

1 Effects of Aortic Root Motion on Wall Stress in the Marfan Aorta Before and After
2 Personalised Aortic Root Support (PEARS) Surgery

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13

14 **ABSTRACT**

15 Aortic root motion was previously identified as a risk factor for aortic dissection due to
16 increased longitudinal stresses in the ascending aorta. The aim of this study was to investigate
17 the effects of aortic root motion on wall stress and strain in the ascending aorta and evaluate
18 changes before and after implantation of personalised external aortic root support (PEARS).

19
20 Finite element (FE) models of the aortic root and thoracic aorta were developed using
21 patient-specific geometries reconstructed from pre- and post-PEARS cardiovascular magnetic
22 resonance (CMR) images in three Marfan patients. The wall and PEARS materials were
23 assumed to be isotropic, incompressible and linearly elastic. A static load on the inner wall
24 corresponding to the patients' pulse pressure was applied. Cardiovascular MR cine images
25 were used to quantify aortic root motion, which was imposed at the aortic root boundary of
26 the FE model, with zero-displacement constraints at the distal ends of the aortic branches and
27 descending aorta.

28
29 Measurements of the systolic downward motion of the aortic root revealed a significant
30 reduction in the axial displacement in all three patients post-PEARS compared with its pre-
31 PEARS counterparts. Higher longitudinal stresses were observed in the ascending aorta when
32 compared with models without the root motion. Implantation of PEARS reduced the
33 longitudinal stresses in the ascending aorta by up to 52%. In contrast, the circumferential
34 stresses at the interface between the supported and unsupported aorta were increase by up to
35 82%. However, all peak stresses were less than half the known yield stress for the dilated
36 thoracic aorta.

39 **Introduction**

40 Acute aortic dissection is the most prevalent cause of death in patients with Marfan
41 syndrome. Aortic wall abnormalities and aortic dilatation are known to influence mechanical
42 stresses in the aortic wall and are the most common risk factors for aortic dissection and
43 rupture (Beller et al., 2004). It is well-known that in most acute dissections of the ascending
44 aorta there is a transverse intimal tear a few centimetres distal to the aorto-ventricular
45 junction (Hirst et al., 1958). More recent studies have suggested that aortic root motion may
46 be a factor for occurrence of dissection and the site of the intimal tear due to increased
47 longitudinal wall stresses (Beller et al., 2004, Beller et al., 2008b).

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49 Ventricular relaxation and contraction during every heartbeat provides a driving force for the
50 downward movement of the aortic annulus, which is then transmitted to the aortic root,
51 ascending aorta, transverse aortic arch and aortic branches. Beller et al. (2004) used
52 aortograms to analyse the extent of aortic root motion in 40 patients with coronary artery
53 heart disease. It was found that the peak downward axial displacement of the aortic root
54 during a cardiac cycle ranged between 0% and 49% of the sinotubular junction (STJ)
55 diameter, with a median of 14% (IQR 7% to 22%). Other cardiac pathology also affected
56 aortic root movement, where patients with aortic insufficiency showed increased aortic root
57 motion because of increased left ventricular stroke volume while patients with left ventricular
58 systolic dysfunction displayed reduced aortic root motion because of reduced ventricular
59 contraction.

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61 Stress analysis of the thoracic aorta was then carried out to investigate the influence of aortic
62 root motion on wall stress in the ascending aorta (Beller et al., 2004) and evaluate the risk of
63 aortic dissection (Beller et al., 2008b). A finite element (FE) model of an average adult

64 human aortic root (excluding the sinuses of Valsalva), aortic arch and aortic branches was
65 constructed using measurements obtained from a silicone mould of a normal human aorta
66 while the arch spatial orientation was obtained from 3D reconstruction of MR images of a
67 healthy volunteer (Beller et al., 2008b). An 8.9 mm axial displacement was imposed at the
68 aortic root base, followed by a 6° twist. These values were obtained from healthy volunteers
69 in studies by Kozerke et al. (1999) (for displacement) and Stuber et al. (1999) (for twist). Key
70 findings were that pressurisation alone did not appreciably deform the model, but including
71 the axial displacement caused significant deformation to the ascending aorta and
72 brachiocephalic trunk. In the control model (without aortic root motion), high stress
73 concentrations were found at the ostia of the aortic arch branches. Upon addition of the aortic
74 root motion, there were no marked change in circumferential or longitudinal stresses between
75 these branches, but the longitudinal stress in the ascending aorta (approximately 2 cm above
76 the STJ) increased by 50%. Furthermore, including the twist did not result in any appreciable
77 changes in the deformation or longitudinal stresses.

78

79 In spite of the high stress concentrations at the ostia of the aortic arch branches, mechanical
80 failures are not typically observed in these regions. However, increased longitudinal stress in
81 the ascending aorta may render this region at increased risk of degeneration of the aortic
82 media and intimal rupture (Beller et al., 2004, Beller et al., 2008b), especially in patients with
83 a vulnerable aortic wall due to connective tissue disease. As an aortic aneurysm dilates, the
84 longitudinal stress in the dilated region also increases significantly, and may result in rupture
85 (Thubrikar et al., 1999). If located in the ascending aorta, aortic root motion may then result
86 in an additional increase in the longitudinal stress of the aneurysm, consequently enhancing
87 the risk of rupture of small aneurysms, which are not usually considered for surgery (Beller et
88 al., 2008b). Furthermore, aortic root motion may dislodge atherosclerotic debris from the

89 aortic wall, leading to stroke or other embolic events, or lead to accelerated degeneration of
90 homografts, autografts and bioprosthetic valves (Beller et al., 2008b). Changes in the
91 magnitude of aortic root motion before and after aortic valve replacement (AVR) was
92 evaluated in patients with aortic insufficiency, aortic stenosis and proximal aortic dissection
93 (Beller et al., 2008a). Postoperative aortic root motion was significantly reduced after AVR
94 in patients with initial aortic insufficiency, while it was appreciably increased in patients with
95 initial aortic stenosis. However, based on their findings from the FE study (Beller et al., 2004,
96 Beller et al., 2008b), increased aortic root motion caused higher longitudinal wall stress,
97 which may in turn have harmful consequences in the context of a thinned, post-stenotic,
98 dilated aorta.

