



Clark, D., Stevens, J. M., Tortonese, D., Whitehouse, M., Simpson, D., & Eldridge, J. (2019). Mapping the contact area of the patellofemoral joint: the relationship between stability and joint congruence. *Bone and Joint Journal*, 101-B(5), 552-558.  
<https://doi.org/10.1302/0301-620X.101B5.BJJ-2018-1246.R1>

Peer reviewed version

Link to published version (if available):  
[10.1302/0301-620X.101B5.BJJ-2018-1246.R1](https://doi.org/10.1302/0301-620X.101B5.BJJ-2018-1246.R1)

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This is the author accepted manuscript (AAM). The final published version (version of record) is BJS at <https://online.boneandjoint.org.uk/doi/full/10.1302/0301-620X.101B5.BJJ-2018-1246.R1> available online via . Please refer to any applicable terms of use of the publisher.

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1       **Mapping the contact area of the patellofemoral joint: the**  
2                   **relationship between stability and congruence**

3

4   **AUTHORS:**

5   Damian Clark [1], Jarrad M Stevens [1], Domingo Tortonese [2], Michael R.  
6   Whitehouse[1,3,4], Danielle Simpson [5], Jonathan Eldridge[1],

7

8   **INSTITUTION:**

9   1: Avon Orthopaedic Centre, Southmead Hospital Bristol, UK

10  2: Centre for applied anatomy, Univeristy of Bristol, UK

11  3: Musculoskeletal Research Unit, Translational Health Sciences, Bristol Medical  
12  School, 1st Floor Learning & Research Building, Southmead Hospital, Bristol, BS10  
13  5NB

14  4: National Institute for Health Research Bristol Biomedical Research Centre,  
15  University Hospitals Bristol NHS Foundation Trust and University of Bristol

16  5: University of Nottingham Medical School

17

18  Damian Clark MBBS, FRCS, MSc

19  Jarrad Stevens, MBBS, ChM, FRACS, FAOrthA

20  Domingo Tortonese, D.V.M, PhD

21  Michael R Whitehouse PhD, MSc, BSc, MB ChB, FRCS(T&O), PG Cert(HE), FHEA

22  Danielle Simpson, BSc

23  Jonathan Eldridge, MBChB, BSc, FRCS, FRCS(T&O)

24

25  **CORRESPONDENCE:** [drjarradstevens@hotmail.com](mailto:drjarradstevens@hotmail.com)

26 This study was supported by the NIHR Biomedical Research Centre at University  
27 Hospitals Bristol NHS Foundation Trust and the University of Bristol. The views  
28 expressed in this publication are those of the author(s) and not necessarily those of the  
29 NHS, the National Institute for Health Research or the Department of Health and Social  
30 Care.  
31

32 **Abstract:**

33

34 **Aims:** (1) To determine and contrast the congruency through articular contact area of  
35 the patellofemoral joint during both active and passive movement of the knee with the  
36 use of an MRI control mapping technique. (2) Using the same method, to compare joint  
37 congruency for stable and unstable patellofemoral joints.

38

39 **Method:** A prospective case-control MRI imaging study of patients with a history of  
40 patellofemoral joint instability and volunteers with no knee symptoms was performed.  
41 The patellofemoral joints were imaged with the use of an MRI scan during both passive  
42 and active movement from 0 through to 40 degrees of flexion. The congruency through  
43 contact surface area was mapped in 5mm intervals on axial slices.

44

45 **Results:** Forty people took part in this study. The cases group included 31 patients  
46 who had symptomatic patellofemoral instability and the control group included nine  
47 asymptomatic volunteers. The unstable patellofemoral joints were demonstrably less  
48 congruent than the stable patellofemoral joints throughout the range of knee movement.  
49 The greatest mean differences between unstable and stable patellofemoral joint  
50 congruency were observed between 11 and 20 degrees flexion ( $1.73\text{cm}^2$  vs  $4.00\text{cm}^2$ ,  
51  $p<0.005$ ).

52

53 **Conclusion:** The congruency within the two groups for active and passive range of  
54 movement is closely correlated. The unstable patellofemoral joint is less congruent than  
55 the stable patellofemoral joint throughout knee movement. This approach to mapping

56 patellofemoral joint congruency may aid in the design of operations to increase stability  
57 and serve to assess pre- and post-operative interventions as a measurable outcome.

58

## 59 **Introduction**

60

61 The patellofemoral joint (PFJ) is geometrically complex, asymmetric and heavily  
62 influenced by kinematic forces about the knee. Patella engagement and subsequent  
63 congruence of the patella in the trochlear groove provides stability and dispersion of  
64 forces across the articulating surfaces with conformity of shape and movement.

65 In 1976, Goodfellow described changes in contact area that occur in the normal  
66 knee with the distal patella engaging in extension while the proximal patella articulated  
67 in flexion [1]. In the unstable joint, the patella will articulate in an abnormal manner to  
68 produce uneven distribution of forces presenting as subluxation and even dislocation of  
69 the patella. Incongruency of the patellofemoral joint, even without patella dislocation,  
70 leads to degenerative changes [2-7].

