



**Gislason, M. K. and Foster, E. and Main, D. and Fusiek, G. and Niewczas, P. and Bransby-Zachary, M. and Nash, D. H. (2016) Mechanical testing and modelling of the Universal 2 implant. Medical Engineering and Physics, 38 (6). pp. 511-517. ISSN 1350-4533 , <http://dx.doi.org/10.1016/j.medengphy.2016.02.008>**

This version is available at <http://strathprints.strath.ac.uk/56528/>

**Strathprints** is designed to allow users to access the research output of the University of Strathclyde. Unless otherwise explicitly stated on the manuscript, Copyright © and Moral Rights for the papers on this site are retained by the individual authors and/or other copyright owners. Please check the manuscript for details of any other licences that may have been applied. You may not engage in further distribution of the material for any profitmaking activities or any commercial gain. You may freely distribute both the url (<http://strathprints.strath.ac.uk/>) and the content of this paper for research or private study, educational, or not-for-profit purposes without prior permission or charge.

Any correspondence concerning this service should be sent to the Strathprints administrator: [strathprints@strath.ac.uk](mailto:strathprints@strath.ac.uk)

# Mechanical testing and modelling of the Universal 2 implant

M.K. Gislason<sup>1,2</sup>, E. Foster<sup>2</sup>, D. Main<sup>2</sup>, G Fusiek<sup>2</sup>, P Niewczas<sup>2</sup>, M Bransby-Zachary<sup>3</sup>, D.H. Nash<sup>2</sup>

1. Department of Biomedical Engineering, School of Engineering and Technology, University of Reykjavik, Reykjavik, Iceland
2. Faculty of Engineering, University of Strathclyde, Glasgow, UK
3. Southern General Hospital, Glasgow, UK

\*Corresponding author. Department of Biomedical Engineering, School of Engineering and Technology, University of Reykjavik, Reykjavik, Iceland, Menntavegur 1, 101 Reykjavik, Iceland

Tel.: +354 599 6344; fax: +354 599 6201

E-mail address: [magnuskg@ru.is](mailto:magnuskg@ru.is)

## **Abstract**

Understanding the load mechanics of orthopaedic implants is important to be able to predict their behaviour in-vivo. Much research, both mechanical and clinical, has been carried out on hip and knee implants, but less has been written about the mechanics of wrist implants. In this paper, the load mechanics of the Universal 2 wrist implant have been measured using two types of measuring techniques, strain gauges and Fibre Bragg Grating measurements to measure strains. The results were compared to a finite element model of the implant. The results showed that the computational results were in good agreement with the experimental results. Better understanding of the load mechanics of wrist implants, using models and experimental results can catalyse the development of future generation implants.

Keywords: Wrist implants, finite element modelling, strain measurements, mechanical testing

32

33 **Introduction**

34

35 The design of wrist implants has varied greatly in the last decades. The Swanson wrist  
36 implant was one of the first implants to gain a commercial success in the US and was based  
37 on the concept of a silicone spacer aimed to increase stability in the radiocarpal joint [1].  
38 Fixation was achieved through a proximal radial stem and a distal stem passing through the  
39 capitate and into the third metacarpal. With time, a number of fractures on the distal stem  
40 were reported [2], leading to a revision of the mechanical design. The next generation implant  
41 designs were the Volz [3], and the Meuli [4] implants which demonstrated considerable  
42 changes in the overall design compared to the Swanson and used a metal stem made from  
43 CoCr and a ball in socket articulations. Other designs followed such as the semi-constrained  
44 Trispherical, the Guépar and the biaxial prosthesis which all then were eventually removed  
45 from the market [5].

46

47 In 2005 Shepherd and Johnston [6] evaluated the design criteria for a total wrist prosthesis in  
48 terms of loading conditions, contact stresses, wear rate amongst others. The challenges that  
49 engineers face in terms of the overall design of a wrist implant are mainly the small area to  
50 fixate the implant components to the bone, in particular in the distal attachment, and the  
51 variability of the loads and range of motion. In lower limb implants, such as the knee and the  
52 hip, the loading conditions are well defined in terms of gait, ascending, descending stairs etc.  
53 The load cases on the upper limb are more ambiguous where gripping, lifting and pushing  
54 with the wrist in multiple different positions can occur during activities of daily living. It has  
55 been shown that during a key turn action in rheumatoid arthritic patients, the average  
56 resultant load on the index finger is 13.9 N [7]. Using a biomechanical model, Fowler and

57 Nicol [7], also calculated the joint contact forces on an MCP implant to find that during the  
58 same key turn action, the contact force was on average 182.5 N, which represents the load of  
59 a single digit, namely the index finger. Kanellopoulos [8] measured external forces on all  
60 fingers during gripping with the wrist in various different positions for young healthy  
61 subjects of both sexes and reported that the resultant force on the index finger was on average  
62 23.1 N. It has also been reported [9] that the load distribution between the fingers was in the  
63 ratios 35:30:21:14 between the index, long, ring and little finger respectively. Internal loads  
64 acting over all five digits were calculated [9] with the wrist in neutral gripping position, using  
65 the biomechanical model presented by Fowler and Nicol [7] to find an average resultant force  
66 of 1472 N (standard deviation of 320 N) acting on the MCP joints. Chadwick and Nicol [10]  
67 reported overall wrist joint reaction forces exceeding 2000 N, during the horizontal power  
68 grip in healthy young subjects. Fok and Chou [11] concluded that the joint reaction forces on  
69 the MCP joint could be up to 30 times higher than the external forces applied to the fingers.  
70 Although a few studies of the biomechanical modelling of the hand exist, there are large  
71 variations in the load application to the hand, but all indicate that during gripping the forces  
72 through the wrist can be on the order of 1-2 times bodyweight which is a considerably high  
73 load given the small size of the joints in the hand and wrist.