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100 These findings form the underlying interest in the effect of aortic root motion on mechanical
101 stresses in the Marfan aorta upon insertion of personalised external aortic root support
102 (PEARS; ExoVasc®, Exstent Ltd, Tewkesbury, UK) (Treasure et al., 2011). Follow-up
103 cardiovascular magnetic resonance (CMR) imaging studies of the aortic root upon insertion
104 of PEARS revealed that in addition to preventing further dilatation (Pepper et al., 2010a,
105 Pepper et al., 2010b), the stiffer PEARS also caused a reduction in the aortic root motion
106 (Izgi et al., 2015). In a previous study, FE models were developed to compare the stress and
107 strain fields in Marfan aortas pre- and post-PEARS implantation, where one of the
108 assumptions made was zero-displacement at the aortic root (Singh et al., 2015). The present
109 study investigates the effects of aortic root motion on wall stress and strain in patient-specific
110 Marfan aortas before and after implantation of PEARS.

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112 **Methods**

113 **Patient-Specific Geometry**

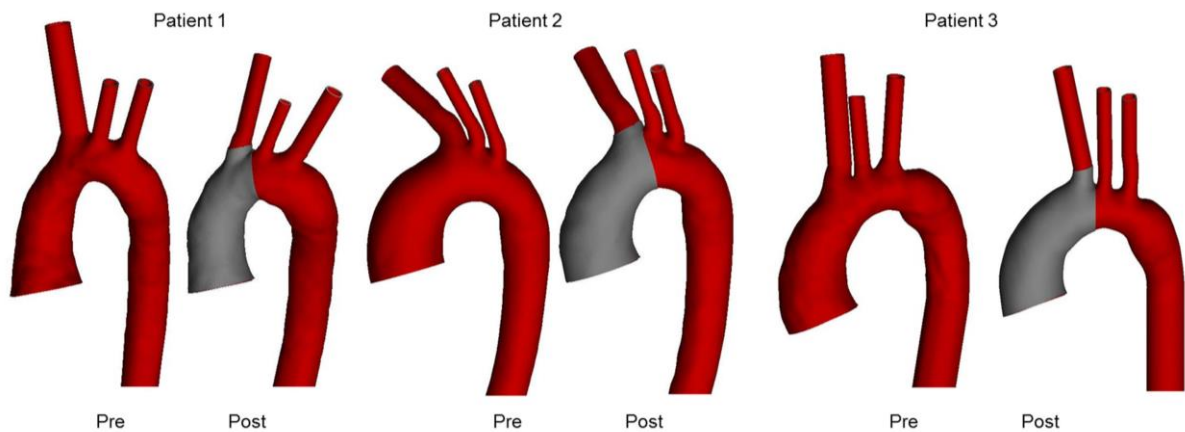
114 MR images before and after implantation of PEARS were obtained (see Table 1 for imaging
 115 parameters). These were used to reconstruct patient-specific models of the aorta using
 116 Mimics (Materialise, Louvain, Belgium).

117

118 Table 1: Magnetic resonance imaging parameters for Patients 1, 2 and 3

| | | Echo | Flip | Pixel | Slice | Interslice | Image | |
|-----------|------|------------|------|-------|-------|------------|-----------|-------|
| | | Repetition | time | angle | size | thickness | distance | |
| | | time (ms) | (ms) | (°) | (mm) | (mm) | (mm) | |
| | | | | | | | frequency | |
| | | | | | | | (MHz) | |
| Patient 1 | Pre | 292.10 | 1.22 | 80 | 1.328 | 6.0 | 3 | 63.67 |
| | Post | 296.38 | 1.07 | 70 | 0.594 | 1.5 | var. | 63.67 |
| Patient 2 | Pre | 221.00 | 1.40 | 90 | 0.781 | 0.8 | 0.8 | 63.68 |
| | Post | 251.00 | 1.45 | 70 | 0.625 | 2.0 | 2.0 | 63.68 |
| Patient 3 | Pre | 338.87 | 1.22 | 80 | 1.328 | 6.0 | 3.0 | 63.68 |
| | Post | 292.10 | 1.22 | 80 | 1.328 | 6.0 | 3.0 | 63.68 |

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121 Figure 1: Reconstructed patient-specific geometries for Patients 1, 2 and 3 before and after implementation of PEARS