71 Visualising the congruency of the PFJ through imaging modalities is useful for  
72 establishing diagnosis, planning operative intervention and evaluating post-operative  
73 intervention [8]. Methods for assessing the PFJ include plain radiographs, ultrasound  
74 scan, computerised tomography (CT), magnetic resonance imaging (MRI) and three-  
75 dimensional computer navigation [8-12]. Accurate assessment of the congruency of the  
76 PFJ is vital in understanding the relationship of the bone and cartilage architecture,  
77 vectors about the joint and soft tissue restraints.

78 In order to improve objective MRI analysis of the unstable PFJ, we sought to  
79 map contact area through a range of passive and quadriceps active movement. Although  
80 this technique is not designed to be utilised as a routine investigation, we have

81 undertaken this study to document quantifiable measurements of the unstable PFJ.  
82 Additionally, we performed this imaging study on a control group of stable knees for a  
83 comparison and documentation of normal contact area throughout range of movement.  
84 Our hypothesis is that the unstable joint will be less congruent than the stable joint  
85 through passive and quadriceps active range of movement when mapped on multiple  
86 sequence MRI scan. With the ability to quantify congruency, the authors intend to  
87 compare pre- and post-stabilisation surgery contact area utilising this same technique.  
88 The clinical importance of this is demonstrated through the ability to objectively  
89 measure PFJ contact area and hence compare the pre-operative unstable joint with the  
90 change in contact area and perhaps the effectiveness of surgery with post-operative  
91 MRI mapping. With the aid of the results from this study, researchers will be able to  
92 compare surgical cases to a baseline cohort of patients with stable knees.

93         The aims of the study were: (1) To describe the articulating surface area of the  
94 PFJ in both active and passive movement; (2) To compare joint contact area using this  
95 method for stable and unstable patellofemoral joints.

96

## 97 **Material and methods**

98

99 This study has ethical approval (12/SW/0155) and all participants gave written  
100 informed consent. A single centre, prospective case-control MRI imaging study of  
101 patients with PFJ instability (cases n=31) and volunteers with no PFJ symptoms  
102 (controls n=9) was performed. An MRI scan was used to capture the PFJ articular  
103 cartilage contact area in a range of degrees of knee flexion in both quadriceps active  
104 and passive positions for both cohorts. MRI was selected as it permits assessment of  
105 anatomy in the axial, coronal and sagittal plan but can be oriented to any anatomical

106 axis which was needed for the dynamic assessment performed in this study. The  
107 advantage over CT is that it permits more accurate assessment of congruence by  
108 accounting for articular cartilage as well as bone. It is non-destructive and does not  
109 involve ionising radiation and is therefore suitable for cases and controls.

110 The cohort size was based on a two sample independent t-test with a mean difference  
111 of 2cm<sup>2</sup> with equal standard deviation of 1.75, power of 80%, and type I error =0.05  
112 with a sampling ratio of 3:1 (cases:controls) yielding a minimum required sample size  
113 of 27 cases and nine controls. Our actual study size was 31 cases and nine controls.

114 Inclusion criteria for the cases cohort included patellofemoral joint instability  
115 for consideration of surgical management. The diagnosis of instability was a  
116 culmination of history (which included at least two prior episodes of patella  
117 dislocation), examination, and imaging investigations. Inclusion into the control group  
118 required volunteers who reported no symptoms currently or previously from the PFJ,  
119 and demonstrated normal knee examination with no clinical signs of instability.

120 The exclusion criteria included patients who were unable to provide valid  
121 consent, were unwilling to participate, aged 17 years or less, suffered degenerative knee  
122 joint disease (including any evidence of osteoarthritis observed on radiographs AP,  
123 lateral and skyline views), were pregnant, a history of metal objects or the possibility  
124 of metal object in soft tissues, particularly brain, eye, heart, spinal cord or if they were  
125 uncontactable by telephone.

126 The case subjects were recruited from the patient waiting list for surgery at a  
127 tertiary elective orthopaedic unit. Ninety-one consecutive patients were considered to  
128 be potentially eligible case subjects based on inclusion criteria. Of these, 72 were  
129 willing to discuss the study and 39 agreed to participate. There were eight patient  
130 withdrawals, leaving a cohort size of 31 (flowchart seen in Figure 1).

131 Information regarding; age, symptoms, previous dislocations, hypermobility  
132 and imaging results (Tibial Tuberosity Trochlear Groove, Insall Salvati Ratio, Biedert  
133 Patellotrochlear Index, Dejour grade) were obtained from patient notes and Picture  
134 Archiving and Communications Systems (PACS).

135 The control group was used to define normal values and validate the study  
136 methodology. Nine healthy volunteers were recruited from the hospital staff and  
137 researcher group who demonstrated normal knee and no history of patellofemoral joint  
138 symptoms. No formal imaging prior to the MRI scan was organised for participants in  
139 the control group.

140

141 **Figure 1:** Flowchart of patient inclusion and exclusion.