74

75 Given the success of the hip and knee implants over the years, patient expectations have  
76 grown, to have a pain free and a stable joint after total joint arthroplasty. The design and  
77 manufacturing process of a joint implant is subjected to vigorous standards from regulating  
78 authorities [12]. Development of wrist implants is ongoing and since the introduction of the  
79 Swanson implant, many designs have been marketed and some with limited success. Third  
80 generation implants like the Universal, the ReMotion and the Maestro are now popular in  
81 clinical practice. They all are designed based on using an elliptical contact area between the

82 proximal and the distal aspect which has been shown by Grosland et al [13] to have an  
83 improved property compared to a toroidal shape in terms of stability. All are constructed with  
84 a metal stem, a polyethylene spacer and a distal carpal metal plate with screws. Different  
85 design aspects can be seen between various implants currently available. This difference can,  
86 in particular, be seen between the Universal 2 and the ReMotion on one side and the Maestro  
87 on the other. The Universal 2 and the ReMotion have the polyethylene component attached to  
88 the distal component in a convex configuration, whereas the Maestro implant has the  
89 polyethylene component attached to the proximal stem in a concave configuration, thus  
90 resembling more the geometrical features seen in the hip and the knee.

91

92 The finite element method is a powerful tool to calculate in vivo stresses on the structural  
93 aspect of the human body and has been used with much success to predict loading behaviour  
94 on hip and knee implants [14, 15]. It is widely used during design processes of various  
95 components and can be of great importance for orthopaedic implants where experimental  
96 work can be difficult to carry out [16]. Little has been written about modelling of the wrist  
97 implants. McCullough [17,18] studied the contact area of various wrist implants under  
98 simulated muscle loading from the 3 extensor muscles (extensor carpi radialis longus/radialis  
99 brevis/ulnaris) and the 2 flexor muscles (flexor carpi radialis/ulnaris) and demonstrated that  
100 the Universal 2 implant had greater contact area than the Biax and the Universal total wrist  
101 implant as well as lower maximum stress. Bajuri et al [19] published one of the first finite  
102 element model of the implanted wrist, focussing on the ReMotion implant. Otherwise little  
103 has been published on the mechanical properties of the total wrist implants where many  
104 studies have looked at the mechanics of total hip and total knee implants.

105

106 The presented study, demonstrates validation work carried out on the Universal 2 wrist  
107 implant and compares with a finite element model created of the implant. Two different types  
108 of strain measurements were carried out, firstly using strain gauges and secondly using Fibre  
109 Bragg Grating to measure the strain inside the prosthesis. Fibre Bragg grating is an  
110 established technique in determining strains in various application, given its light weight,  
111 flexibility and resistance to corrosion to name a few [20] and has previously been used to  
112 measure the strains in bone tissue [21] and contact pressure in total knee arthroplasty [22].

113

114 Validation work is difficult to carry out on the wrist joint, as the joint is small and applying  
115 measuring devices requires a high degree of joint exposure which will destroy the stabilizing  
116 effects of the soft tissue around the joint, thus making it prone to buckling during a uniaxial  
117 compression test. In vivo, the load cases on the total wrist implant are more complex than  
118 simple uniaxial compression, but by carrying out measurements using a simplified loading  
119 scenario and compare to FE model predictions, it will give indications about the mechanical  
120 behaviour under more complex load cases. That would be the first step in validating the finite  
121 element models. In the presented study, the Universal 2 implant from Integra was used, as it  
122 is one of the leading implant used in the UK and the US.

123

## 124 **Methods**

125

### 126 **Finite element model**

127 A Universal 2 wrist implant in size large was obtained. It consisted of 3 components: a radial  
128 component, a carpal component and a polyethylene component. All three components were  
129 scanned using an industrial scanner at the Advanced Forming Research Centre at the  
130 University of Strathclyde in Glasgow where the geometry was reversed engineered into an

131 STL model. The STL geometry was imported into Mimics (Materialise) where the three  
 132 components manually aligned with each other and virtually inserted into the radius bone. The  
 133 components were surface meshed using a semi-automated mesher and imported into Abaqus  
 134 (v.6.11). There the surface meshes were converted into 10 node tetrahedral elements, of type  
 135 C3D10M. The total number of elements was 246.888 for the full model. The total volume  
 136 was 10616 mm<sup>3</sup>, resulting in element density of 23.3 elements/mm<sup>3</sup>. Interaction between the  
 137 components was defined either using a surface to surface contact formulation or tie  
 138 constraints. The connections between the components are listed in Table 1.  
 139