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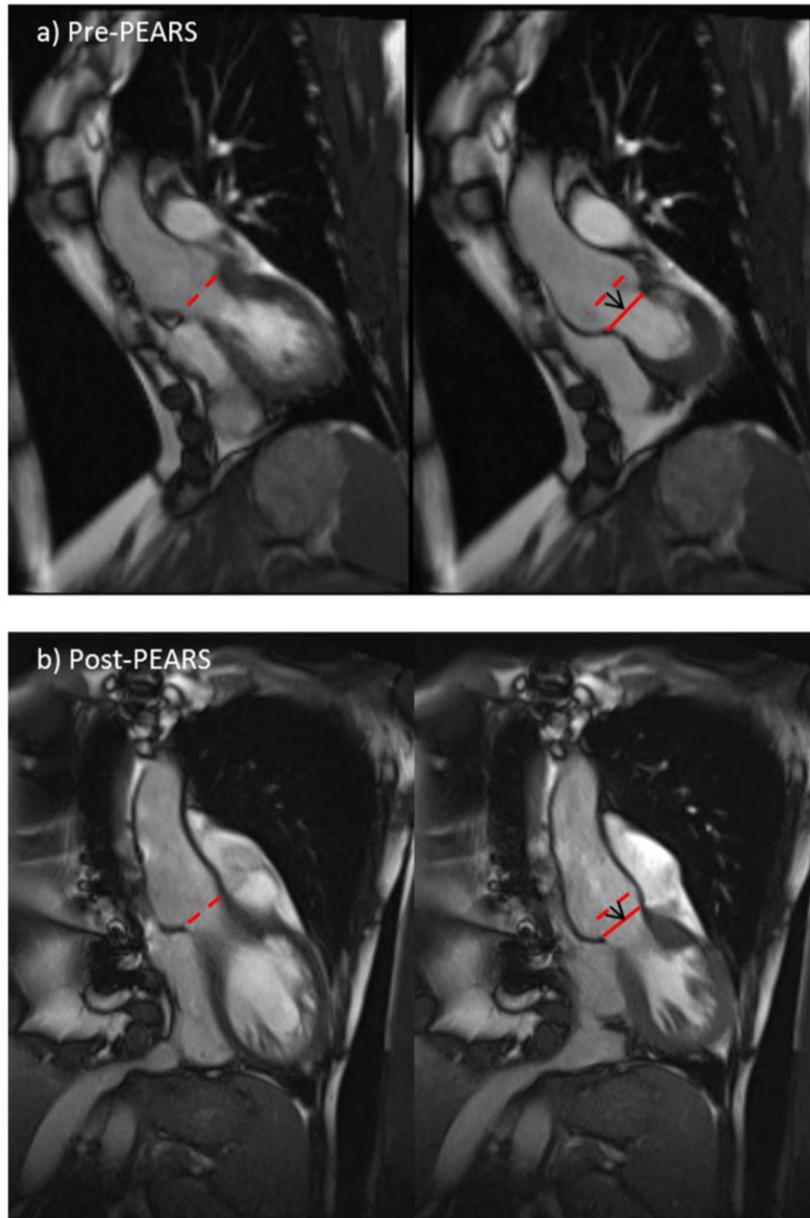
123 A uniform wall thickness was assumed for each aorta; the post-PEARS wall was thicker to
124 account for the formation of a periarterial fibrotic sheet (Verbrugghe et al., 2013). The aortic
125 branches were assumed to have the same thickness as the aorta. ANSYS ICEM CFD
126 (ANSYS, Canonsburg, PA, USA) was used to discretise the resulting geometries using
127 hexahedral elements. Mesh independence tests were performed using mesh sizes of 1.0×10^5 ,
128 2.5×10^5 and 5.0×10^5 elements. The differences in terms of peak displacement, peak stress and
129 peak strain were less than 1.5% between the 1.0×10^5 element mesh and the 2.5×10^5 element
130 mesh and less than 1.0% between the 2.5×10^5 and 5.0×10^5 element mesh. Computational
131 time deficit was negligible in all cases, as each simulation was completed within 3 hours.
132 Consequently, the number of elements used was between 2.5×10^5 and 5.0×10^5 elements.

133

134 **Assessment of Aortic Root Motion**

135 The aortic root motion was defined as the systolic downward motion of the aortic valve
136 annulus. The left ventricular outflow tract cross-cut (LVOTxc) CMR cine images were used
137 to identify the aortic valve annular plane in diastole and systole. These two planes were not
138 parallel to each other due to the three-dimensional motion of the aortic root. Therefore, the
139 systolic downward motion was measured as the length of the perpendicular line connecting
140 the mid-point of the diastolic annulus plane and its intersection with the systolic annulus
141 plane (see Figure 2) (Izgi 2015).

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149 **Material Properties**

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Figure 2: Measurement of the systolic downward aortic root motion (in Patient 1) for the (a) pre-PEARS aorta and (b) post-PEARS aorta. The annular plane at end-diastole is illustrated by the dashed line, while the plane at end-systole is illustrated by the solid line. The aortic root motion is quantified as the length of the perpendicular line connecting the mid-point of each annular plane

The aortic wall was modelled using a linear elastic constitutive equation, assuming it to be incompressible, homogenous and isotropic. It was assumed that the aortic branches had the same properties as the pre-PEARS aorta. The material properties are summarised in Table 2.

153 The justification for the choice of material properties for the post-PEARS material can be
 154 found in our previous work (Singh et al., 2015).

155

156 Table 2: Wall material properties used in the finite element models

| | Pre-PEARS | Post-PEARS |
|-----------------------|----------------------|-------------------------|
| Elastic modulus (kPa) | 3000 | 6750 |
| Poisson's ratio | 0.49 | 0.45 |
| Wall thickness (mm) | 1.0 | 1.5 |
| References | Nathan et al. (2011) | Verbrugge et al. (2013) |

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159 **Boundary Conditions**

160 A static load corresponding to the patients' pulse pressure (see Table 3) was applied
 161 perpendicular to the inner surface of the aorta. At the aortic root, an axial downward motion
 162 was specified based on the measurements obtained for each patient. Zero-displacement
 163 constraints were set at the distal ends of the brachiocephalic, left common carotid and left
 164 subclavian arteries, and in the mid-descending aorta.

165

166 Table 3: Patient data used in this study

| | Patient 1 | | Patient 2 | | Patient 3 | |
|------------------------------|-----------|------|-----------|------|-----------|------|
| | Pre | Post | Pre | Post | Pre | Post |
| Blood Pressure (mmHg) | | | | | | |
| Systolic | 135 | 130 | 110 | 110 | 118 | 110 |
| Diastolic | 78 | 70 | 60 | 60 | 84 | 70 |
| Pulse | 57 | 60 | 50 | 50 | 34 | 40 |

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168 ANSYS Mechanical (ANSYS, Canonsburg, PA, USA) was employed to obtain numerical
169 solutions. Large-displacement (non-linear) static analyses were performed with the pressure
170 and displacement loads ramped over several sub-steps. A preconditioned conjugate gradient
171 (PCG) solver was selected and convergence was controlled by defining a square-root-sum-of-
172 squares (SRSS) residual of 10^{-8} , which was achieved within 6-12 iterations. Simulations were
173 performed using a 16.0 GB RAM personal computer with Intel® Core™ i7-2600 3.40 GHz,
174 running Windows 7 Enterprise.

175

176 **Results**

177 **Aortic Root Motion**

178 The systolic downward motion of the aortic root in all three patients, pre- and post-PEARS
179 implantation was measured and the results are given in Table 4. It shows clearly that PEARS
180 implantation significantly reduced the axial root displacement in all three patients.

