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1 **Are there clinically relevant anatomical differences of the proximal femur in**
2 **patients with mild dysplastic and primary hip osteoarthritis?**

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A CT-data based matched pairs cohort study

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30 patent-licensing arrangements.

31

32

33 **Abstract**

34 Purpose: The study aimed to investigate the three dimensional anatomy and shape of the
35 proximal femur, comparing patients with secondary OA due to mild developmental dysplasia
36 of the hip (DDH) and primary hip osteoarthritis (OA).

37 Methods: This retrospective radiographic CT-data based study investigated the proximal
38 femoral anatomy in a consecutive series of 84 patients with secondary hip OA due mild DDH
39 (Crowe type I&II/ Hartofilakidis A) compared to 84 patients with primary hip OA, matched for
40 gender, age at surgery and body-mass index.

41 Results: Men with DDH showed higher neck shaft angles ($127^\circ \pm 5^\circ$ vs. $123^\circ \pm 4^\circ$; $p < 0.001$),
42 while women with DDH had a larger femoral head diameter (46 ± 4 vs. 44 ± 3 mm; $p = 0.002$),
43 smaller femoral offset (36 ± 5 vs. 40 ± 4 mm; $p < 0.001$), decreased leg torsion ($25^\circ \pm 13^\circ$ vs. 31°
44 $\pm 16^\circ$; $p = 0.037$) and higher neck shaft angle ($128^\circ \pm 7^\circ$ vs. $123^\circ \pm 4^\circ$; $p < 0.001$). Similar patterns
45 of the three-dimensional endosteal canal shape of the proximal femur, but a high inter-
46 individual variability for femoral canal torsion at the meta-diaphyseal level for both groups.

47 Conclusion: Patients with secondary hip OA due to mild DDH can be equally treated with
48 cementless stem designs compared to primary hip OA, however subtle anatomical differences
49 of the proximal femur should be respected.

50 Keywords: anatomy, proximal femur, hip, osteoarthritis, dysplasia

51 Level of evidence: Diagnostic Level IV

52

53 **Introduction**

54 Total hip arthroplasty in secondary forms of OA continue to pose a clinical challenge as
55 patients are of younger age and proximal femoral anatomy is highly variable in patients with
56 hip dysplasia¹⁻³. Cementless femoral reconstruction with standard or short stems may hence
57 be technically challenging as anatomic variations may compromise primary stem stability,
58 increase the risk for intraoperative periprosthetic fractures and make the reconstruction of
59 offset and leg length more difficult, which are essential for functional outcome⁴⁻⁶.

60 Few studies have evaluated the three dimensional anatomy in patients with hip dysplasia,
61 reporting substantial differences between dysplastic and healthy femora, particularly with
62 respect to femoral neck version, neck length, rotational deformities and size^{7,8}. These studies
63 have concluded that in femora with higher degree of deformity (Crowe >II, Hartofilakidis B/C)
64 modular or specially designed stems may be necessary to accommodate for the dysplastic
65 abnormalities of joint geometry and endosteal canal shape⁷. As these studies excluded
66 patients with osteoarthritis, there is a paucity of data on potential differences in femoral
67 anatomy between patients with primary hip OA and patients with secondary OA due to mild
68 DDH (Crowe I/II, Hartofilakidis A). This leads to debate as to what the optimal method choice
69 of femoral implant is for such patients in order to achieve secure endosteal fit.

70 Therefore, this study aims to investigate the three dimensional anatomy and shape of the
71 proximal femur, comparing patients with end stage primary hip OA and secondary OA due to
72 mild DDH (Crowe type I/II, Hartofilakidis A), specifically asking:

- 73 1) How do the anatomic parameters for femoral head size, femoral offset, femoral
74 anteversion, neck shaft angle, femoral canal torsion and leg torsion differ between
75 both groups of patients?
76 2) Are there specific patterns of proximal femur canal shapes and rotational alignment of
77 the lower extremities comparing both groups of patients?
78

79 Patients and Methods

80

81 Study Cohort

82 This retrospective radiographic matched-pairs cohort study investigated preoperative
83 computed tomography (CT) scans of a consecutive case series of 84 patients with end stage
84 osteoarthritis due to mild developmental dysplasia of the hip (Crowe type I/II) and 84 matched
85 patients with primary hip osteoarthritis. All patients gave informed consent and the study was
86 approved by the institutional review board (S-272/2009). The study was conducted according
87 to the Helsinki Declaration of 2008.