Components	Type of contact
Distal part – polyethylene	Tie
Polyethylene – radial part	Surface to surface contact
Radial part – radius bone	Tie

Table 1: Interaction between the components

140  
 141 Loading was applied as uniaxial compressive load to the distal component, simulating  
 142 compressive forces ranging between 0 and 2000 N [10], which can be expected during  
 143 gripping motion. Figure 1 shows the finite element models.  
 144



Figure 1a – Finite element model of the Universal 2 implant

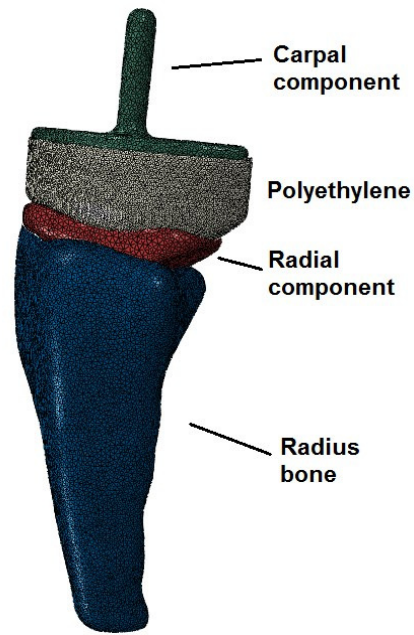


Figure 1b – Prosthesis inserted into the radius bone

145

146 The loading was applied as a pressure over the distal surface of the carpal component. Matlab  
 147 procedure was written to estimate the surface area by summing up individual areas from each  
 148 element located at the surface. The overall area was calculated as 349.6 mm<sup>2</sup> and a pressure  
 149 of 5.72 MPa would represent a total load of 2000 N. No slip boundary conditions were  
 150 applied to the proximal end of the implant.

151

152 The materials were obtained from the manufacturer. The radial component was made from a  
 153 cast CoCr alloy (ASTM standard F75, ISO standard 5832-4), the carpal plate component was  
 154 made from titanium alloy (Ti-6Al-4V ELI, ASTM standard F136, ISO 5832-3) and the  
 155 polyethylene was made from UHMWPe (ASTM Standard 648, ISO Standard 5834-1 +2).

156 The material properties can be seen in Table 1.

157

Material	Modulus	Yield	Tensile strength	Elongation [%]	Poisson's ratio



	[GPa]	[MPa]	[MPa]		
CoCr	207 (220-234)	450	655	8	0.31
Titanium	113.8	970	1450	14	0.30
Cortical bone	20				0.2
Cancellous bone	0.1				0.25

Table 1: Material properties

158

159 The polyethylene was modelled using the Bergstöm-Boyce model [23] and the material  
 160 model was obtained from MCalibration (Veryst Engineering) and the model parameters  
 161 fitted. The reported parameters for the polyethylene model can be seen in Table 2.

162

163

$\mu$	$\lambda$	D
24.45	1.486	0.004

Table 2: Polyethylene material coefficients

164 The finite element model was solved using the implicit solver in Abaqus

165

166 **Mechanical testing**

167

168 The Universal2 implant was mechanical tested in two different ways. Firstly the external  
 169 strains on the implant were measured using strain gauges and secondly the internal strain of  
 170 the implant was measured using a Fiber Bragg Grating sensor.

171

172 **Strain gauges**

173

174 Strain gauges were placed on the radial stem of the implant and the polyethylene component.

175 The polyethylene component and the carpal component were glued together so that no

176 relative motion was allowed between those two components. The implant was placed in

177 uniaxial compression. The experimental setup and location of strain gauges can be seen in

178 Figures 2a and 2b.

179

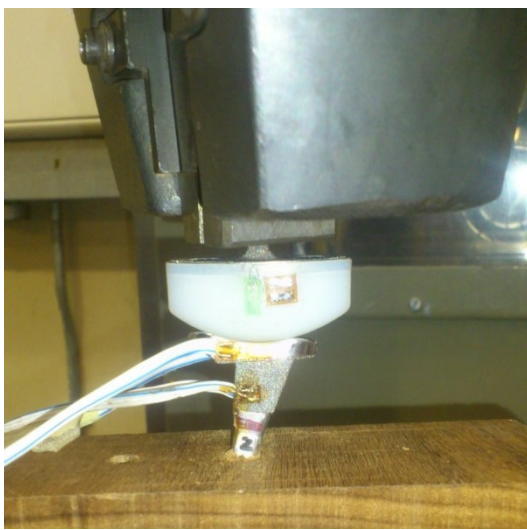


Figure 2a: Experimental setup of the mechanical testing.

