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1 **Evaluation of the magnitude of hip joint deformation in subjects with avascular necrosis**
2 **of the hip joint during walking with and without Scottish Rite Orthosis**

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26 **Abstract:**

27 The femoral head in subjects with leg calve perthes disease (LCPD) is generally considerably
28 deformed. It is debatable whether this deformation is due to an increase in applied loads, a
29 decrease in bone mineral density or a change in containment of articular surfaces. The aim of
30 this study was to determine the influence of these factors on deformation of the femoral head.
31 Two subjects with LCPD participated in this study. Subject motion and the forces applied on
32 the affected leg were recorded using a motion analysis system (*QualsisTM*) and a Kistler force
33 plate. *OpenSim* software was used to determine joint contact force of the hip joint whilst
34 walking with and without a Scottish rite orthosis. 3D Models of hip joints of both subjects
35 were produced by *Mimics software*. The deformation of femoral bone was determined by
36 *Abaqus*.

37 Mean values of the force applied on the leg increased while walking with the orthosis. There
38 was no difference between bone mineral density (BMD) of the femoral bone of normal and
39 LCPD sides (p-value>0.05) and no difference between hip joint contact force of normal and
40 LCPD sides. Hip joint containment appeared to decrease follow the use of the orthosis.

41 It can be concluded that the deformation of femoral head in LCPD may not be due to change
42 in BMD or applied load. Although the Scottish rite orthosis is used mostly to increase hip
43 joint containment, it appears to reduce hip joint contact area. It is recommended that a similar
44 study is conducted using a higher number of subjects.

45 **Key words:** LCPD, orthosis, Scottish rite, walking, joint contact force, hip joint deformation

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50

51 **Introduction**

52 In Leg Calve Perthes Disease (LCPD) the blood supply of femoral head is disconnected and
53 the femoral head temporarily dies (1). The incidence of this disease varies from a country to
54 country from 0.45 to 10.5 per 100000 and occurs mostly in children between 5 and 12 years
55 (1-4). Although it is claimed that genetic or deprivation factors influence the incidence of this
56 disease, its etiology is likely to be multifactorial and is not clear (1).

57

58 A variety of different approaches to treatment have been used for LCPD, including surgery,
59 the use of orthoses, observation and physical therapy (5-12). The main reason for treatment is
60 to reduce deformation of the femoral bone (7) which may increase the incidence of hip joint
61 degeneration and pain in adolescence (13, 14).

62

63 Treatment approaches used to decrease femoral head deformation are based on reducing the
64 applied load on the femoral head and increasing hip joint containment (5, 7, 10, 15, 16).
65 Containment of the femoral head within acetabulum is achieved by putting the hip joint in a
66 few degrees of abduction and internal rotation until the femoral epiphysis is well inside
67 Perkins line (5, 12, 17).

68

69 Offloading of the hip joint has being conducted using assistive devices such as the
70 Birmingham splint, Snider sling, or Ischial weight bearing orthoses (10, 11, 15, 16).

71

72 The main LCPD treatment aims are to contain and prevent further deformity of the femoral
73 head; relieve painful symptoms and restore hip joint range of motion (7). Results of various
74 research studies demonstrate no difference between the outputs of treatment based on

75 surgery, orthoses, physical therapy or observational treatment. This means current treatment
76 pathways have not demonstrated success in relation to treatment aims (7).

77

78 It remains unclear exactly why the femoral bone is deformed in this disease. The deformation
79 of the femoral bone is currently presumed to be as a result of increase in the applied loads,
80 decrease in bone density or a decrease in femoral head containment within acetabular cavity
81 (7).

82

83 Results of previous studies have demonstrated no significant difference between forces
84 applied between normal and LCPD legs (18, 19). Moments applied on the hip joint in the
85 LCPD side may actually be less than that of normal side (20). It was concluded that these
86 subjects altered their walking pattern to decrease the hip joint moment and hence load on hip
87 joint (21, 22). Although previous studies have examined hip joint load of LCPD subjects, all
88 are based on inverse dynamics and kinematics (18,19, 22). To the best of our knowledge, no
89 study on hip joint contact forces has previously been described in this group of subjects.