88 Between June 2008 and December 2009 a total of 597 primary cementless THAs were
89 performed at the Diakonie-Klinikum Stuttgart, Germany. We included all European/White
90 Caucasian consecutive patients in the study cohort with the diagnosis of advanced
91 osteoarthritis of the hip due to developmental dysplasia of the hip (DDH) Crowe type I and II/
92 Hartofilakidis A^{3,9}. In patients with bilateral THA, only the first hip to undergo THA was
93 included in the study cohort. Patients with mild DDH were identified according to the following
94 radiographic criteria evaluated on digital low-centered anteroposterior (AP) radiographs of
95 the pelvis: center-edge angle <25° (CEA), Sharp angle (SA) >42°, acetabular index (AI) <38°¹⁰.
96 Patients with prior hip surgery were not excluded from the study cohort. Eighty-four patients
97 with “mild” developmental dysplasia and end stage secondary OA of the hip were identified.
98 These patients were matched to patients with the diagnosis of primary osteoarthritis without
99 any deformity of the hip according to gender, age at surgery and body-mass index⁷. Patients
100 with secondary osteoarthritis due to trauma, infection, rheumatic disease, osteonecrosis of
101 the femoral head, Legg-Calvé-Perthes disease or slipped capital femoral epiphysis were
102 excluded from the study cohort. In all patients a cementless custom-made titanium femoral
103 component was implanted, which was manufactured on the basis of standardized
104 preoperative CT scans of the affected hip¹¹. Demographic patient data is presented in table 1.

105

106 Table 1: Patient demographics and distribution of study and control group; mean (SD)

Variable	Study group (Secondary OA due to DDH)	Control group (Primary OA)	p value
Number of hips	84	84	-
Gender (F:M)	54 : 30	54 : 30	-
Age at surgery (yrs.)	54.0 (8.2)	55.1 (7.6)	0.385
Body mass index (kg/m ²)	27.5 (6.8)	26.8 (5.5)	0.446

107

108 Radiographic Assessment

109 Preoperative digital low-centered calibrated anteroposterior (AP) radiographs of the pelvis
110 were taken with the patient in the supine position, legs in 15° internal rotation and centered
111 x-ray beam on the symphysis pubis. Radiographic measurements of the CEA, SA and AI,
112 indicating the acetabular inclination, depth and coverage of the femoral head were performed
113 standardized with TraumaCad software (Version 2.2, Voyant Health, Petach-Tikva, Israel)¹².

114 Preoperative CT scans were performed with a Toshiba Aquilion 16 CT scanner (Toshiba, Tokyo,
115 Japan) in all patients and supine position with their legs in neutral rotation as confirmed by

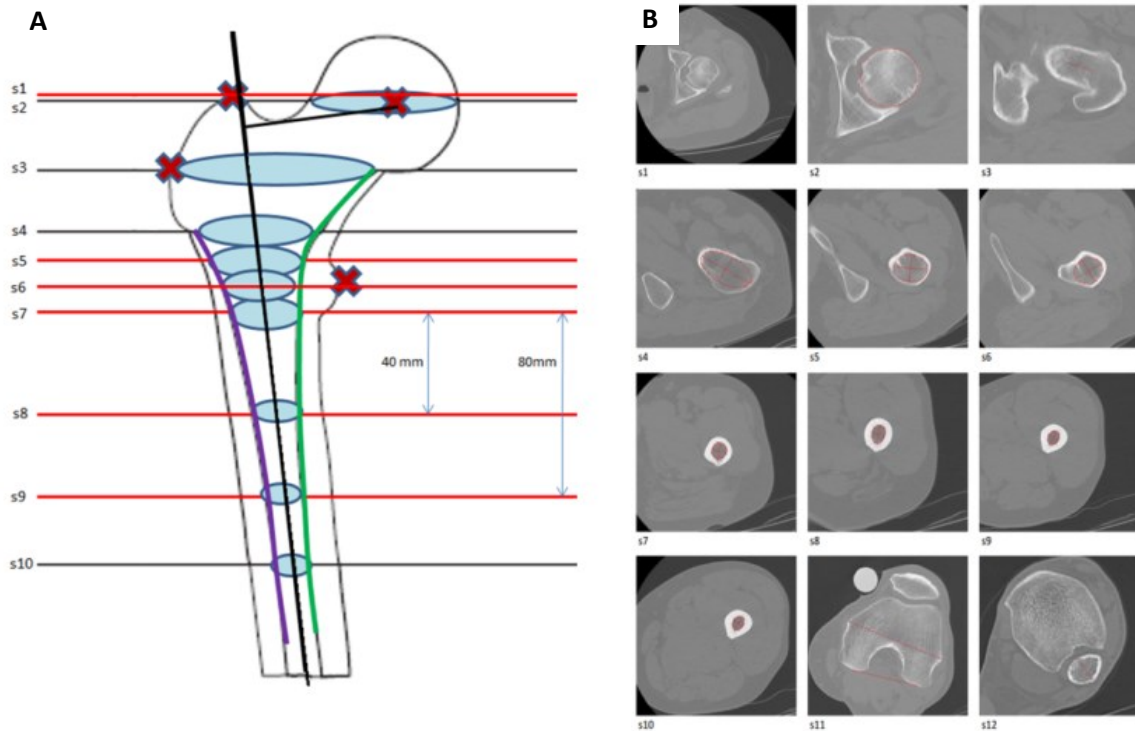
116 scout views. The scans were obtained in three sets: (1) from the cranial aspect of the
117 acetabulum to below the lesser trochanter, (2) from below the lesser trochanter to a point 50
118 mm distal to the femoral isthmus, and (3) four to six slices of the knee (slice spacings 4, 8 and
119 2 mm, gantry tilt 0°, 120 kV, field of view 250 mm)¹¹.