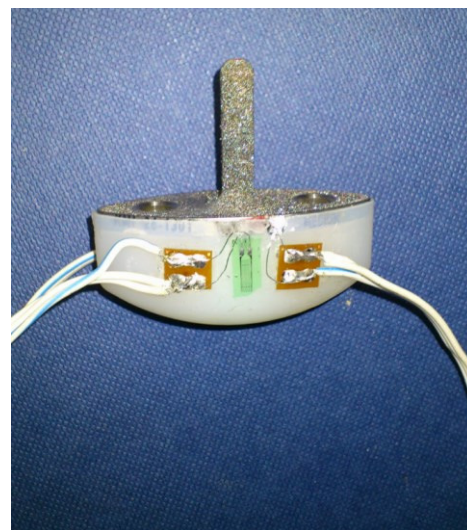


Figure 2b: Strain gauges applied onto the polyethylene component.

180

181 Strain data were collected at 100 N intervals with the total force ranging from 0 to 2000 N.

182

### 183 **Fiber Bragg Grating**

184

185 The internal strain in the tested implant was additionally monitored using a Fiber Bragg

186 Grating (FBG) sensor. An FBG being a periodic modulation of the refractive index within a

187 section of an optical fibre, when illuminated by a broadband light, reflects a narrow set of

188 wavelengths interfering with each other. The reflected spectrum can be approximated with a

189 Gaussian, and the wavelength at the maximum reflection is denoted as Bragg wavelength,  $\lambda_B$ .  
190 An FBG responds to both strain and temperature, and the resultant Bragg wavelength shift  
191 can be described by the following equation:

$$192 \quad \frac{\Delta\lambda_B}{\lambda_B} = (1 - p)\Delta\varepsilon + (\alpha + \xi)\Delta T$$

193 where  $p$  is the photo-elastic coefficient,  $\alpha$  and  $\xi$  are the thermal expansion and thermo-optic  
194 coefficients, respectively. For a standard FBG having the Bragg wavelength at 1550 nm the  
195 strain and temperature response coefficients are approximately 1.2 pm/ $\mu\varepsilon$  and 10 pm/ $^\circ\text{C}$ ,  
196 respectively.

197

198 A 1 mm diameter hole and 37 mm long was drilled into the proximal aspect of the stem of the  
199 radial component using an Electrical Discharge Machining (EDM) where the removal of the  
200 metal was carried out by using electrical discharge between an electrode and the implant.  
201 This allowed for a long thin hole to be created having minimal effects on the structural  
202 integrity of the implant. The optical fibre was placed 37 mm into the stem from the proximal  
203 side. The fibre was cleaved so that the grating was located 2 mm away from the end, in order  
204 to obtain measurements as close as possible towards the end of the hole. The fibre was fixed  
205 using epoxy resin glue.

206

207 The prosthesis was implanted into a saw bone which was done by an orthopaedic surgeon  
208 allowing the optic fibre to run through the proximal aspect of the bone.

209

210 The experimental setup can be seen in Figure 3a and 3b. The implant was tested in a uniaxial  
211 compression with load increments of 100 N ranging from 0 to 800 N.

212



Figure 3a: Overview of the experimental setup



Figure 3b: Experimental setup

213

## 214 **Results**

215

216 The finite element model was run under the given loading conditions. The stress distribution  
217 was analysed and strain results were compared to the findings from the mechanical tests.

218

## 219 **Finite element model**

220

221 Figures 4a and 4b show the stress distribution on the whole implant under compressive  
222 loading of 2000N and the strain distribution on the polyethylene component respectively.

223

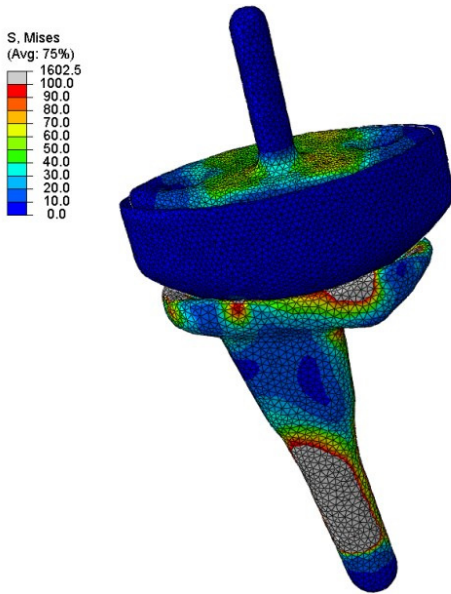


Figure 4a. Von Mises stress distribution on the whole implant under compressive loading of 2000 N

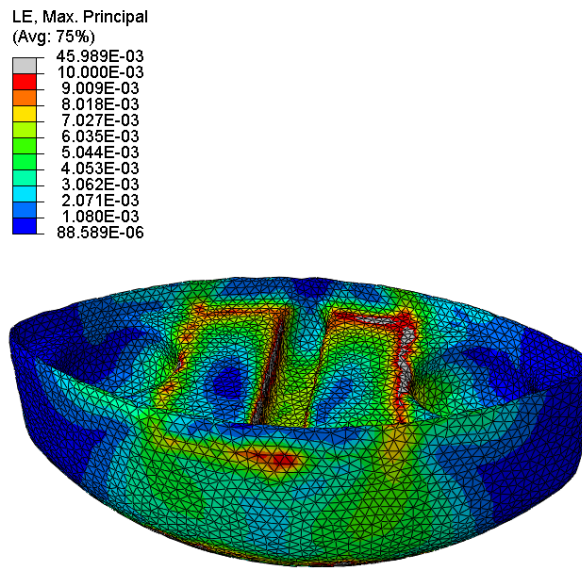


Figure 4b. Strain distribution on the polyethylene component under compressive loading of 2000 N

224

225 From Figure 4a and 4b, it can be seen how the load applied on the carpal component is  
 226 transmitted through the radial component. The strains on the polyethylene component are  
 227 highest around the surface of the holes in which the carpal component articulates.