142

143 **MRI Scanner:**

144 MRI was performed with a GE Discovery MR450 1.5 tesla scanner and an eight-  
145 channel cardiac coil. The subject underwent a standard checklist where they were asked  
146 specific questions regarding comfort and safety in the MRI scanner.

147

148 **Patient Position:**

149 The subject lay supine on the MRI table with a triangular wedge under the knee and a  
150 strap over the thighs in order to maintain the position of the femur during the  
151 examination (Figure 2A). Data was captured in both passive and quadriceps active  
152 movement.

153

154 The initial localiser MRI sequence performed was an ultrafast gradient echo 3 plane  
155 localiser. The localiser scan permitted the technician to identify the boundaries of the



156 trochlea and plan the location of the definitive scan. The scan boundaries were placed  
157 beyond the boundaries of the trochlea in order to ensure full capture of the area of  
158 interest. Blocks of axial images were captured with one sagittal localiser to calculate  
159 the precise knee flexion position. The axial image was centred over the trochlea and  
160 then as the knee extended the patella came into view, maintaining at all times the same  
161 series of images of the trochlea.

162

163 **Passive movement imaging:**

164 The patient was secured as above and the knee permitted to rest at 40 degrees of flexion,  
165 a series of images was captured. A further foam cushion was placed under the heel to  
166 attain a scan at 20 degrees of flexion, finally a further cushion was placed to attain a  
167 scan at 0 degrees of flexion and the series repeated a further time (Figure 2B). The angle  
168 of flexion was recorded by means of tibiofemoral angle on the sagittal localiser image  
169 as opposed to the thigh-calf angle used to position the patient.

170

171 **Quadriceps active imaging:**

172 The patient was positioned supine with a triangular foam pillow under the knee. A  
173 beach ball was placed anterior to the tibia with a valve under the control of the subject  
174 (Figure 3). The subject was requested to extend the knee, pushing the lower leg against  
175 the balloon, causing it to deflate (Figure 2C). Subjects were advised that it would be  
176 expected to take two minutes to achieve this. The MRI operator informed the subject  
177 that the scan was due to start so as to coincide this with the beginning of the scan. As  
178 the knee extended the scan was begun and repeated whilst the subject deflated the  
179 balloon.

180

181 Rapid sequence axial images were captured whilst the ball was permitted to continue  
182 to deflate under the subject's control. The deflation rate was dependent upon the  
183 exertion of the patient and was not externally controlled. Five to eight sequences were  
184 captured per deflation.

185

186 **Imaging sequence:**

187 After the localiser scan located the distal femur, the sequence placement was planned  
188 so that the entire trochlea could be imaged. In both the active and passive modes, the  
189 thigh did not move due to control by strapping and it was possible to attain adequate  
190 quality imaging of the trochlea, without motion artefact. In each sequence, images  
191 captured included one sagittal slice and 10-18 axial slices (dependent on patient size)  
192 at 5mm intervals.

193

194 In any given scan, up to 5 images demonstrated contact between the patella and the  
195 trochlea and at any given moment, the entire trochlea was captured in order to ensure  
196 all the relevant images along the path of the patella were captured.

197

198 **Image interpretation:**

199

200 Using digital data supplied by the institutional PACS (GE Healthcare Centricity™ &  
201 Fujifilm Synapse™) the operator manually identified boundaries of cartilage contact  
202 between the patella and femur on both sides of the trochlear sulcus on the axial view.  
203 These measurements were recorded as linear distances. Each slice is 5mm wide and the  
204 surface area of each slice was calculated by multiplying the length by 5mm. Each slice  
205 surface is then summed to reach a measure of the surface area in contact between the

206 articulating surfaces to give a measure of congruency in each measurement condition.  
207 This was recorded on a “flattened” 2D coronal plane image for visual interpretation of  
208 contact area (Figure 4).

209

210 Statistical methods:

211 The repeatability of the measurements of MRI congruity were assessed by  
212 Pearson’s correlation coefficient. The measurements were repeated by the primary  
213 investigator at a second timepoint to give a measure of intra-observer error. The  
214 measurements were repeated by another observer for assessment of inter-observer  
215 error. Comparison between case and control variables was made with a Fisher’s exact  
216 test or Chi<sup>2</sup> test for categorical variables depending upon number of groups or  
217 independent t-tests for continuous data. Two-tailed independent sample t-tests were  
218 used to compare the mean joint congruence (cm<sup>2</sup>) between cases and controls during  
219 the different phases of knee flexion during quadriceps activation (0 degrees, 0-10, 11-  
220 20, 21-30, 31-40, >40 and combined). All statistical analyses were performed using  
221 SPSS (IBM SPSS Statistics, Armonk, NY, USA).