120 Standardized CT measurements were performed using a validated software (Matlab, version
121 7.10; The MathWorks, Natick, Massachusetts)¹¹. The femoral shape was determined by
122 analyzing the manually set “best fit” circle, oval or axis on the following axial CT slices in each
123 patient on twelve standardized levels: most cranial point of the major trochanter, maximum
124 diameter of the femoral head, transition femoral head to neck, centroid of the metaphysis,
125 upper edge of the lesser trochanter, maximum diameter of the lesser trochanter, lower edge
126 of the lesser trochanter, 40 and 80 mm below the lesser trochanter, femoral isthmus, distal
127 femur with the most prominent posterior aspect of the lateral and medial condyles, ankle with
128 medial and lateral malleolus (Figure 1 A & B).

129 From these slices, femoral head diameter, offset, anteversion, shank torsion, leg torsion, NSA
130 and distal femoral canal shape were calculated in the three-dimensional coordinate system of
131 the CT scanner^{8,11}. Femoral offset was defined as the distance between the center of rotation
132 of the femoral head and proximal femoral shaft axis, connecting the mid points of the slices
133 at the center of the metaphysis (s4) and the isthmus of the femur (s10). Femoral anteversion
134 was measured as the angle between the femoral neck axis and the posterior condylar axis.
135 The femoral neck axis was defined using the single-slice method as described by Sugano *et al*⁸
136 and the posterior condylar axis as the line between the most posterior aspect of the lateral
137 and medial condyles (slices 3&11). Shank torsion was measured as the angle between
138 posterior condylar axis of the knee and the axis of the ankle, connecting the most prominent
139 aspect of the medial malleolus and the midpoint of the syndesmotoc lateral tibial groove (slices
140 11&12). Leg torsion was calculated as the sum of femoral anteversion and shank torsion. The
141 neck-shaft angle (NSA) was measured between the femoral neck axis in the coronal plane,
142 defined by the line connecting the center of the femoral head and the centroid of the
143 metaphysis (slices 2&4) and the proximal femoral shaft axis (FSA). In order to analyze the
144 three-dimensional endosteal shape of the proximal femur and endosteal femoral torsion, the
145 area of each ellipse on the levels s4-s10 was measured in cm² (Figure 2). Furthermore, the
146 Canal Flare Index (CFI) was calculated for the slices s4-9 to quantify the endosteal increment
147 of the proximal femur canal size as illustrated by the green and purple line in Figure 1 ($CFI_x =$
148 $area\ slice_x / area\ slice_{10}$; with x ranging from 4 to 9).