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Table 4: Downward systolic aortic root motion measurements

| | Aortic Root Motion (mm) | |
|-----------|-------------------------|------------|
| | Pre-PEARS | Post-PEARS |
| Patient 1 | 15.5 | 8.3 |
| Patient 2 | 15.7 | 8.3 |
| Patient 3 | 10.5 | 7.0 |

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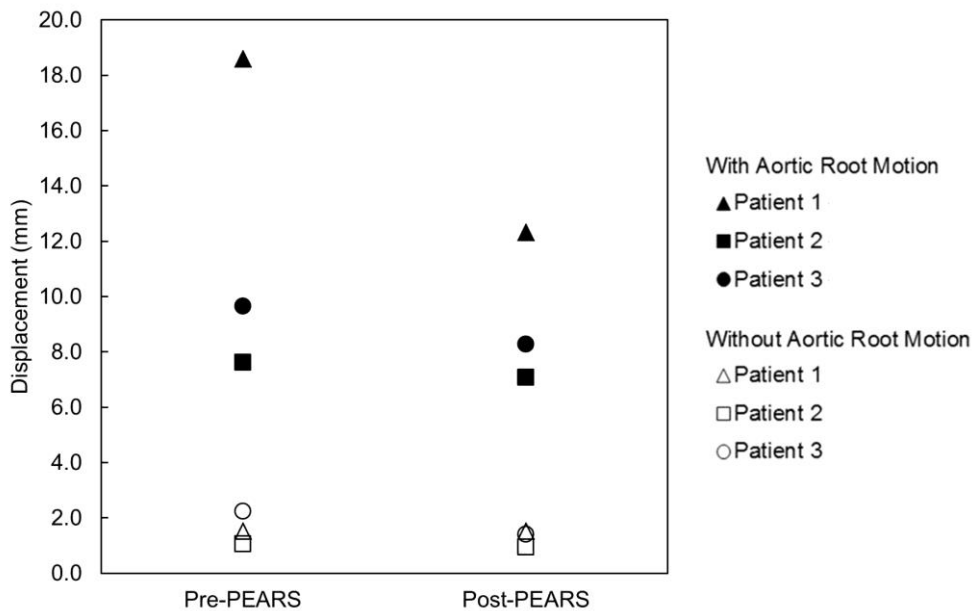
184 This is consistent with the study by Izgi et al. (2015) who examined a cohort of 24 patients
185 (pre- and post-PEARS) and reported that the average systolic downward motion of the aortic
186 root prior to implantation of PEARS was 12.6 ± 3.6 mm while after implantation, it decreased
187 to 7.9 ± 2.9 mm.

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189 **Deformation**

190 In all the models, introduction of the aortic root motion resulted in significantly greater
191 deformation of the aorta compared to pressurisation alone, as shown in Figure 3. **Error!**
192 **Reference source not found.** highlights the changes in spatial distributions of displacements
193 in each aorta. Without aortic root motion, peak displacements in the pre-PEARS and post-
194 PEARS models were found at different locations: these were in the proximal ascending aorta
195 and around the aortic arch pre-PEARS, but in the descending aorta post-PEARS. Upon
196 introduction of root motion, peak displacements were shifted to the moving aortic root
197 boundary. The general trends can be summarised as follows:

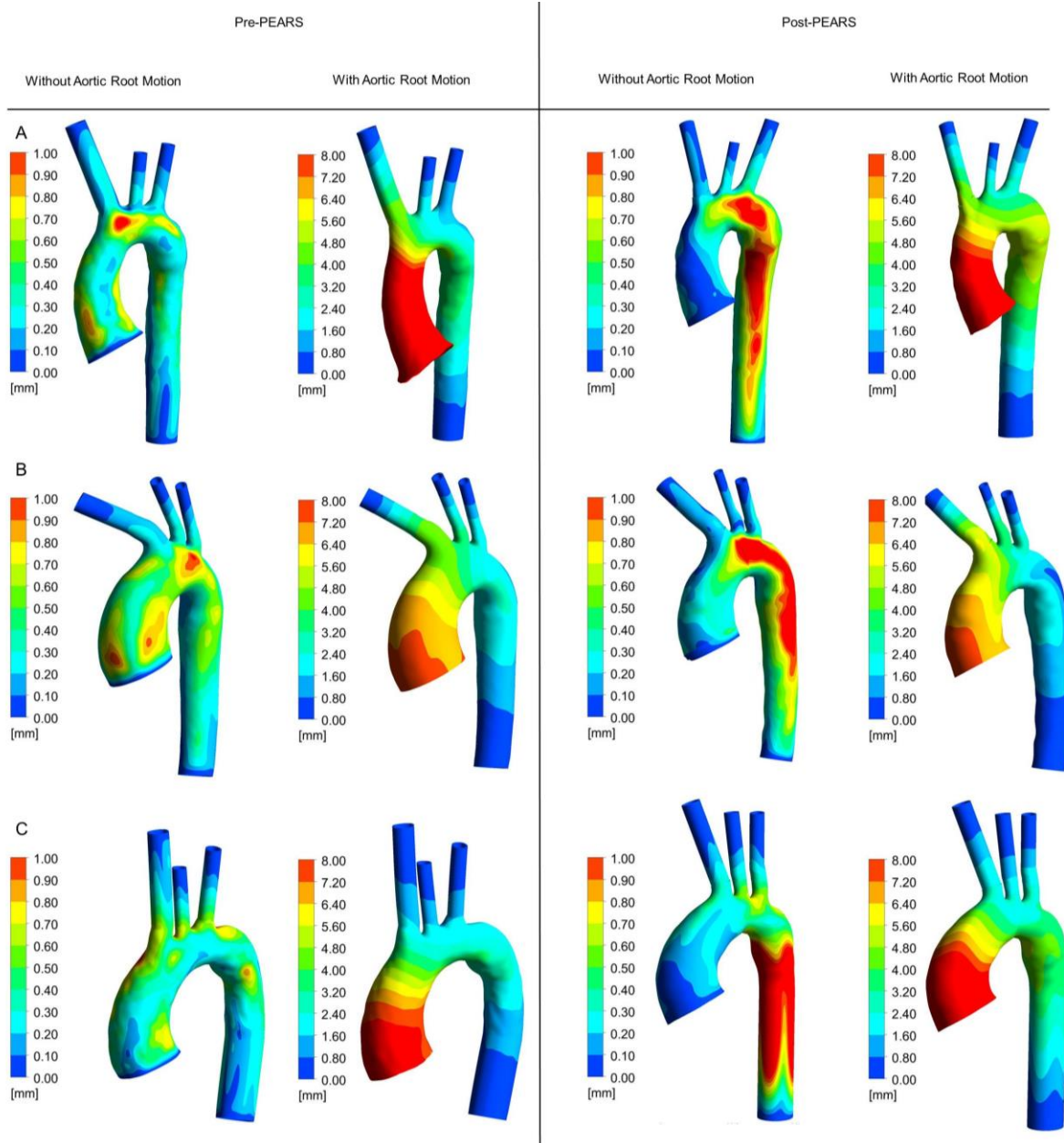
- 198 • Post-PEARS models showed a reduction in maximum displacement when compared with
199 its pre-PEARS counterparts, with and without aortic root motion; and
- 200 • Including aortic root motion resulted in significant increases in peak displacement in all
201 models.