222

223 **Results:**

224

225 Between the cases and controls, the ages were well balanced. The mean age was  
226 25 (range: 16-42; SD 6.9) in the case group and 26 (range: 19-32; SD 5.1) in the controls  
227 (p=0.690; Table 1). There were 19 females and 12 males in the cases group (p=0.060;  
228 Table 2). Laterality (side studied) was also well balanced, 36% being left amongst the  
229 cases and 44% amongst the controls (p=0.705). The other co-variates of interest that  
230 are associated with the pathology were more frequent amongst the cases than the

231 controls (Table 2). All patients in the cases group had sustained at least 2 dislocations  
232 with 19 (61%) sustaining more than 2 dislocations. Seven (22.6%) of the cases cohort  
233 have hypermobility with a Beighton score of four or more. Only six (19%) patients in  
234 the cases cohort demonstrated a normal trochlear groove with the 14 patients (45%)  
235 displaying Dejour C abnormalities. Unsurprisingly, all control group patients  
236 demonstrated a normal trochlear groove.

237         The radiological measurements were highly correlated for intra-observer error  
238 (0.985) and for inter-observer error (0.910). The congruency within the two groups for  
239 active and passive range of movement is closely correlated (Figure 5). The histogram  
240 illustrates the trend from incongruence to congruency as the knee flexes (Figure 6). The  
241 greatest differences in congruency between controls and cases is seen in the quadriceps  
242 active group between the range of zero and twenty degrees. The greatest mean  
243 differences and greatest statistical significance is at the 11-20 degree range (Figure 6).  
244 The curves match well between controls and cases; the exception is at the 40+ range  
245 where there only one case has been recorded and the trend for increased congruence is  
246 not observed.

247

#### 248 **Discussion:**

249         The clinical importance of this study is to establish a direct measurement of PFJ  
250 contact area. With the ability to quantify congruency, the authors intend to use this  
251 technique to compare pre-operative and post-operative in cases where stabilisation  
252 surgery is performed.

253         With the aid of the results from this study, researchers will be able to compare  
254 surgical cases to a baseline cohort of patients with stable knees. The range 11-20

255 degrees (tibiofemoral angle) is the most sensitive. Clinicians may use the routine MRI  
256 performed in this position to evaluate congruence by this technique.

257         The PFJ is a complex articulation for which accurate assessment of congruence  
258 and morphology may remain elusive with a single imaging modality or if viewed in a  
259 single plane [13,14]. Our sequential MRI scans during active and passive range of  
260 movement of the knees demonstrated close correlation of contact area within the groups  
261 for both active and passive range of movement. When the control and cases groups are  
262 compared, the mean contact area was greater in the control group through all ranges of  
263 movement in both passive and quadriceps active with the exception of quadriceps active  
264 in extension. This may be secondary to an abnormal articulation of the unstable patella  
265 within the trochlear by activation of the quadriceps in this position.

266         The greatest mean differences between unstable and stable patellofemoral joint  
267 congruency during quadriceps active series were observed between 11 and 20 degrees  
268 ( $1.73\text{cm}^2$  vs  $4.00\text{cm}^2$ ,  $p<0.001$ ). This is important as lateral patellar displacement has  
269 been shown to occur with the lowest restraining forces required at 20 degrees of knee  
270 flexion [15].

271         Understanding articular contact through imaging modalities is problematic with  
272 significant mismatch between osseous landmarks observed in radiographs or CT scans  
273 and the articular cartilage of the patella and trochlea obtained by an MRI [16]. Patella  
274 position has been evaluated with the use of many different indexes, such as the Insall-  
275 Salvati [17], the modified Insall-Salvati [18] the Blackburne-Peel [19], the Caton-  
276 Deschamps [20] and the Sagittal Patellofemoral Engagement (SPE) Index [21].  
277 Radiographic classifications have been also reproduced with MRI [22]. Whilst patella  
278 height and engagement can be assessed in the sagittal plane, an appreciation of  
279 congruency especially through range of movement is not achieved.

280           Axial imaging provides information on the position of the patella within the  
281 trochlear groove, however, static knee position images provide little information  
282 toward the congruency or tracking through the range of movement. Skyline plain  
283 radiographs have been found to be unreliable [23,24], because they can be difficult to  
284 obtain at degrees of flexion less than 30 where subluxation is most prevalent. It is for  
285 these reasons we sought to evaluate the patellofemoral joint by means of contact area  
286 through axial MRI imaging during active movement as cartilage contact is the  
287 functional basis of force transmission. Several other authors have previously given  
288 attention to activation of the quadriceps mechanism during capture of axial imaging  
289 [24-26].

290           Brossmann et al. used dynamic MRI to analyse patella tracking in healthy  
291 volunteers and patients with maltracking [25]. They reported significantly different  
292 patellar tracking patterns between the two groups and statistically significant tracking  
293 differences between static and dynamic scanning of the PFJ although the contact  
294 surface area was not a measured outcome. While McNally et al. described the  
295 morphological traits of instability with dynamic axial MRI there was no recording of  
296 congruency or contact area [26]. They demonstrated with the use of dynamic MRI that  
297 patella subluxation was present in 40% of patients with anterior knee pain and  
298 challenged the clinical relevance of mild subluxation of the PFJ. Martinez et al. utilised  
299 CT scans at set intervals of 0, 20 and 45 degrees of flexion to establish the effect of  
300 activation of the quadriceps on the centralisation and tilt of the patella [27]. The  
301 individuals assessed had asymptomatic knees and were considered healthy. They  
302 concluded that Quadriceps contraction had little influence on the patellar centralisation  
303 and did not effect patellar tilt unless in full extension. The effect on unstable PFJs was  
304 not explored by these authors.