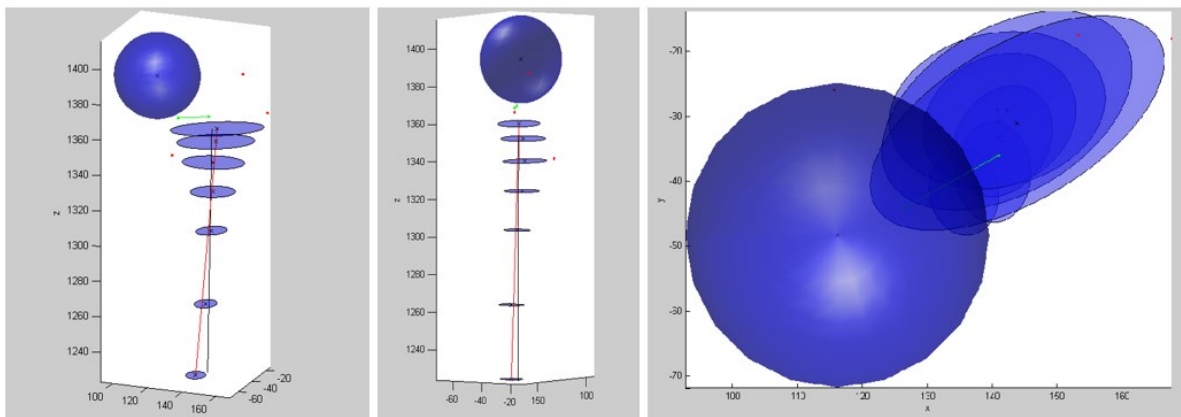
149 Measurements were performed by one reviewer (SH), who was not involved in index surgery.
150 A second analysis was performed by two reviewers (SH, CM) four weeks after initial
151 radiographic analysis for twenty randomly selected data sets in a blinded fashion. Intra- and
152 inter-observer reliabilities were calculated, using single-measure correlation coefficients with
153 a two-way random effects model for absolute agreement¹³.

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Figure 1 A & B illustrating the three-dimensional analysis of the shape of the proximal femoral torsion measuring the rotation and area of each ellipse on the levels s4-s10.



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Figure 2 illustrating the three-dimensional model describing the shape and geometry of the proximal femoral measuring the rotation and area of each ellipse on the levels s4-s10.

163 Statistical analysis

164 Continuous variables were expressed as mean values in millimeters or degrees including
165 standard deviations (SD). Variables were tested for normal distribution using a Kolmogorov-
166 Smirnov test and parametric tests were used. Spearman correlation coefficients (rs) were used
167 to evaluate associations among continuous variables. Both research questions were tested by
168 using parametric tests (t-test). P values of <0.05 were considered significant. Statistical
169 analysis was performed using SPSS software (Version 21.0, IBM SPSS Statistics, Chicago, IL,
170 USA).

171 **Results**

172 The inter-observer and intra-observer correlation coefficients were classified as “good” for
 173 HD, NSA and “very good” for all other radiographic measurements, with coefficients ranging
 174 from 0.79 (95 % CI; 0.53 – 0.91) to 0.99 (95 % CI; 0.97 – 0.99).

175 Comparing both groups, only minor differences were observed. Patients with DDH showed a
 176 slightly larger femoral head diameter, smaller femoral offset and a higher NSA. Analysis by
 177 gender demonstrated a higher NSA in males with DDH compared to primary OA. Females with
 178 DDH had a significantly larger femoral head diameter, smaller femoral offset, a higher NSA
 179 and decreased leg torsion compared to females with primary OA (Table 2).

181 Table 2: Radiographic measurements for the study and control group; mean (SD)

	Study group (Secondary OA due to DDH)	Control group (Primary OA)	p value
Head diameter (all patients)	47.9 (4.5)	45.9 (3.6)	0.002*
men	50.5 (3.4)	49.0 (2.8)	0.072
women	46.4 (4.4)	44.2 (2.7)	0.002*
Femoral Offset (all patients)	38.6 (6.2)	41.8 (4.4)	<0.001*
men	43.3 (5.7)	44.9 (3.9)	0.232
women	36.0 (4.8)	40.1 (3.7)	<0.001*
Neck shaft angle (all patients)	127.7 (6.2)	123.1 (3.5)	<0.001*
men	127.2 (5.1)	122.8 (3.6)	<0.001*
women	127.9 (6.8)	123.2 (3.5)	<0.001*
Femoral antetorsion (all patients)	16.1 (12.6)	14.8 (11.2)	0.447
men	11.3 (9.9)	12.4 (8.4)	0.646
women	18.7 (13.2)	16.1 (12.3)	0.285
Shank torsion (all patients)	-43.7 (9.2)	-43.9 (12.4)	0.892
men	-43.6 (9.9)	-38.5 (14.2)	0.113
women	-43.7 (8.9)	-46.9 (10.2)	0.088
Leg torsion (all patients)	-27.6 (13.1)	-29.2 (14.8)	0.476
men	-32.3 (12.3)	-26.1 (13.1)	0.064
women	-25.0 (12.9)	-30.8 (15.5)	0.037*

182 * indicating significance (p < 0.05)

183
 184 Analyzing the three-dimensional shape of the proximal femur (s4-10), a slightly larger absolute
 185 cross sectional size of the medullary canal was detected on the level of the lesser trochanter
 186 in DDH patients compared to primary OA patients (s6: +0.4 cm²; p=0.047), while the femoral
 187 canal showed a less pronounced narrowing distally (s8: +0.2 cm²; p=0.010; s9: +0.1; p=0.023)
 188 Both groups showed a comparable pattern pattern of endosteal femoral torsion, however a
 189 high inter-individual variability for both groups at the meta-diaphyseal level was observed(S7:
 190 10.3°, SD 43.4 & 5.6°, SD 49.1) (Table 3 & Figure 3 A-C).

