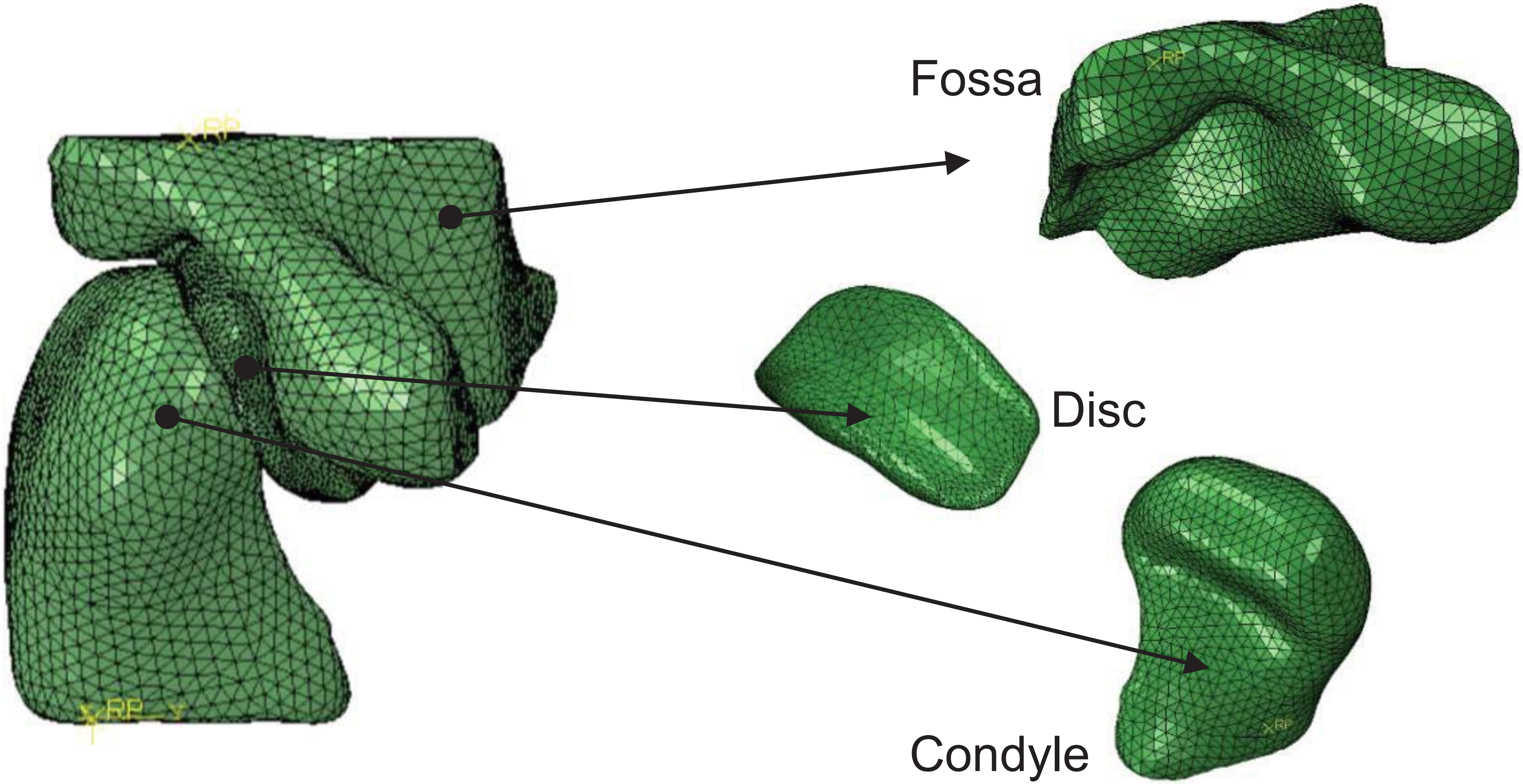
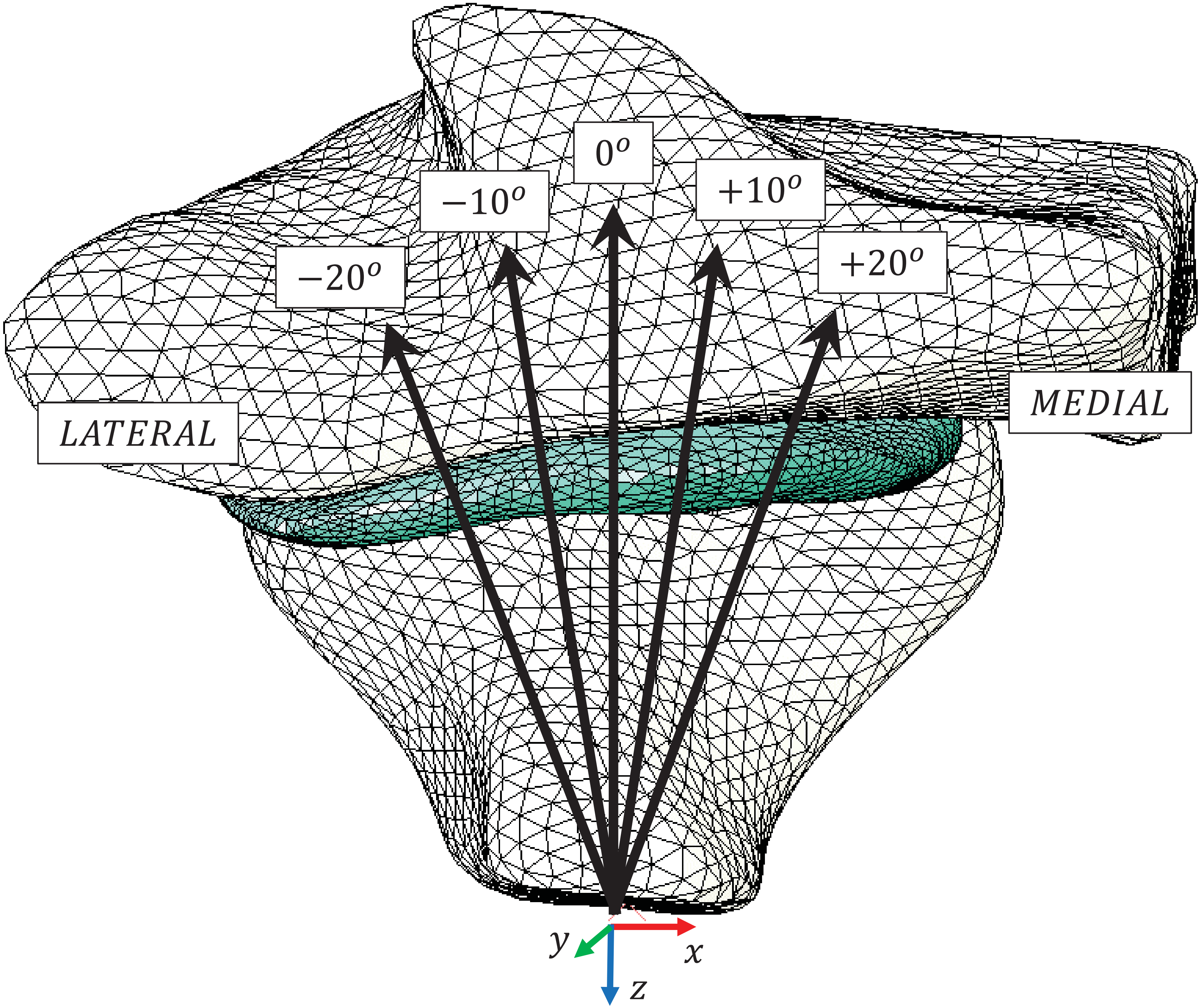
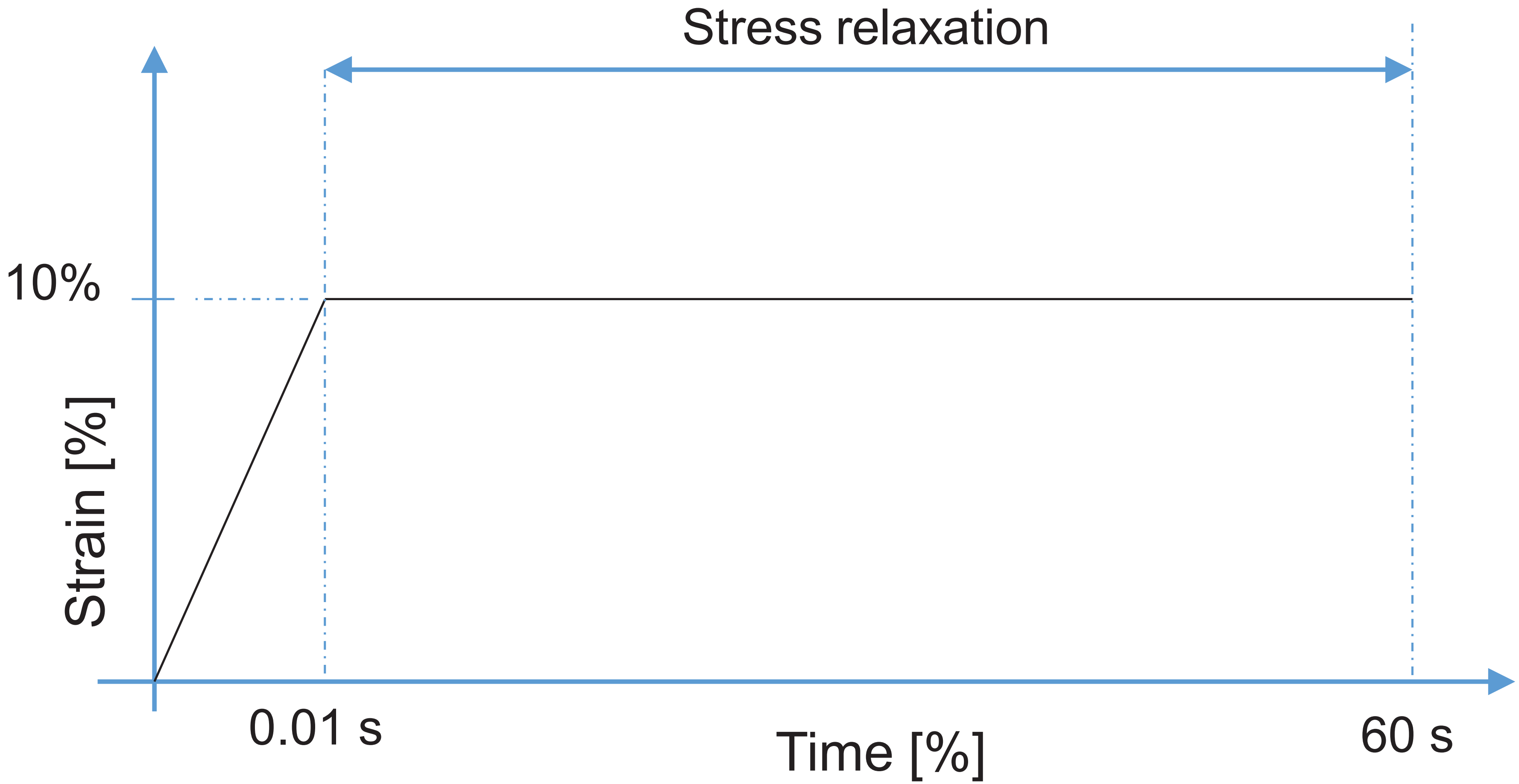
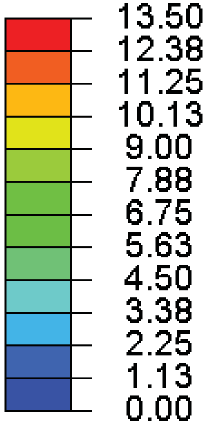
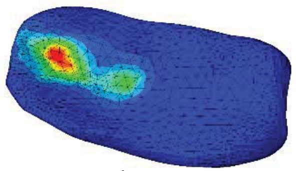
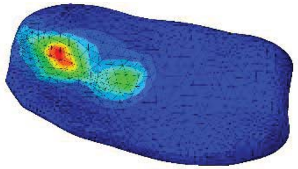
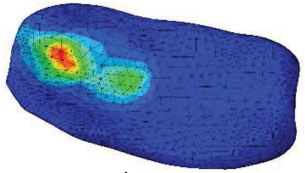
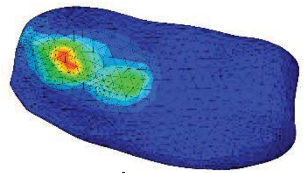