305           We have sought to quantify the congruency of the PFJ through dynamic MRI  
306 mapping and 2D representation of contact surface area. We have documented the  
307 difference in contact surface area between the stable and unstable PFJ. The potential to  
308 use this MRI mapping methodology to establish the change in congruency for pre- and  
309 post-stabilisation surgeries will allow for objective evaluation of treatment modalities.

310           Despite the small sample size of this study there were significant differences in  
311 the contact area at all ranges between 0 and 40 degrees when comparing cases and  
312 controls. The gender imbalance of male n=7 to female n=2 in the control group is seen  
313 by the authors as a weakness of the study as the majority of PFJ instability cases are  
314 seen in the female population. The disadvantages of adding a dynamic element to MRI  
315 imaging has the potential for generation of movement artefact with the addition of a  
316 further variable which may increase the variance of the data. The issue of motion  
317 artefact was minimal as the rapid sequence MRI scan coupled with stabilisation of the  
318 femur resulted in clear and accurate images for interpretation. Despite the risk of  
319 motion artefact, the authors believe dynamic imaging of the PFJ may be more  
320 representative of the physiologic conditions that are present during ambulation.  
321 The range of movement is limited to 40 degrees of flexion due to the physical  
322 constraints of the MRI scanner.

323           The articulation of the PFJ, if accurately measured in terms of contact area, will  
324 provide useful information in determining the effectiveness of surgeries aimed at  
325 increasing congruency. The authors aim to compare a cohort of patients pre- and post-  
326 stabilisation surgery using this methodology to quantify the effects of surgical  
327 modalities on PFJ congruence.

328

329

330 **Conclusion:**

331

332 The unstable patellofemoral joint is less congruent than the stable patellofemoral joint  
333 throughout knee movement. The unstable PFJ has less contact surface area and this will  
334 inversely increase the contact pressure for a given force leading an increased risk of  
335 degeneration of the joint. This approach to mapping of the patellofemoral joint may aid  
336 in the design of operations to increase stability and serve to provide a means of  
337 assessing pre- and post-operative joint congruency as an outcome measure. If a single  
338 axial series is to be obtained on MRI scan, the authors recommend 10-20 degrees of  
339 tibiofemoral flexion as this was shown to have the greatest difference in contact surface  
340 area between the cases and controls group.

341

342



343 **Figure 1:** Flow chart of case inclusion and exclusion.

344 **Figure 2:** A: The subject lay supine on the MRI table with a triangular wedge under  
345 the knee. B: Foam blocks were placed for passive range of movement at 0, 20 and 40  
346 degrees flexion. C: Deflating balloon against resistance with multiple sequence scans  
347 for Quadriceps active.

348 **Figure 3:** A beach ball was placed anterior to the tibia to provide resistance and achieve  
349 quadriceps activation. The subject controlled a valve to control the rate of deflation.

350 **Figure 4:** "Flattening" of axial imaging. Slices are at 5mm intervals. The width of each  
351 slice in which there is contact between femur and patella cartilage is multiplied by  
352 5mm. Each measurement is then summed to give a total area of congruence.

353 **Figure 5:** Control vs Instability group in passive and active movement.

354 **Figure 6:** Histogram in quadriceps active, control and instability

355

356 **Table 1:** Age, Tibial Tuberosity Trochlear Groove (TTTG) distance (mm), Insall  
357 Salvati Ratio (ISR), Biedert Patellotrochlear Index, SD = standard deviation, n =  
358 number.

359 **Table 2:** Clinical comparison between cases and controls.

360 **Table 3:** Comparison of mean joint congruence between case and controls during  
361 quadriceps active knee movement.