228

229 **Strain measurements on implant using strain gauges.**

230

231 Strain gauge values were read as a function of the applied load on the prosthesis. The load  
 232 was applied slowly and held for some time at each load interval. The results from the strain  
 233 gauges were compared with the finite element model. The results from the strain  
 234 measurements on the polyethylene and the computational predictions can be seen in Figure 5.

235

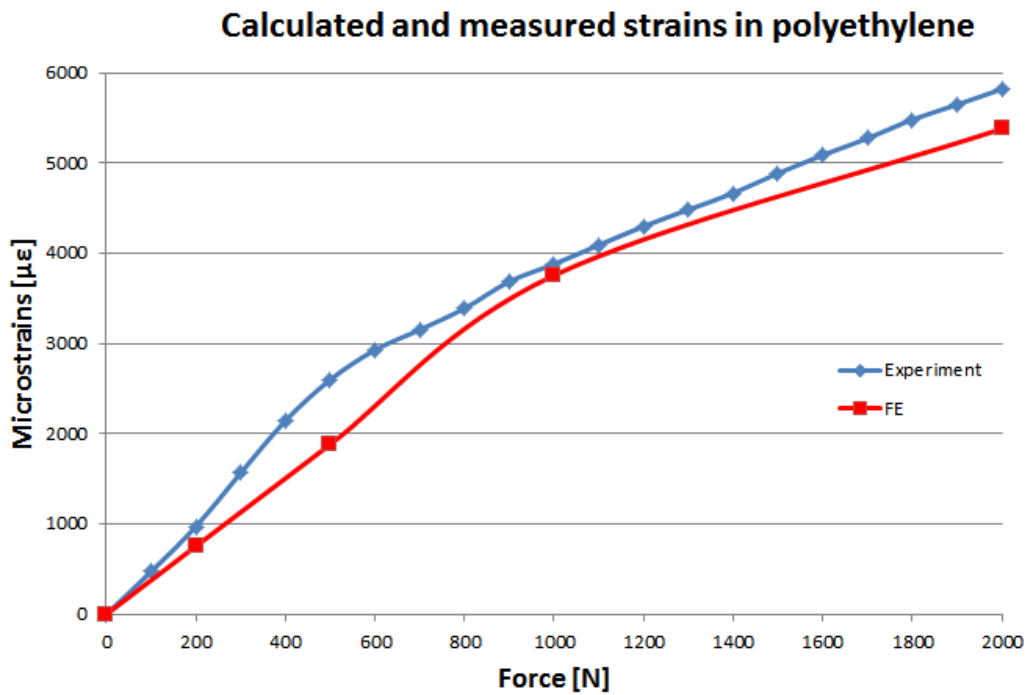


Figure 5: Strain as a function of load on the polyethylene component

236

237 Strain measurements were additionally obtained from the radial stem, with one strain gauge  
 238 applied towards the distal aspect of both dorsal and volar aspect of the radial component. The  
 239 results can be seen in Figure 6.