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203 Figure 3: Peak displacement observed in the pre- and post-PEARS models with and without aortic root motion

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211 **Stresses without Aortic Root Motion**

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Figure 4: Displacement contours in the pre- and post-PEARS models with and without aortic root motion (A: Patient 1; B: Patient 2; C: Patient 3). Note the models with and without aortic root motion are displayed using different colour maps; the models without aortic root motion are illustrated with a maximum displacement (red) of 1 mm while the models with aortic root motion are illustrated with a maximum displacement (red) of 8 mm.

Without aortic root motion, the pre-PEARS models displayed higher longitudinal and circumferential stresses in the proximal ascending aorta compared with the post-PEARS

214 models, as shown in Figure 5 and Figure 6. The high longitudinal and circumferential stress
215 regions in the post-PEARS were located at the interface between the supported and
216 unsupported aorta (between the BCA and the left common carotid artery (LCCA)) and
217 regions distal to this interface.

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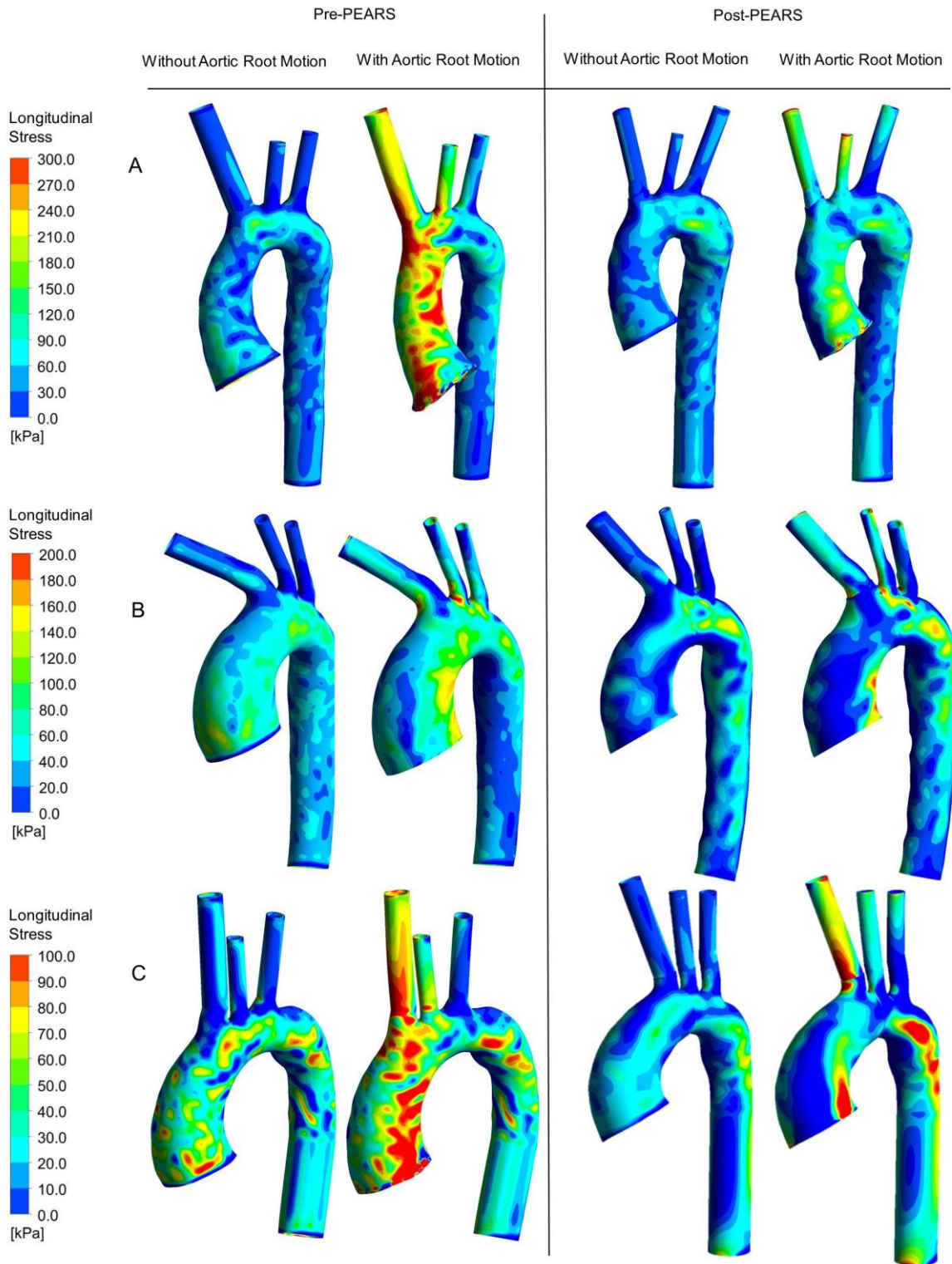
219 **Stresses with Aortic Root Motion**

220 It can immediately be recognised from Figure 5 that the aortic root motion resulted in higher
221 longitudinal stresses, particularly in the pre-PEARS models. The stiffer post-PEARS models,
222 on the other hand, experienced slightly more conservative increases. Additionally, elevated
223 longitudinal stress in the ascending aorta was located at the inner curvature and then extended
224 to the outer curvature proximal to the brachiocephalic trunk. Circumferential stress
225 distributions, shown in Figure 6, with and without aortic root motion, are quite similar.
226 Unlike the longitudinal stress patterns, high circumferential stress regions were found mostly
227 on the outer curvature of the ascending aorta. The absolute values of the changes in
228 circumferential and longitudinal stresses at two specific regions, with and without aortic root
229 motion, for all models are shown in **Error! Reference source not found.** Since each model
230 was constructed using patient-specific geometries and loadings, the quantitative results were
231 different among the patients. However, the qualitative effects of aortic root motion are quite
232 similar and these are summarised as follows:

- 233 • Circumferential stress between the BCA and LCCA: this was reduced in all models,
234 except for the pre-PEARS model of Patient 2 which showed an increase;
- 235 • Circumferential stress in the proximal ascending aorta: no change was observed in the
236 pre-PEARS models of Patients 1 and 2, while Patient 3 showed a 25% decrease; in the
237 post-PEARS, all models showed increased circumferential stress in this region;

- 238 • Longitudinal stress between the BCA and LCCA: a significant increase was observed in
239 the pre- and post-PEARS models of Patient 2 and 3, while Patient 1 displayed a modest
240 increase;
- 241 • Longitudinal stress in the proximal ascending aorta: again, all models showed significant
242 increases.