362

363

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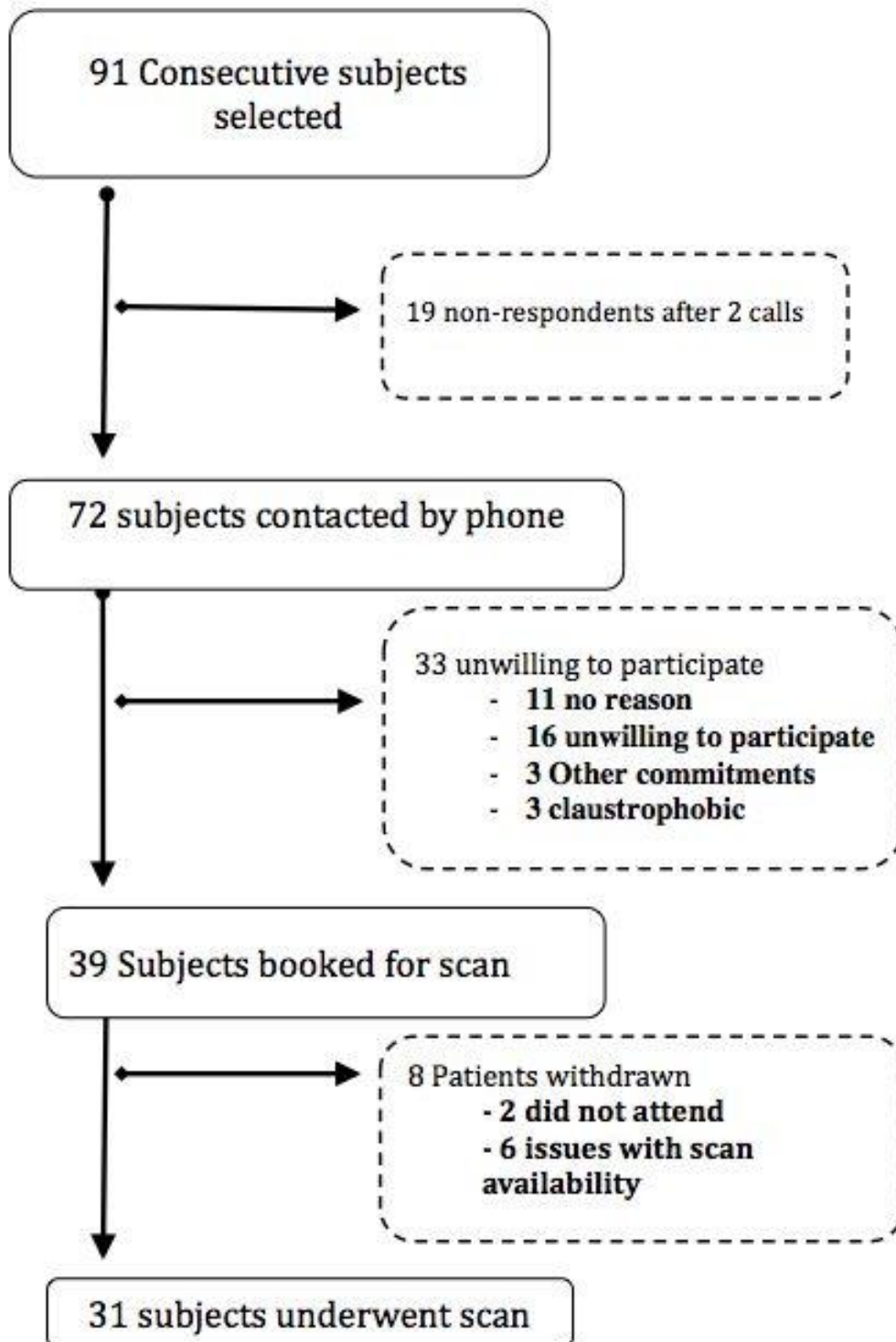
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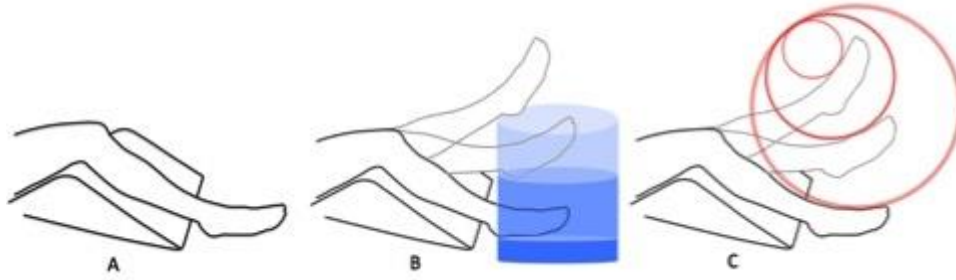
467 **Figure 1:** Flow chart of case inclusion and exclusion.

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471 **Figure 2:** A: The subject lay supine on the MRI table with a triangular wedge under  
472 the knee. B: Foam blocks were placed for passive range of movement at 0, 20 and 40  
473 degrees flexion. C: Deflating balloon against resistance with multiple sequence scans  
474 for Quadriceps active