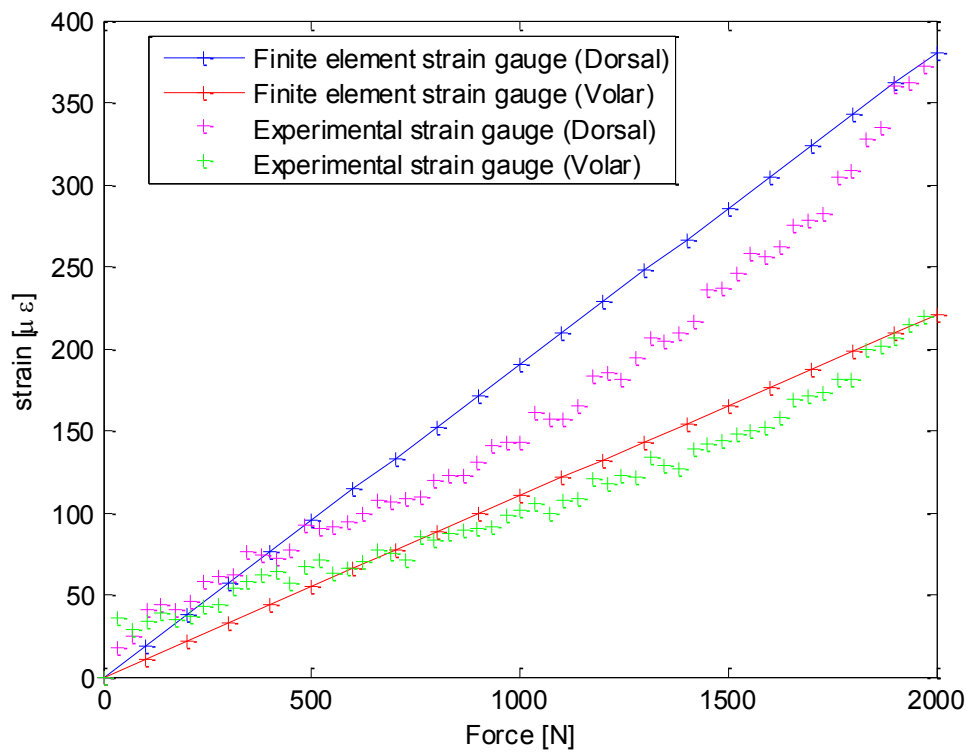


Figure 6: Strain measurements on the distal aspect of the radial component

240

241

242 **Strain measurements on implant and saw bone using fibre Bragg grating**

243

244 A node point was identified on the finite element part of the radial stem, corresponding to the

245 position of the fibre Bragg sensor within the implant. The results of the fibre Bragg grating

246 measurements were compared with the findings of the finite element model as can be seen in

247 Figure 7.

248

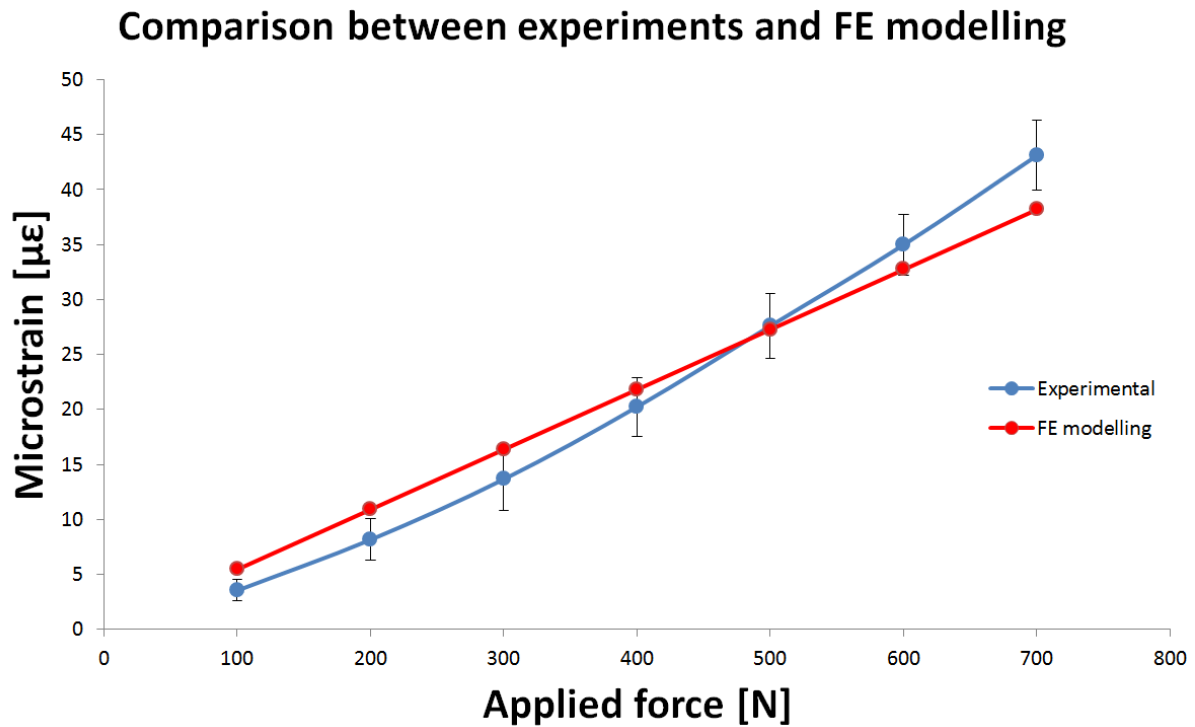


Figure 7: Comparison between Fiber Bragg Grating measurements and finite element model

249

250

## 251 Discussion

252 Measuring the load transfer through a wrist implant in vivo is a difficult task. Bergmann et al  
 253 [24] demonstrated that by placing force transducers inside a prosthesis, it is possible to  
 254 measure the joint contact forces in larger joints such as the hip and the knee. Such  
 255 implementation is difficult for the wrist given its small nature. Apart from biomechanical  
 256 models, few studies have looked at the wrist loading of cadaveric specimens [25.26], but  
 257 none at the loading of the implanted wrist as it is prone to buckling under uniaxial load in  
 258 cadaveric specimens.