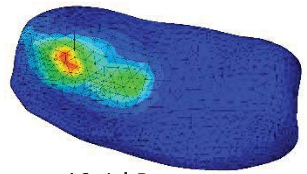
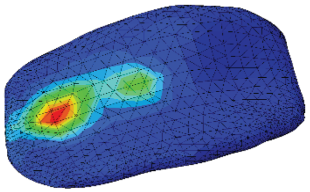
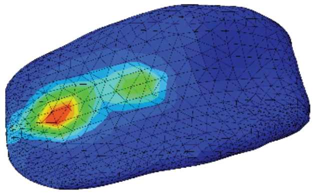
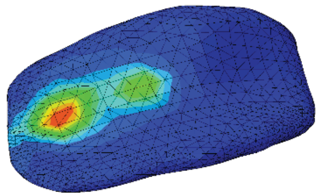
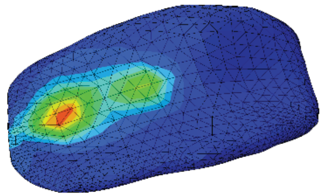
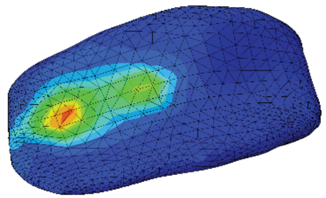
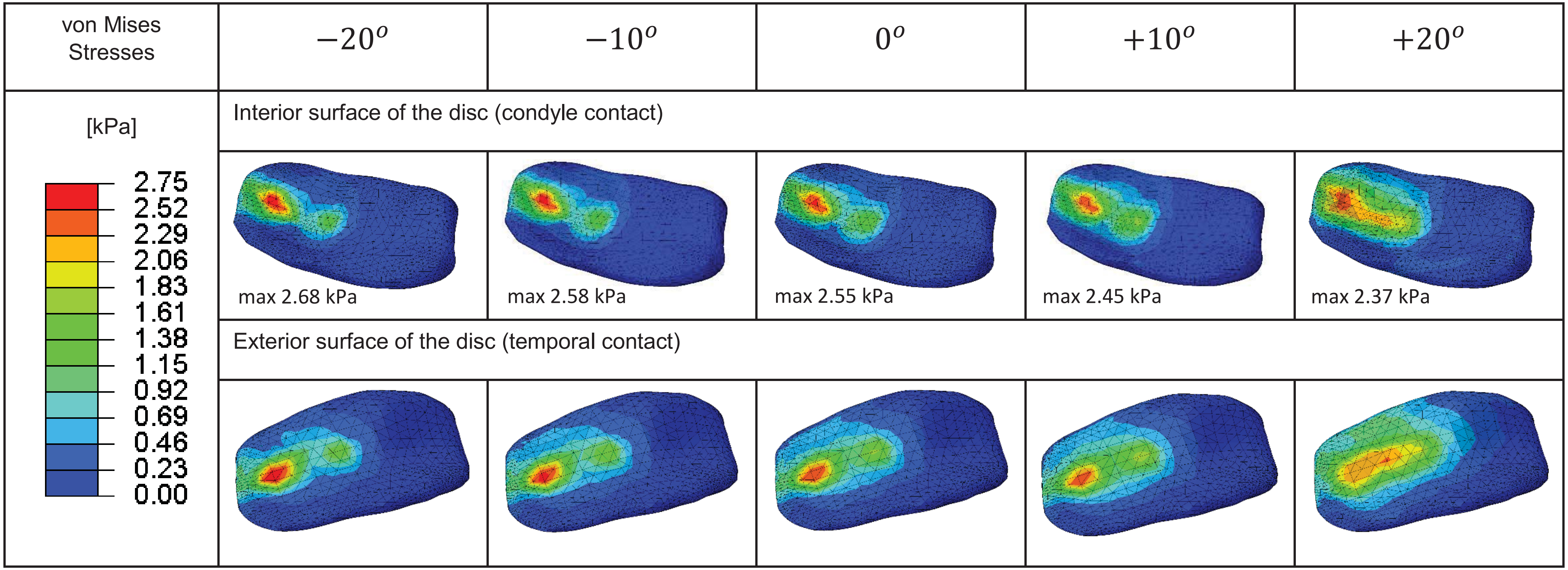

Fossa
Disc
Condyle



0^o
-10^o
$+10^o$
-20^o
$+20^o$
LATERAL
MEDIAL
y
x
z


Stress relaxation
10%
Strain [%]
0.01 s
Time [%]
60 s

von Mises Stresses	-20^o	-10^o	0^o	$+10^o$	$+20^o$
[kPa] 	Interior surface of the disc (condyle contact)				
	 max 13.5 kPa	 max 13.1 kPa	 max 12.9 kPa	 max 12.4 kPa	 max 12.1 kPa
	Exterior surface of the disc (temporal contact)				
					


von Mises Stresses
-20^o
-10^o
0^o
$+10^o$
$+20^o$
[kPa]
2.75
2.52
2.29
2.06
1.83
1.61
1.38
1.15
0.92
0.69
0.46
0.23
0.00
Interior surface of the disc (condyle contact)
max 2.68 kPa
max 2.58 kPa
max 2.55 kPa
max 2.45 kPa
max 2.37 kPa
Exterior surface of the disc (temporal contact)