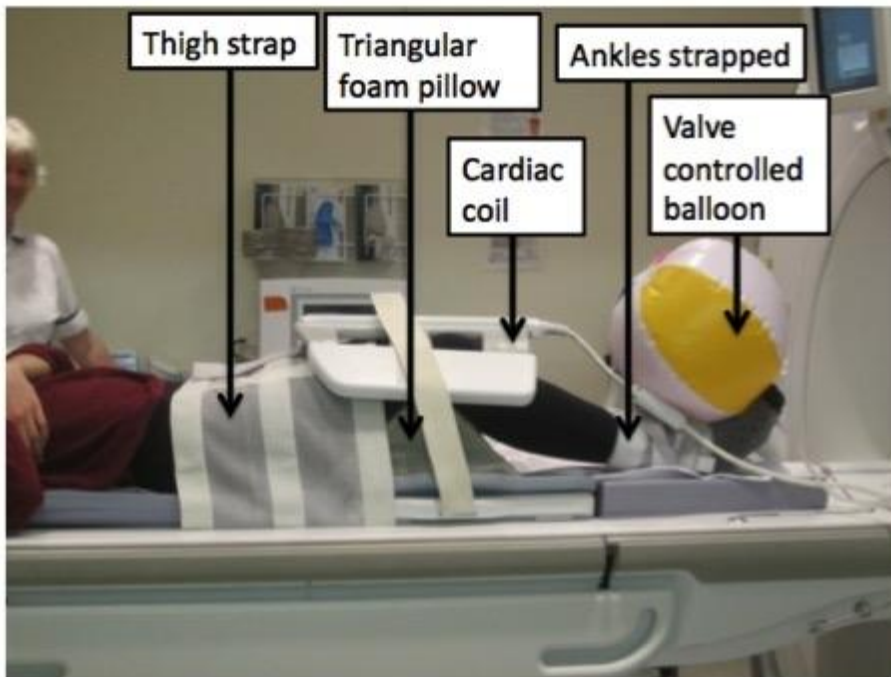
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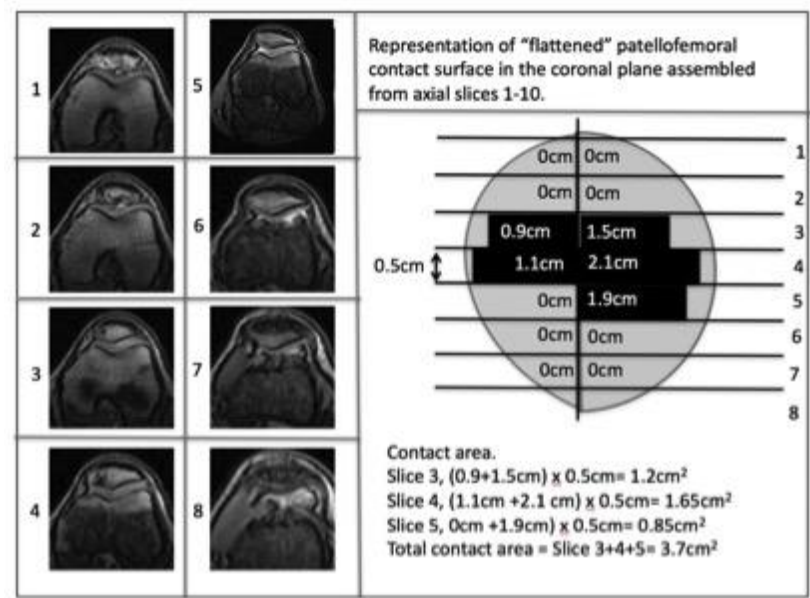
479 **Figure 3:** A beach ball was placed anterior to the tibia to provide resistance and achieve  
480 quadriceps activation. The subject controlled a valve to control the rate of deflation.



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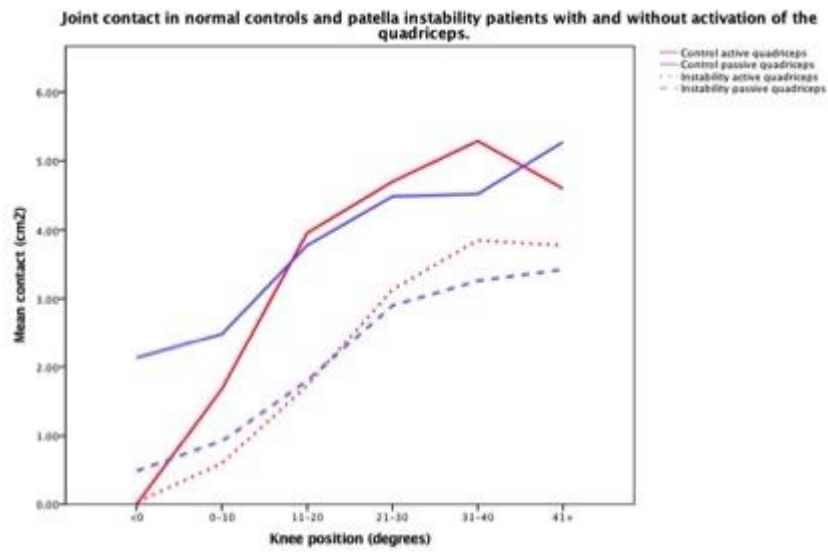
484 **Figure 4:** "Flattening" of axial imaging. Slices are at 5mm intervals. The width of each  
 485 slice in which there is contact between femur and patella cartilage is multiplied by  
 486 5mm. Each measurement is then summed to give a total area of congruence.