259 The presented work is the one of the first attempt to create a simplified finite element model  
 260 of the implanted total wrist prosthesis in conjunction with experimental validation. The



261 experimental work was carried out using a simplified uniaxial loading and compared with the  
262 findings from a finite element model. In-vivo loading conditions during gripping have been  
263 shown [9] to be a combination of proximally, dorsally and ulnarly (radially for the thumb)  
264 directed joint contact forces and therefore much more complex than the loads presented in  
265 this paper. However the overall magnitude of in-vivo joint contact force acting on the wrist is  
266 high and the mechanical trials aimed to simulate extreme loading conditions which are  
267 unlikely that patients with total wrist arthroplasty are able to generate. It is however  
268 important to understand how the implants behave under a simplified mechanical loading to  
269 further understand how they are going to behave under the more complex in-vivo loading and  
270 boundary conditions. For the stand alone experiment, the prosthesis was fixed on the  
271 proximal aspect of the radial component, whereas for the fibre Bragg experiment the implant  
272 was placed into a saw bone to try to mimic in-vivo fixation. From the experimental results it  
273 can be seen that the dorsal aspect of the prosthesis experiences higher loading than the volar  
274 aspect which partially can be explained by the volar offset of the geometry of the stem. From  
275 Figure 6, it can be seen that the results from the finite element model are in good agreement  
276 with the volar strain gauge, although the model over predicts the strain on the dorsal side. The  
277 measured strain values from the polyethylene component also demonstrated a good  
278 agreement with the experimental results. It can be argued that using the Bergström-Boyce  
279 material model will give accurate results, when used to model polyethylene orthopaedic  
280 materials.

281 From the strain gauge and the fibre Bragg grating measurements on the radial component, it  
282 can be seen, by comparing the strain levels in Figure 6 to the ones in Figure 7, that the strain  
283 decreases towards the centre of the radial stem. The total load for the implanted prosthesis  
284 was 800 N compared to the 2000 N for the stand alone prosthesis, which was due to the  
285 fragility of the optical fibre and the presence of bending loads in the experimental setup.

286 From the Fibre Bragg data, hysteresis in conjunction with a non-linear strain curve was seen  
287 in the experimental results which can be explained by the interaction between the optic fibre,  
288 the epoxy resin to which it was attached and the metal implant. However the overall trend is  
289 well in agreement with the results of the finite element model. Using the Fibre Bragg method  
290 gives experimental results in locations that otherwise would have been impossible to reach  
291 using strain gauges and therefore can give more in depth analysis of the three-dimensional  
292 strain field within the prosthesis.

293 From table 1, it can be estimated that the proportionality of the strain for the cobalt chrome is  
294 around  $3100 \mu\epsilon$  but the maximum strain around the surface was measured and calculated to  
295 be around  $380 \mu\epsilon$  under 2000 N compressive load. This demonstrates that the strains on the  
296 radial stem are substantially lower than the yield limit and that the stem would be unlikely to  
297 fracture in vivo, even though subjected to more complex multi-axial loading scenario. The  
298 model does though not take into account poor bone material quality as can be seen in some  
299 patients, making proximal and distal fixation a greater challenge. However more research is  
300 needed to understand the load mechanics of the prosthesis in-vivo and to quantify the overall  
301 loading the whole implant is exposed to during activities of daily living of total wrist implant  
302 patients. Future work will incorporate a full three dimensional modelling of the implanted  
303 wrist to obtain further information about the load transfer characteristics of the Universal 2  
304 wrist implant subjected to multi-axial loading.

305

### 306 **Limitations**

307 There are many limitations to the presented study, in particular how the loading is applied as  
308 well as other boundary conditions. The modelling and testing does not incorporate the  
309 implant interaction with human bone. The bone quality will vary with each patient and poor

310 bone quality will difficulty in fixation which were not incorporated into the model. The  
311 model only looks at the loading in a steady state but doesn't incorporate any time dependent  
312 loading behaviour. A full detailed convergence study was not performed on the number of  
313 elements, due to the fact that orphan meshes were used to construct the model and changing  
314 the element density would require a new model for each case. However a small comparison  
315 between a finer mesh model and a coarser mesh model was made and based on the results it  
316 was assumed that the element density presented in the paper was sufficient to obtain accurate  
317 results.

318

### 319 **Acknowledgements**

320 The authors would like to thank Mr. Juan Fuente Gonzalez and the staff at the University of  
321 Strathclyde's Advanced Forming Research Centre for the help of scanning and creating three  
322 dimensional models from the Universal 2 implant.

323 **References**

324

325 1. Swanson A. Flexible implant arthroplasty for arthritic disabilities of the radiocarpal  
326 joint. A silicone rubber intramedullary stemmed flexible hinge implant for the wrist  
327 joint, *Orthop Clin North Am.*, 1973 , 4(2), pp:383-94.

328 2. Jolly SL, Ferlick DC, Clayton ML, Dennis DA, Stringer EA. Swanson silicone  
329 arthroplasty of the wrist in rheumatoid arthritis: A long-term follow-up, *Journal of*  
330 *Hand Surgery*, 1992, 17(1), pp:142-149.

331 3. Volz RG. Clinical experience with a new total wrist prosthesis, *Archiv für*  
332 *orthopädische un Unfall Chirurgie*, 1976, 85, pp: 205-209.

333 4. Meuli HC, Meuli total wrist arthroplasty, *Clinical Orthopaedic Related Research*,  
334 1984, 187, pp:107-111.

335 5. Sheperd DET and Johnstone AJ. D. A new design concept for wrist arthroplasty,  
336 *Mechanical Engineering and Physics*, 2002, 24, pp: 641-650.