90

91 Bone mineral density (BMD) is another important parameter which is mostly dependent on
92 applied femoral load. Baily et al. demonstrated that BMD of femoral head in LCPD side was
93 less than that of sound side, which may be due to decrease in loads applied. It was
94 demonstrated that the maximum difference of density related to the femoral neck region (20).
95 Based on these findings it may be fair to conclude that a decrease in BMD may be related to a
96 reduction in applied load, which should return to expected values if the subjects walked
97 normally.

98

99 Although the theory of femoral head containment within the acetabulum was described more
100 than 50 years ago, there are no studies which evaluate the effects of this hip joint position on
101 increase of the contact area of the hip joint (7).

102

103 There are no studies which evaluate hip joint contact forces in LCPD. The effect of hip joint
104 containment on the acetabular contact area in these subjects remains undecided; there is little
105 information on the effect of containment on the stress and final deformation of the femoral
106 bone. Therefore, the aim of this study was to examine the effect of orthotic management on
107 the resulting stress which develops in the hip joint and to determine the effects of alignment
108 change in relation to this stress.

109

110 **Methods**

111 Two seven year old boys with symptoms of avascular necrosis of the hip joint participated in
112 this study, Table 1. Both had involvement of hip joint on the right side. The severity of LCPD
113 was determined based on the latest X-ray of the patients (Mose et al)(23). Ethical approval
114 was obtained from Isfahan University of Medical Sciences, Ethical Committee , a consent
115 form was signed by the parents of each participant before data collection.

116

117 Both subjects were asked to walk with and without Scottish rite orthosis. This is a well-
118 developed orthosis for the subjects with LCPD and holds the hip joint in some degree of
119 abduction and medial rotation to increase hip joint containment. The Scottish rite orthosis is
120 one of the most popular used orthoses for the subjects with LCPD and was originally
121 developed at Scottish rite hospital for crippled children in Atlanta in 1971. This orthoses
122 consists of three main parts, including plastic thigh cuffs, a pelvic band and a single axis hip
123 hinge. The main reason to use this orthoses is to put the hip joint in an abducted and

124 internally rotated posture. (18, 24). It should be emphasised that the orthosis was built
125 specifically for each subject and the subjects used their orthosis for at least 6 months before
126 participated in this study. The following parameters were evaluated in this study:
127 Spatiotemporal gait parameters during walking with and without orthosis, forces applied on
128 the leg, kinematic of the lower limb joints and pelvic, hip joint moments, joint contact forces
129 of the hip joints, the containment of the hip joint in various aligned positions, and the stress
130 and strain of hip joint in walking with and without orthosis.

131 **Procedure:**

132 **Kinetic and kinematic analysis:** A motion analysis system consisted of seven high speed
133 camera (Qualysis motion analysis system) and Kistler force plates were used to collect the
134 kinetic and kinematic parameters. 22 markers were attached on the right and left anterior and
135 posterior superior iliac spines, right and left greater trochanters, right and left medial and
136 lateral sides of knee joint, right and left medial and lateral malleolus, first and fifth metatarsal
137 heads, right and left heels and right and left acromioclavicular joints. Additionally, four
138 markers clusters were attached on the lateral side of thighs and shanks in both right and left
139 sides. The subjects were asked to walk at a comfortable self-selected speed with and without
140 the orthosis. Tests were repeated to collect five successful trials.

141

142 Force plate data and cameras were collected with frequency of 120 Hz. Data was filtered with
143 Butterworth low pass filter with cut off frequency of 10 Hz. Markers were labeled in
144 *QualysisTM Tract Manager Software* and were exported as 3-D files. Files were opened with
145 *MokkaTM software* to produce *trc* files to be analyzed with *OpenSIMTM* software. *OpenSIMTM*
146 software is open source software developed by Stanford University, USA. It can be used to
147 analysis kinetic, kinematic, muscles forces, muscles length and joint contact forces. Figure 1

148 shows the procedure used to determine joint contact forces of the hip joint by use of
149 *OpenSIMTM* software (25).

150 The scaling was done with high accuracy as was recommended by *OpenSIMTM* developer
151 (25), the RMS of error was less than 2mm for whole model. Moreover, the RMS of model
152 error was evaluated in inverse kinematic frame by frame. (Based on the reports produced by
153 the software automatically the RMS of error was less than 2cm.)