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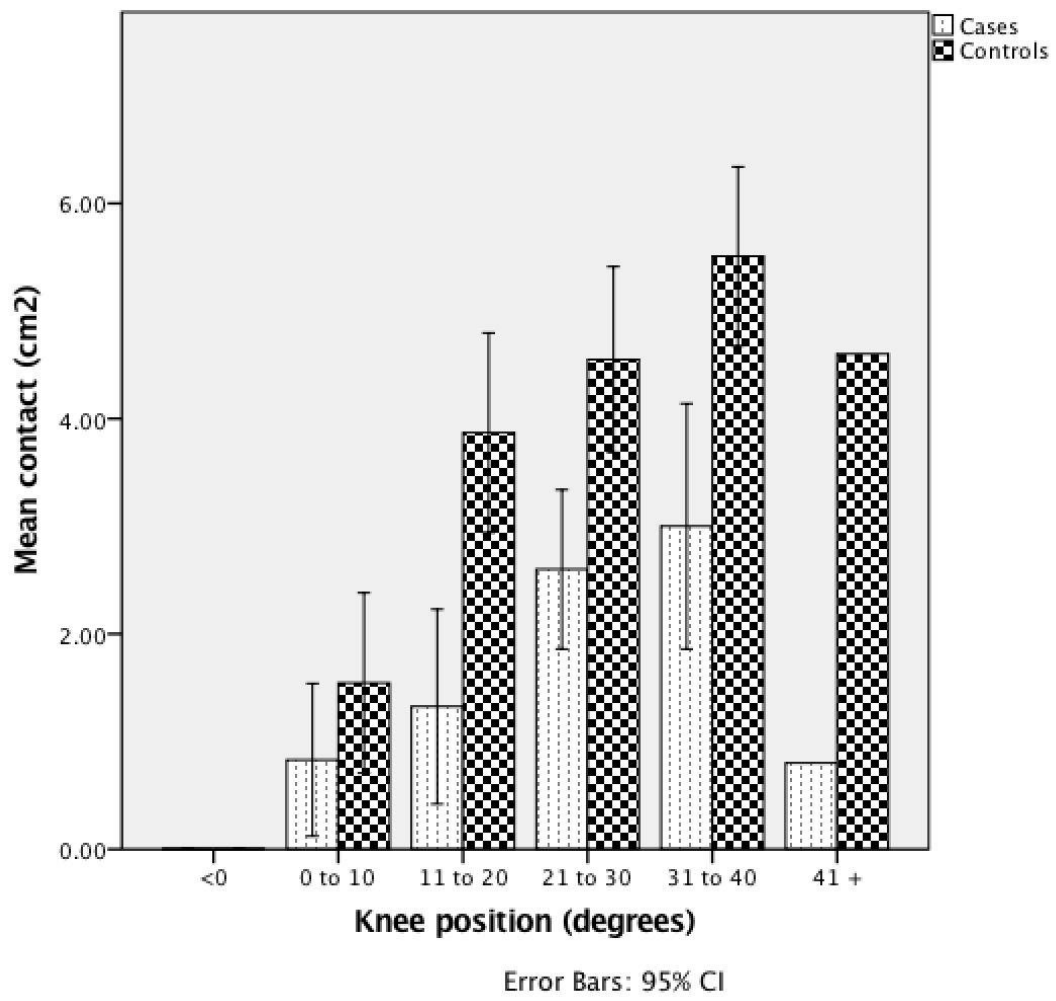
490 **Figure 5:** Control vs Instability group in passive and active movement.



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494 **Figure 6:** Histogram in quadriceps active, control and cases groups



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	Cases			Controls			p value
	Mean	SD	n	Mean	SD	n	
Age	25	6.9	31	26	5.1	9	0.690
TTTG	13.3	4.6	31	11.9	3.2	9	0.400
ISR	1.37	0.2	31	1.19	0.09	9	0.013
Biedert	32.5	23	31	38.2	3.3	9	0.470
Age at 1st dislocation	14.9	3.8	21	-	-	-	

498

499 **Table 1:** Age, Tibial Tuberosity Trochlear Groove (TTTG) distance (mm), Insall

500 Salvati Ratio (ISR), Biedert Patellotrochlear Index, SD = standard deviation, n =

501 number

502

503

		Cases		Control		p value
		n	%	n	%	
Sex (female - male)		19 - 12	61 female	2-7	22.2 female	0.060
Laterality (left - right)		11 - 20	36 left	4-5	44 left	0.705
Dejour grade	Normal	6	19	9	100	0.001
	A	3	10	0	0	
	B	5	16	0	0	
	C	14	45	0	0	
	D	3	10	0	0	
Hypermobile (Beighton Score of 4+)		7/31	22.6	0/9	0	0.175
Previous surgery		7/31	22.6	0/9	0	0.175
Subjects with >2 dislocations		19/31	61	0/9	0	0.001

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**Table 2:** Clinical comparison between cases and controls

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Quadriceps active: knee position.		n	Mean joint congruence cm2	mean diff	95% lower	95% upper	P
<0	Case	7	0.029	0.029	-0.10	0.16	0.626
	Control	2	0.00				
0-10	Case	26	0.59	-1.09	-1.80	-0.38	0.004
	Control	11	1.68				
11-20	Case	26	1.73	-2.22	-3.16	-1.27	0.000
	Control	9	4.00				
21-30	Case	24	3.13	-1.57	-2.64	-0.49	0.006
	Control	8	4.70				
31-40	Case	18	3.85	-1.44	2.58	-0.30	0.016
	Control	5	5.29				
40+	Case	9	3.77	-0.83	-4.51	2.85	0.618
	Control	1	4.60				
Combined	Case	110	2.17	-1.24	-1.91	-0.55	0.000
	Control	36	3.40				

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509 **Table 3:** Comparison of mean joint congruence between case and controls during

510 quadriceps active knee movement

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