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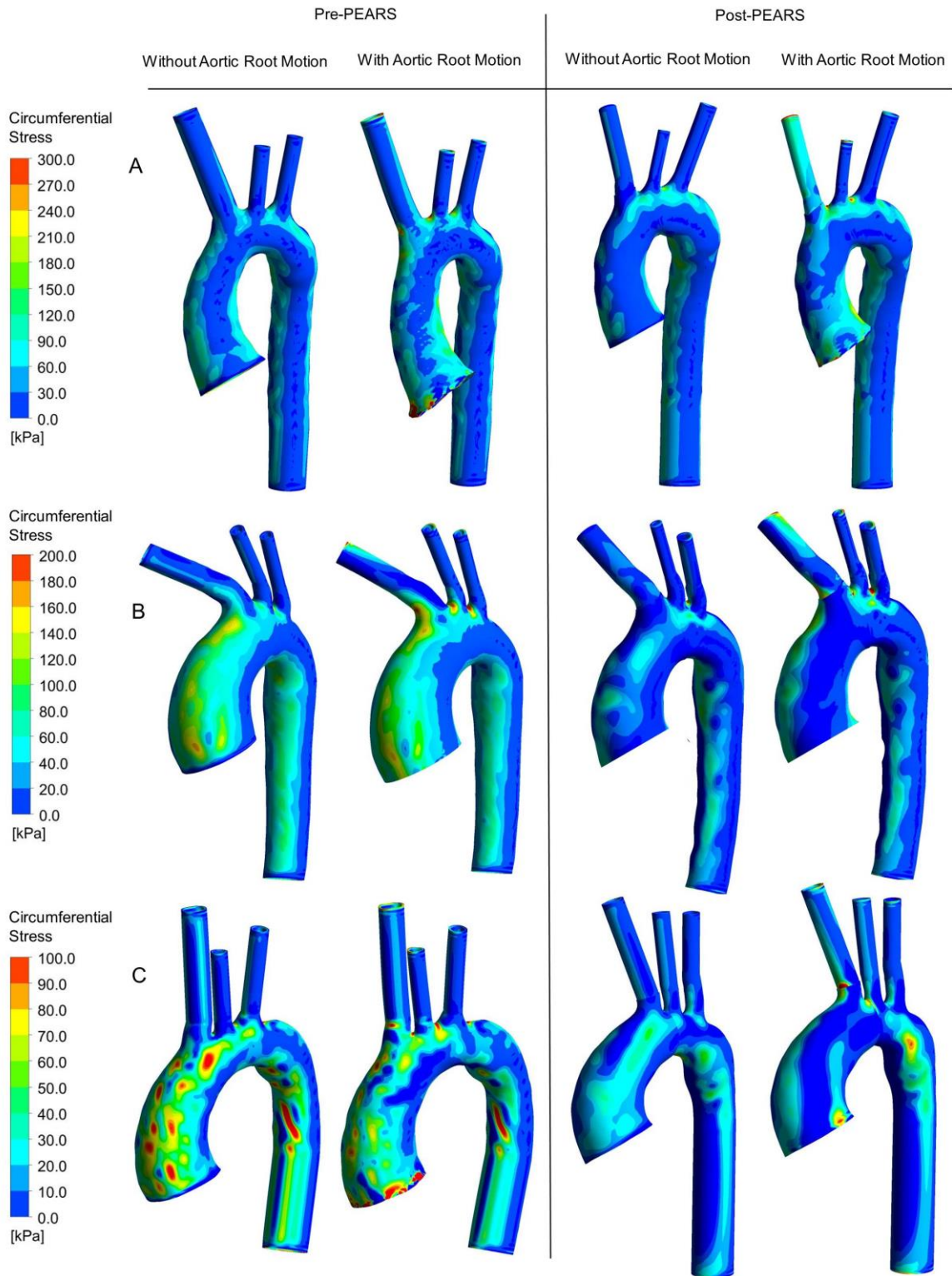
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245 Figure 5: Longitudinal stress contour plots for the pre- and post-PEARS models of Patients 1, 2 and 3 (labelled A, B and C,

246 respectively), with and without aortic root motion. Note that each patient is illustrated using a different contour colour map