154 **Producing 3-D files of hip joint:** 3-D modeling of the hip joint with specific material
155 assignment was done by use of *MimicsTM* and *AbaqusTM* software, based on CT scan slices of
156 the patient's hip joint. Hip joint files were opened in *MimicsTM* software to produce a 3-D
157 mask and different segments (femoral and pelvic) modeled individually. Resulting segments
158 were exported to *AbaqusTM* software to change the format of the mesh from 'tri' to 'tet'. INP
159 files were then imported to *MimicsTM* to assign the material.

160

161 The software defines a number of sampling points within each element and interpolates the
162 gray level relating to their coordinate from the original CT. Gray level is proportional to
163 apparent bone density. Young Modules (E) was automatically calculated by mimics software
164 based on equation developed by Schileo et al. and Morgan et al. (26, 27) :

165 $E=6850\rho^{1.49}$

166 In which, E was Young Modules of elasticity and ρ was appearance bone density.

167 Hip joint alignment changes (femoral head and pelvic components) were simulated using
168 *MimicsTM* software. The femoral bone was placed in abduction, external rotation, and internal
169 rotation with respect to the acetabulum (pelvic). The influence of changes in alignment of hip
170 joint on joint containment was determined based on the number of nodes of femoral head
171 which were covered by acetabulum of hip bone. Resulting femoral head stress developed in

172 various positions and deformation was determined based on the forces obtained from
173 *OpenSIMTM* software. It was done by help of Abaqus software. Due to lack of information
174 regarding stress analysis of femoral bone in children the analysis was done based on elastio-
175 plastic approach in *AbaqusTM* software.

176

177 Mean values of the kinematic, kinetic parameters and joint contact forces were determined in
178 walking with and without orthosis conditions. At least 10 successful trials for each subject
179 was collected under each condition. Statistical analysis was conducted separately for each
180 subject, based on conditions (walking with and without orthosis). The difference between the
181 mean values of the gait parameters was evaluated by use of two sample tests.

182

183 **Results**

184 The mean values of the gait parameters of both subjects while walking with orthosis and
185 without orthosis are shown in Table 2. As can be seen from this table, walking speed and
186 stride length decreased especially while walking with orthosis (P-value of difference < 0.05
187 for subject 1).

188 Hip and pelvic kinematics were also evaluated in this study, Table 3. Although the range of
189 flexion and extension motions of hip joint did not decrease significantly in subject 1, they did
190 so in subject 2 following the use of orthosis (29.75 ± 3.14 without orthosis vs. 9.6 ± 1.52 when
191 walking with an orthosis). In contrast, the hip joint range of motion in frontal plane decreased
192 significantly in both subjects (P-value < 0.05). The pelvic range of motion in the frontal plane
193 increased notably in both of participants (Table 3). Although the peaks of the ground reaction
194 force components applied on the leg increased while walking with orthosis, the difference
195 was only significant for mediolateral force (P-value = 0.04 and 0.01 for the first and second,

196 subjects, respectively), Table 4. Most of the peaks of hip joint moments increased
197 significantly during walking with the orthosis in both subjects (p-value<0.05), Table 5.

198

199 The hip joint contact force of both subjects while walking with and without orthosis are
200 shown in Table 6. Vertical component peaks of hip joint contact force were 13.74 ± 6.13 and
201 6.27 ± 2.53 N/BW in subject 1 in walking without and with the orthosis, respectively. In
202 contrast, it was 9.96 ± 3.54 and 12.8 ± 2.1 N/BW, in subject 2 for walking without and with
203 orthosis. Although the mean values of anteroposterior component of hip joint contact force
204 increased in both subjects, the difference was not significant (p-value > 0.05). The hip joint
205 contact force of the sound side was also evaluated in this study. As can be seen from Table 7,
206 there was no difference between hip joint contact force between involved and healthy sides
207 (p-value>0.05).

208

209 Mean values of femoral bone density and femoral bone Young Modules of elasticity of the
210 involved side were 805129.9 ± 467632.5 g/m³ and $4770396420 \pm 2770722483$ Pascal for
211 subject 1 and 900077.3 ± 564158 g/m³ and $4648782493 \pm 2642671981$ Pascal for subject 2,
212 respectively. There was no difference between density and Young modulus of elasticity
213 between involved and sound sides, Table 8. The results of joint containment in various
214 alignment of hip joint are shown in Table 9. As can be seen from this table, the maximum
215 contact area of hip joint was in neutral position in both subjects. However, the minimum
216 number of nodes was in abduction and internal rotation in subject 1 and abduction in subject
217 2.

