**Supplementary section**

**Finite element analysis of a ball-and-socket artificial disc design to suppress excessive loading on facet joints: a comparative study with ProDisc**

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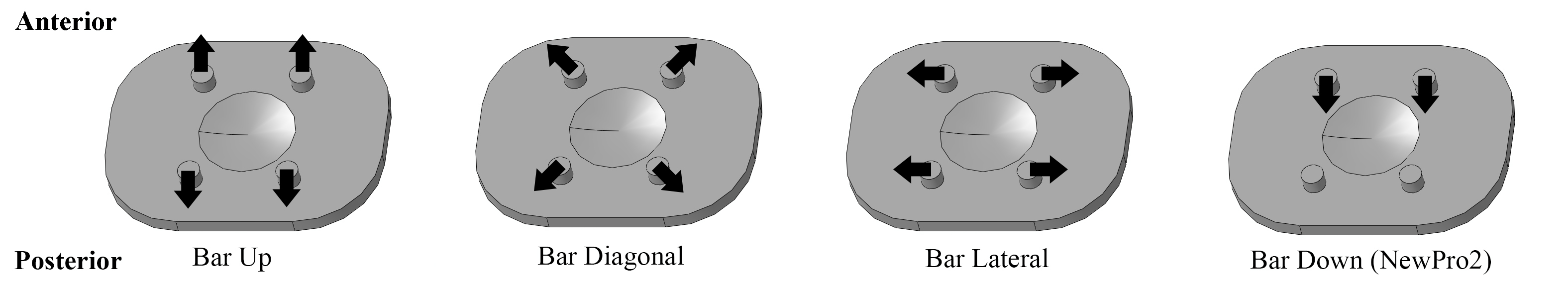
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**Changes in ROM and facet contact force according to the location of constraining bars**

The range of motion (ROM) and facet contact force according to the movement of the bars in the anterior, diagonal, lateral, and posterior directions were investigated. The surgical model with the NewPro and the direction of bar movement are shown in Fig. S1. The four bars were moved as the arrows indicate, as shown in Fig. S2. In case of ‘bar down’, which is named as ‘NewPro2’, the anterior bars were moved by 1 mm in the posterior direction while the posterior bars were unmoved.



**Fig. S1.** Surgical model with NewPro at surgical level (L3/4) in sagittal plane (left) and the geometry of NewPro2 (right), where the anterior bars are moved in the posterior direction by 1mm compared with NewPro. ‘A’ and ‘P’ indicate anterior and posterior, respectively.



**Fig. S2**. Geometries of ‘bar up’, ‘bar diagonal’, ‘bar lateral’ and ‘bar down (NewPro2)’ models. The arrows indicate the directions in which the bar locations were changed from the original NewPro model shown in Fig. 1. In case of ‘bar up’, the anterior bars were moved in the anterior direction while the posterior bars were moved in the posterior direction, by 1 mm. In case of ‘bar diagonal’, all four bars were moved outward diagonally, by 1.4 mm. In case of ‘bar lateral’, the left bars were moved to the left while the right bars were moved to the right, by 1 mm. In case of ‘bar down’, only the anterior bars were moved in the posterior direction, by 1 mm.

**Table S1.** ROM with ‘bar up’, ‘bar diagonal’, ‘bar lateral’ and ‘bar down’ models was compared with that of NewPro in extension, flexion, lateral bending and torsion. The numbers in brackets represent the percentage change compared to the NewPro model.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **ROM** | **NewPro** | **Bar Up** | **Bar Diagonal** | **Bar Lateral** | **Bar Down (NewPro2)** |
| **Extension** | 3.1 | 3.1 | 3.1 | 3.1 | 2.8 (-9.7%) |
| **Flexion** | 2.7 | 2.6 (-3.7%) | 2.6 (-3.7%) | 2.6 (-3.7%) | 2.6 (-3.7%) |
| **Bending** | 3 | 3 | 4 (+33.3%) | 4 (+33.3%) | 3 |
| **Torsion** | 1.7 | 1.7 | 2.9 (+70.6%) | 3 (+76.5%) | 1.8 (+5.9%) |

**Table S2.** Facet contact force (FCF) of ‘bar up’, ‘bar diagonal’, ‘bar lateral’ and ‘bar down’ models was compared with that of NewPro in extension, flexion, lateral bending and torsion. The numbers in brackets represent the percentage change compared to the NewPro model.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **FCF** | **NewPro** | **Bar Up** | **Bar Diagonal** | **Bar Lateral** | **Bar Down (NewPro2)** |
| **Extension** | 188 | 188.2 (+0.1%) | 188.2 (+0.1%) | 188.2 (+0.1%) | 118.9  (-36.8%) |
| **Flexion** | 10.9 | 10.8  (-0.9%) | 10.8  (-0.9%) | 10.8  (-0.9%) | 10.8  (-0.9%) |
| **Bending** | 139.5 | 139  (-0.4%) | 177.5 (+27.2%) | 178.2 (+27.7%) | 132.5  (-5%) |
| **Torsion** | 83.3 | 78.8  (-5.4) | 147.8 (+77.4%) | 150.9 (+81.2%) | 78.8  (-5.4%) |

The ROM was changed by -9.7% while the facet contact force was changed by -36.8% with ‘bar down (NewPro2)’ model in extension compared with the NewPro. In flexion, there were no changes in ROM and facet contact force among all surgical models, as the bars were not in contact with the grooves of the inlay. In lateral bending, the ROM and facet contact force were changed by +33.3% and +27.7 % in ‘bar lateral’ model and +33.3% and +27.2% in ‘bar diagonal’ model. The changes were similar between ‘bar lateral’ and ‘bar diagonal’ models. In axial torsion, the ROM and facet contact force were changed by +76.5% and +81.2 % in ‘bar lateral’ model and +70.6% and +77.4% in ‘bar diagonal’ model. The movement of the bars in the lateral direction maximally changed the ROM and facet contact force by +76.5% and +81.2% in axial torsion compared with the NewPro.