247 scale owing to differences in biomechanical properties

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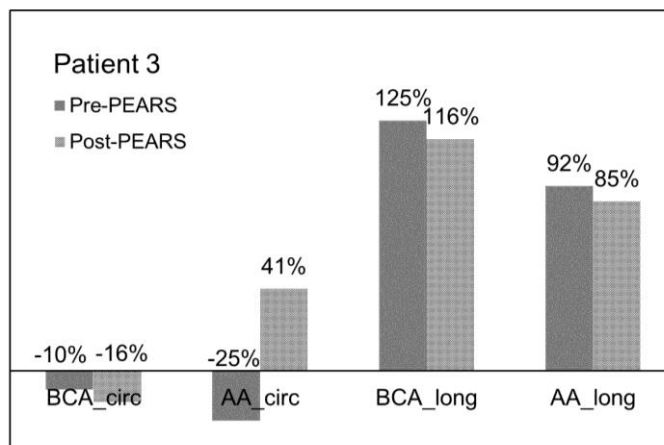
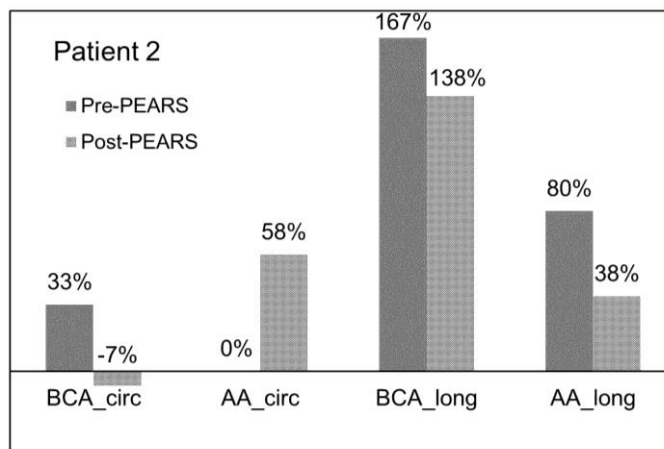
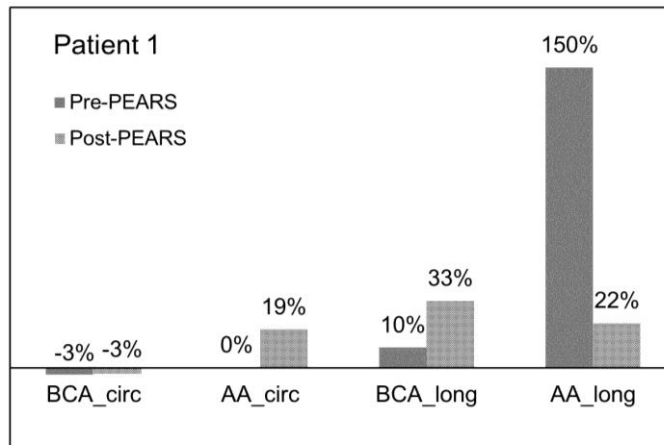
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Figure 6: Circumferential stress contour plots for the pre- and post-PEARS models of Patients 1, 2 and 3 (labelled A, B and C, respectively), with and without aortic root motion. Note that each patient is illustrated using a different contour colour map scale owing to differences in biomechanical properties



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Figure 7: Percentage changes in circumferential and longitudinal wall stresses in selected regions for all models, showing the effect of aortic root motion. The percentages shown represent the increase (positive) or decrease (negative) in the wall stress after imposing the aortic root motion boundary. BCA_circ: circumferential stress in the region between the brachiocephalic artery and left common carotid artery; AA_circ: circumferential stress in the proximal ascending aorta; BCA_long: longitudinal stress in the region between the brachiocephalic artery and left common carotid artery; AA_long: longitudinal stress in the proximal ascending aorta

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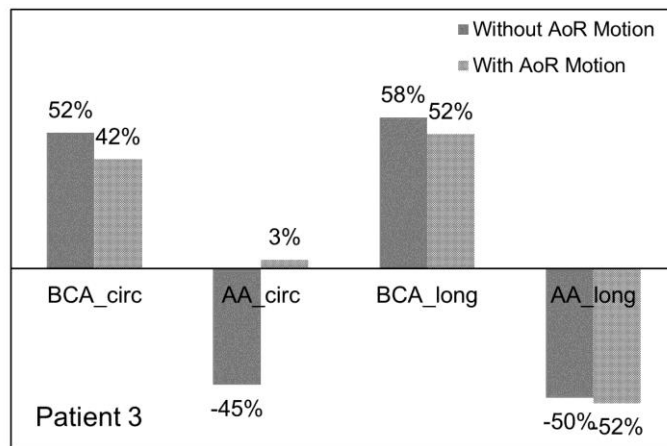
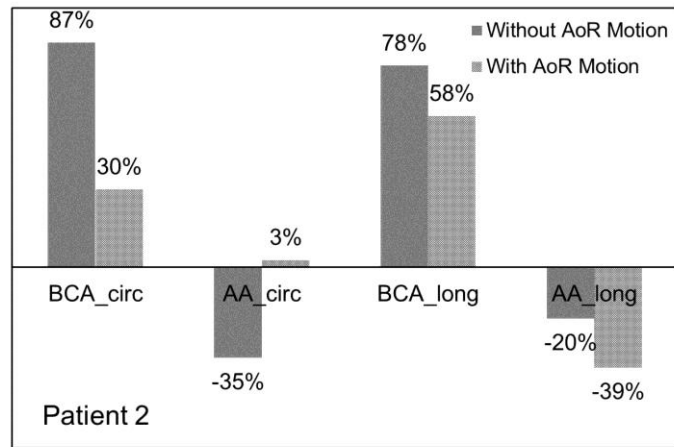
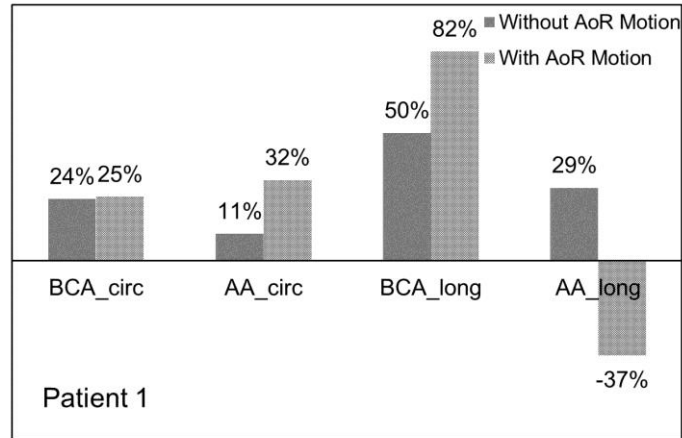
261 **Pre-PEARS vs Post-PEARS**

262 Figure 8 shows changes in circumferential and longitudinal stresses in regions between the
263 BCA and LCCA and the proximal ascending aorta upon addition of the PEARS, with and
264 without aortic root motion. Like the data analysed from Figure 7, the quantitative differences
265 arise due to variations in patient-specific geometries and applied loading. Regardless of the
266 effect of aortic root motion, the post-PEARS models showed qualitatively similar trends
267 when compared to their pre-PEARS counterparts:

- 268 • Circumferential stress between the BCA and LCCA: this was increased in all patients, for
269 models with and without aortic root motion;
- 270 • Circumferential stress in the proximal ascending aorta: there was a significant increase in
271 Patient 2 and 3 when the root was fixed, but no appreciable changes were found when the
272 root motion was included; Patient 1 displayed an increase in circumferential stress both
273 with and without the aortic root motion;
- 274 • Longitudinal stress between the BCA and LCCA: In all models, this stress was increased;
- 275 • Longitudinal stress in the proximal ascending aorta: Patients 2 and 3 showed reductions
276 in this stress both with and without the aortic root motion; Patient 1 however had an
277 increase when the root was fixed but a reduction upon addition of the root motion.