218 Femoral bone deformation and stress magnitude in the femur, (based on the elastic approach),
219 are shown in figure 2. As can be seen from this figure, the stress developed was more than the
220 stress which can feasibly be tolerated by the bone. Therefore, all analysis was conducted

221 based on an elasto-plastic approach. The results of deformation of femoral bone in various
222 aligned positions are shown in Table 10. The average deformation of femoral bone was 2.318
223 mm and 1.964 mm in subject 1 while walking with and without orthosis. Although in subject
224 1 using the orthosis reduced the deformation of the femoral head, in subject 2 the deformation
225 of the bone in walking with orthosis was more than that without orthosis. Regarding the
226 effects of alignment on femoral head deformation, the deformation in abduction and neutral
227 position was less than that in other conditions.

228

229 **Discussion:**

230 Although the etiology of LCPD was described over 100 years ago, there is still a lack of
231 consensus on which treatment approach should be used to decrease the deformities associated
232 with this disease. Although various treatment approaches have being used to decrease the
233 deformation of femoral head and decrease the incidence of hip joint degenerative change,
234 most of them are not successful (7). One of the broadly used methods to reach to this goal is
235 the use of an orthosis. Therefore, the aim of this study was to determine the effect of the use
236 of an orthosis to decrease the load applied on hip joint and hence the deformation of femoral
237 head. Additionally, the study aimed to evaluate the influence of femoral alignment change on
238 containment and stress developed in the hip joint.

239 Femoral bone deformation in this disease may be due to three main reasons which include:
240 Increase in loads applied on the hip joint, change in containment of articular surfaces and
241 decrease in bone mineral density. As can be seen from the results of this study presented in
242 Table 7, there was no difference between joint contact forces of LCPD affected and healthy
243 sides. It may therefore be concluded that femoral bone deformation is not related to an
244 alteration in hip joint load. No other previous studies have been identified to examine the
245 joint contact force in subjects with LCPD.

246 The results of BMD of both subjects demonstrated no difference between BMD and Young
247 modulus of elasticity of LCPD and sound sides, Table 8. Results of this part of this research
248 did not support the finding of Bailey et al (20). Some parameters such as the time between
249 start of disease and follow up may be the reason for the difference. It should be noted that the
250 BMD in the current research was measured based on Shailey et al approach, which was
251 conducted using *MimicsTM* software (26). The BMD of different parts of femur (up to 5cm
252 below the greater trochanter) were evaluated in this study. Although there was no difference
253 between the mean values of BMD of femur, the BMD of specific parts may be decreased due
254 to this disease. Overall, no significant difference was detected between the BMD of LCPD
255 and sound sides.

256

257 Results demonstrate that femoral head deformation in LCPD is not due to a change in BMD
258 or applied load. The remaining reason discussed may be due to a change in hip joint
259 containment. The difference between hip joint containment between LCPD and normal
260 subjects was not evaluated in this study. Therefore, it is recommended that this parameter
261 should be considered in the future.

262

263 However, subjects with LCPD are recommended to use Scottish rite orthosis to increase joint
264 containment and to reduce applied loads. The results of this research also highlighted that
265 although the walking speed and stride length decreased significantly while walking with
266 orthosis, Table 2, the moments applied on hip joints and some components of ground reaction
267 force increased significantly, Tables 4 and 5. This is the same as the results of the study done
268 by Karimi et al (18). However the results of joint contact force demonstrated that although
269 the mediolateral component of hip joint contact force increased in both subjects following the
270 use of the orthosis, the mean value of vertical components increased in subject 2 (it decreased

271 in subject 1), Table 6. Results of this study therefore do not support the use of orthosis to
272 reduce hip joint contact force.