**Raw data of FEA simulation**

Tables S3 to S5 summarize the ROM of intact, ProDisc, NewPro and NewPro2 models under different spinal motions at L2/3, L3/4 and L4/5 levels, respectively. The L3/4 level is the surgical level. The numbers in brackets represent the percentage change compared to the intact model.

**Table S3.** Simulated ROM of different artificial disc models at L2/3 level.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ROM (°) | Intact | ProDisc | NewPro | NewPro2 |
| Extension | 3.04 | 3.11 (+2.3%) | 3.10 (+1.97%) | 3.01 (-0.99%) |
| Flexion | 4.34 | 4.44 (+2.3%) | 4.44 (+2.3%) | 4.44 (+2.3%) |
| Bending | 4.47 | 4.38 (-2.01%) | 4.47 | 4.47 |
| Torsion | 1.61 | 1.77 (+9.94%) | 1.63 (1.24%) | 1.61 |

**Table S4.** Simulated ROM of different artificial disc models at L3/4 (surgical) level.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ROM (°) | Intact | ProDisc | NewPro | NewPro2 |
| Extension | 2.24 | 3.1 (+38.39%) | 3.12 (+39.29%) | 2.81 (+25.45%) |
| Flexion | 4.47 | 2.66 (-40.49%) | 2.65 (-40.72%) | 2.64 (-40.94%) |
| Bending | 3.65 | 5.18 (+41.92%) | 2.97 (-18.63%) | 2.99 (-18.08%) |
| Torsion | 3.01 | 3.14 (+4.32%) | 1.71 (-43.19%) | 1.76 (-41.53%) |

**Table S5.** Simulated ROM of different artificial disc models at L4/5 level.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ROM (°) | Intact | ProDisc | NewPro | NewPro2 |
| Extension | 1.47 | 1.41 (-4.08%) | 1.41 | 1.49 (+1.36%) |
| Flexion | 6.69 | 6.69 | 6.69 | 6.69 |
| Bending | 3.18 | 3.04 (-4.4%) | 3.18 | 3.18 |
| Torsion | 2.1 | 2.1 | 2.11 (+0.48%) | 2.11 (+0.48%) |

Tables S6 to S8 summarize the facet contact force of intact, ProDisc, NewPro and NewPro2 models under different spinal motions at L2/3, L3/4 and L4/5 levels, respectively. The numbers in brackets represent the percentage change compared to the intact model.

**Table S6.** Simulated FCF of different artificial disc models at L2/3 level.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| FCF (N) | Intact | ProDisc | NewPro | NewPro2 |
| Extension | 153.22 | 149.01 (-2.75%) | 149.03 (-2.73%) | 143.34 (-6.45%) |
| Flexion | 0 | 0 | 0 | 0 |
| Bending | 67.17 | 63.75 (-5.09%) | 68.51 (+1.99%) | 68.59 (+2.11%) |
| Torsion | 9.8 | 10.29 (+5%) | 6.83 (-30.31%) | 7.28 (-25.71%) |

**Table S7.** Simulated FCF of different artificial disc models at L3/4 (surgical) level.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| FCF (N) | Intact | ProDisc | NewPro | NewPro2 |
| Extension | 185.92 | 189.74 (+2.05%) | 187.95 (+1.09%) | 118.94 (-36.03%) |
| Flexion | 0 | 11.18 | 10.94 | 10.84 |
| Bending | 133.68 | 162.34 (+21.44%) | 139.54 (+4.38%) | 132.52 (-0.87%) |
| Torsion | 56.87 | 127.14 (+123.56%) | 83.34 (+46.54%) | 78.81 (+38.58%) |

**Table S8.** Simulated FCF of different artificial disc models at L4/5 level.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| FCF (N) | Intact | ProDisc | NewPro | NewPro2 |
| Extension | 302.37 | 295.13 (-2.39%) | 295.11 (-2.4%) | 305.19 (+0.93%) |
| Flexion | 0 | 39.74 | 39.73 | 39.74 |
| Bending | 247.73 | 243.42 (-1.74%) | 247.73 | 247.53 (-0.08%) |
| Torsion | 153.91 | 152.57 (-0.87%) | 153.92 (+0.01%) | 153.81 (-0.06%) |

Table S9 summarizes the von Mises stress in the artificial disc of ProDisc, NewPro and NewPro2 models under different spinal motions.

**Table S9.** Von Mises stress in artificial disc (MPa)

|  |  |  |  |
| --- | --- | --- | --- |
|  | ProDisc | NewPro | NewPro2 |
| Extension | 83.95 | 86.16 | 107.96 |
| Flexion | 154.56 | 154.42 | 155.2 |
| Bending | 107.97 | 165.35 | 165.85 |
| Torsion | 129.83 | 130.03 | 120.24 |