337 6. Sheperd DET and Johnstone AJ. D. Design considerations for a wrist implant, *Proc.*  
338 *IMEchE Part H, Engineering in Medicine*, 2005, 219, pp: 43-52.

339 7. Fowler N and Nicol AC. A biomechanical analysis of the rheumatoid index finger  
340 after joint arthroplasty, *Clinical Biomechanics*, 2002, 17, pp:400-405.

341 8. Kanellopoulos A. Three dimensional biomechanics of the hand and wrist in precision  
342 grip, 2011, PhD thesis, University of Strathclyde, Glasgow, UK.

343 9. Gislason M, Nash DH, Nicol AC, Kanellopoulos A, Bransby-Zachary M, Hems TEJ,  
344 Condon B, Stansfield B. A three dimensional finite element model of maximal grip  
345 loading in the human wrist, *Proc. IMechE Part H, Engineering in Medicine*, 2009, 223  
346 (H7), pp:849-862.

- 347 10. Chadwick EKJ and Nicol AC. Elbow and wrist joint contact forces during  
348 occupational pick and places activities. *Journal of Biomechanics*, 2000, 33, pp:591-  
349 600.
- 350 11. Fok KS and Chou SM. Development of a finger biomechanical model and its  
351 considerations, *Journal of Biomechanics*, 2010, 43, pp:701-713.
- 352 12. Aitchison GA, Hukins DWL, Parry JJ, Shepherd DET, Trotman SG. A review of the  
353 design process for implantable orthopaedic medical devices, *The Open Biomedical*  
354 *Engineering Journal*, 2009, 3, pp:21-27.
- 355 13. Grosland N, Rogge RD, Adams BD. Influence of articular geometry on prosthetic  
356 wrist stability, *Clin Orthop Rel, Res*, 2004, No 421, pp: 134-142.
- 357 14. Knight LA, Pal S, Coleman JC, Bronson F, Haider H, Levine DL, Taylor M,  
358 Rullkoetter PJ. Comparison of long-term numerical and experimental total knee  
359 replacement wear during simulated gait loading, *Journal of Biomechanics*, 2007, 40,  
360 pp: 1550–1558.
- 361 15. Martelli S, Taddei F, Cristofolini L, Schileo E, Rushton N, Viceconti M. A new hip  
362 epiphyseal prosthesis: Design revision driven by a validated numerical procedure,  
363 *Medical Engineering and Physics*, 2011, 33, pp: 1203-1211.
- 364 16. Prendergast P. Finite element models in tissue mechanics and orthopaedic implant  
365 design, *Clinical Biomechanics*, 1997, 12(6), pp: 343-366.
- 366 17. McCullough MBA. Clinical and biomechanical analysis of total wrist arthroplasty  
367 devices, 2006, PhD thesis, University of Iowa, Iowa, USA.
- 368 18. McCullough MB, Adams BD, and Grosland NM. The Effect of Articular Surface  
369 Shape and Tendon Forces of Total Wrist Arthroplasty Systems: A Finite Element  
370 Study. *Journal of Musculoskeletal Research* Volume 15(4), 2012.

- 371 19. Bajuri MN, Kadir MRA, Murali MR, Kamarul T. Biomechanical analysis of the wrist  
372 arthroplasty in rheumatoid arthritis: a finite element analysis, *Medical and Biological*  
373 *Engineering and Computing*, 2013, 51(1), pp:175-186.
- 374 20. Liu RM, Liang DK., Asundi A. Small diameter fibre Bragg gratings and applications,  
375 *Measurement*, 2013, 46, pp: 3440-3448.
- 376 21. Fresvig T, Ludvigsen P, Steen H, Reikerås. Fiber optic Bragg grating sensors: An  
377 alternative method to strain gauges for measuring deformation in bone, *Medical*  
378 *Engineering and Physics*, 2008, 30, pp:104-108.
- 379 22. Mohanty L, Tjin SC, Lie DTT, Panganiban SEC, Chow PKH. Fiber grating sensor for  
380 pressure mapping during total knee arthroplasty, *Sensors and Actuators A*, 2007, 135,  
381 pp: 323-328.
- 382 23. Bergström JS and Boyce MC. Constitutive modelling of the time-dependent and  
383 cyclic loading of elastomers and application to soft biological tissues. *Mechanics of*  
384 *Materials*, 2001, 33, pp: 523–530.
- 385 24. Bergmann G, Deuretzbacher G, Heller M, Graichen F, Rohlmann A, Strauss J, Duda  
386 GN. Hip contact forces and gait patterns from routine activities, *Journal of*  
387 *Biomechanics*, 2001, 34, pp:859-871.
- 388 25. Palmer A and Werner FW. Biomechanics of the distal radioulnar joint, *Clinical*  
389 *Orthopaedics and Related Research*, 1984, 187, pp: 26-35.
- 390 26. Pfaeffle HJ, Fischer KJ, Manson TT, Tomaino MM, Herndon JH, Woo S. A new  
391 methodology to measure load transfer through the forearm using multiple universal  
392 force sensors, *Journal of Biomechanics*, 1999, 32, pp: 1331-1335.
- 393