273

274 The results of stress analysis demonstrated that stress developed in the femoral bone based on
275 elastic approach exceeded the stress which may feasibly be tolerated by the femur. Therefore,
276 it was decided that the stress analysis of the bone be conducted using an elasto-plastic
277 approach. The results of stress analysis demonstrated that the deformation of femoral head
278 decreased in walking with orthosis condition (in neutral condition) in subject 1, compared to
279 an increase in subject 2. As this part of analysis was done in neutral condition the difference
280 in deformation of femoral bone may be due to change in hip joint contact force. As can be
281 seen from Table 6, the vertical component of joint contact force decreased and increased
282 slightly in subjects 1 and 2, respectively.

283

284 The effect of hip joint alignment change was also evaluated in this study. Results indicate that
285 positioning of the hip joint articular surfaces in a neutral position may provide maximum
286 contact area, Table 9. Although abduction and internal rotation increased the contact area of
287 the hip joint surface in subject 2, it decreased the contact surface in subject 1. It may therefore
288 be concluded that the position achieved by use of the orthosis may be not optimal in
289 promoting maximum joint containment.

290

291 The results of stress-strain analysis demonstrated that use of orthosis may decrease the
292 deformation of femoral head in subject 1 but increased it in subject 2. As this part of
293 comparison was done in neutral position it can be concluded that it may be due to a change in
294 applied loads on hip joint. As can be seen from Table 7, the vertical component of hip joint
295 contact force in subject 1 in walking with orthosis was less than that of normal walking,

296 however, this increased in subject 2. Alignment of the hip joint in the aforementioned
297 positions by use of orthosis seems to increase the deformation of femoral head, due to
298 decrease in joint containment.

299

300 The main limitation of this study was the number of participants. It is recommended that
301 future studies should be conducted using a larger sample size. Moreover, it is recommended
302 that bone mineral density of different parts of bone be evaluated in an increased number of
303 subjects with LCPD.

304

305 **Conclusion**

306 Whilst considering the limited number of participants in this study, it may be concluded that
307 the deformation of femoral bone is neither due to a change in hip joint load or a change in
308 bone mineral density. Additionally, results indicate that the containment of the hip joint in the
309 positions aligned by use of the Scottish rite orthosis does not increase the contact area of hip
310 joint in all subjects. It is recommended that further studies be conducted using a larger sample
311 size.

312

313 **Journal:** MEDICAL ENGINEERING &
314 PHYSICS

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319 The following additional information is required for submission. Please note that failure to respond to
320 these questions/statements will mean your submission will be returned to you. If you have nothing to
321 declare in any of these categories then this should be stated.

322

323 **Conflict of interest**

324 All authors must disclose any financial and personal relationships with other people or organisations
325 that could inappropriately influence (bias) their work. Examples of potential conflicts of interest include
326 employment, consultancies, stock ownership, honoraria, paid expert testimony, patent
327 applications/registrations, and grants or other funding.

328

329 **Ethical Approval**

330 Work on human beings that is submitted to *Medical Engineering & Physics* should comply with the
331 principles laid down in the Declaration of Helsinki; Recommendations guiding physicians in biomedical
332 research involving human subjects. Adopted by the 18th World Medical Assembly, Helsinki, Finland,

333

Title of Paper: Evaluation the magnitude of hip joint deformation in subjects with Avascular Necrosis of Hip joint during walking with and without Scottish Rite Orthosis

317 **Declarations**

333 June 1964, amended by the 29th World Medical Assembly, Tokyo, Japan, October 1975, the 35th
334 World Medical Assembly, Venice, Italy, October 1983, and the 41st World Medical Assembly, Hong
335 Kong, September 1989. You should include information as to whether the work has been approved by
336 the appropriate ethical committees related to the institution(s) in which it was performed and that
337 subjects gave informed consent to the work.
338
339

Competing Interests

No competing interests

340
341 **Please state any sources of funding for your research**

No source of funding

342
343 **DOES YOUR STUDY INVOLVE HUMAN SUBJECTS? Please cross out whichever is not**
344 **applicable.**

345 **Yes**

346 **No**

347
348 **If your study involves human subjects you MUST have obtained ethical approval.**
349 **Please state whether Ethical Approval was given, by whom and the relevant Judgement's**
350 **reference number**

The authors state that an ethical approval was obtained from Isfahan University of Medical Sciences, Ethical Committee. Moreover, a consent form was signed by the parents of each participant before date collection.

351
352
353 **This information must also be inserted into your manuscript under the acknowledgements**
354 **section prior to the References.**
355

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