278 The latter finding is of particular interest because it shows the post-PEARS models had
279 reduced longitudinal stress in the proximal ascending aorta when compared to the pre-
280 PEARS models.

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Figure 8: Percentage changes in circumferential and longitudinal wall stresses in selected regions for all models, showing the effect of PEARS. The percentages shown represent the increase (positive) or decrease (negative) in the wall stress upon addition of PEARS. BCA_circ: circumferential stress in the region between the brachiocephalic artery and left common carotid artery; AA_circ: circumferential stress in the proximal ascending aorta; BCA_long: longitudinal stress in the region between the brachiocephalic artery and left common carotid artery; AA_long: longitudinal stress in the proximal ascending aorta

289

290 **Discussion**

291 In a previous FE study (Singh et al., 2015), the overall stress distributions in the pre- and
292 post-PEARS models were investigated under the assumption that the aortic root was fixed. It
293 was observed that in the pre-PEARS models, the ascending aorta and aortic arch had higher
294 von Mises stresses than regions distal to the aortic arch. Upon integration of PEARS into the
295 aortic wall, the high stress regions shifted to the unsupported aortic wall, with peak stresses
296 located at the interface between the supported and unsupported aorta. This study extends the
297 analysis by removing the fixed root assumption and further examining the circumferential
298 and longitudinal stresses separately.

299

300 The first major finding was the increase in aortic wall deformation upon introduction of
301 aortic root motion. In cardiac patients, the aortic root was found to experience a downward
302 movement ranging from 0 to 22 mm (Beller et al., 2008a). The values measured from MR
303 images of the patients included in this study were well within this range, 13.1 ± 5.5 mm (pre-
304 PEARS) and 10.3 ± 2.0 mm (post-PEARS). As expected, the post-PEARS aortas had reduced
305 displacements at the aortic root and ascending aorta due to its stiffer mechanical properties.
306 Stress analyses revealed that there were significant changes in the peak stress values when
307 aortic root motion was included in the models. At the junction between the BCA and LCCA,
308 there was a modest increase in the longitudinal stress for Patient 1, with a 10% increased pre-
309 PEARS and 33% increased post-PEARS. Patients 2 and 3, however, displayed increases of
310 167% and 125% respectively in their pre-PEARS models and 138% and 116% respectively in
311 their post-PEARS models. Similarly, in the ascending aorta, the longitudinal stresses
312 increased by 150%, 80% and 92% in the pre-PEARS models of patients 1, 2 and 3,

313 respectively, and 22%, 38% and 85% in the corresponding post-PEARS models. The effects
314 of aortic root motion on circumferential stresses were more modest.

315

316 It has been reported that about 65 to 87% of aortic dissections occur in the ascending aorta
317 (Hirst et al., 1958, Thubrikar et al., 1999). This, along with observations of increasing
318 longitudinal stresses in aortic aneurysm growth, has led to the postulate that intimal tears in
319 the circumferential direction could be explained on the basis that the tear is caused by rapidly
320 increasing longitudinal stress on the inner surface of the aneurysm. Since aortic root motion
321 has been directly related to increased longitudinal stress, it has been identified as an
322 additional risk factor for aortic dissection (Beller et al., 2008b). Wrapping of the Marfan aorta
323 with the much stiffer PEARS has an obvious additional advantage in reducing aortic root
324 motion and ascending aorta deformation. As expected, the decreased aortic motion then
325 resulted in reduction of longitudinal wall stress in the post-PEARS aortas (by 37-52%) when
326 compared with their pre-PEARS counterparts. However, it also caused an increase in
327 circumferential stress. In a multi-layer analysis of the aortic wall, Gao et al. (2006) suggested
328 that high stress regions were typically found in the stiffer aortic layers. One of the concerns
329 of PEARS is that the aortic wall distal to the support is unprotected and therefore susceptible
330 to abnormal stress patterns and consequently dissection. It was shown that upon addition of
331 PEARS, the circumferential and longitudinal stresses between the BCA and LCCA were
332 increased by 25 to 42% and 52 to 82%, respectively. Nevertheless all peak stresses were
333 below the known yield stress of the dilated thoracic aorta (1.18 ± 0.12 MPa in circumferential
334 and 1.21 ± 0.09 MPa in longitudinal directions) (Vorp et al., 2003), with the maximum
335 longitudinal stress predicted by the models reaching just less than half this value, and
336 therefore did not present an imminent risk.

337

338 In addition to the limitations presented in Singh et al. (2015), this study included two
339 additional assumptions: exclusion of the sinuses of Valsalva and simplification of the aortic
340 root motion by neglecting its twisting. Previous studies revealed that most acute dissections
341 of the ascending aorta were distal within the first few centimetres of the ascending aorta, and
342 so for simplicity, the sinuses of Valsalva were neglected. Additionally, Beller et al. (2004)
343 found that twisting of the aortic root did not appreciably change the wall stresses obtained,
344 and was therefore neglected in these models.

345

346 **Conclusions**

347 After PEARS implantation, the axial downward motion of the aortic root was significantly
348 reduced. Aortic root motion was previously identified as a risk factor for aortic dissection due
349 to the corresponding increase in longitudinal stress in the ascending aorta. In this manuscript,
350 the impact of aortic root motion on stress distribution in the Marfan aorta, pre- and post-
351 PEARS implantation, was investigated. While the qualitative changes in stress were similar
352 with and without aortic root motion, models incorporating aortic root motion were a step
353 closer to a realistic description of the biomechanical environment of the aorta. It was
354 confirmed that with the root motion, there was indeed a concentration of longitudinal wall
355 stress in the ascending aorta of the pre-PEARS models. However, implantation of PEARS
356 reduced this stress by up to 52% in the three patients examined in this study.

357

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