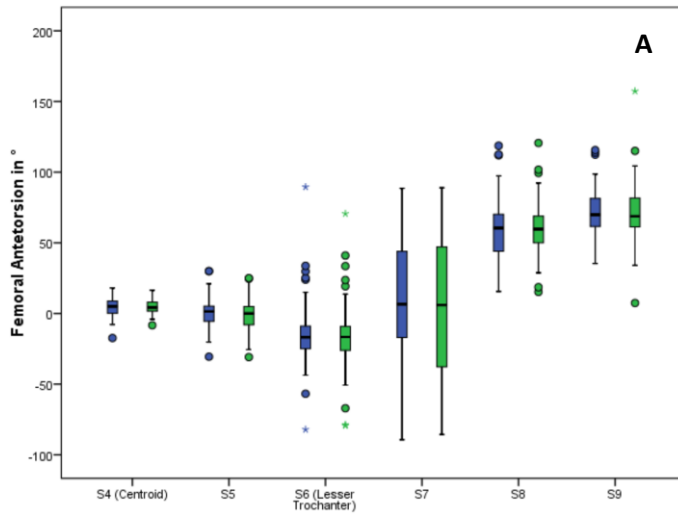
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192 Table 3: Three-dimensional measurements for femoral canal torsion, canal size and canal flare index (CFI) for
 193 each ellipse on the levels s4-s10 of the proximal femur for the study and control group; mean (SD)

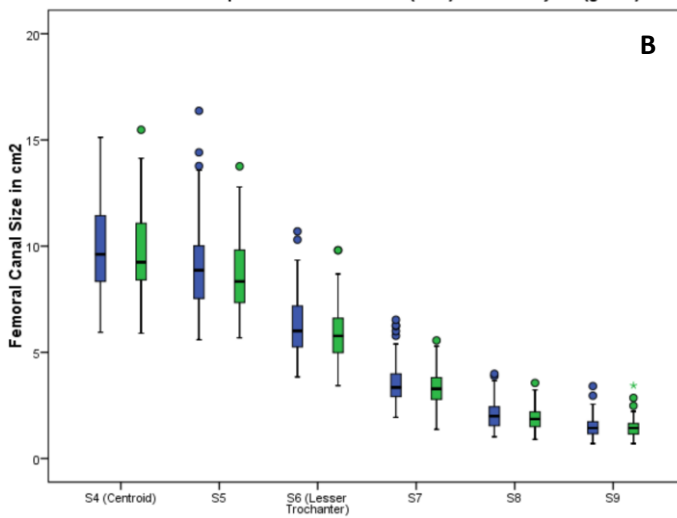
	Study group (Secondary OA due to DDH)	Control group (Primary OA)	p value
Femoral Canal Torsion in °			
S4 (Centroid)	4.5 (36.4)	4.9 (4.5)	0.632
S5	0.6 (9.8)	-1.5 (11.3)	0.208
S6 (Lesser trochanter)	-14.4 (21.2)	-17.5 (21.9)	0.355
S7	10.3 (43.4)	5.6 (49.1)	0.504
S8	59.0 (21.8)	60.1 (18.0)	0.724
S9	71.2 (16.2)	70.7 (19.2)	0.858
Femoral Canal Size in cm²			
S4 (Centroid)	9.9 (2.1)	9.8 (1.9)	0.826
S5	9.1 (2.2)	8.7 (1.7)	0.185
S6 (Lesser trochanter)	6.3 (1.6)	5.9 (1.2)	0.047*
S7	3.5 (1.0)	3.3 (0.8)	0.125
S8	2.1 (0.6)	1.9 (0.4)	0.102
S9	1.5 (0.5)	1.5 (0.5)	0.417
Femoral Canal Flare Index			
S4 (Centroid)	8.7 (2.9)	8.4 (2.6)	0.536
S5	8.0 (2.8)	7.5 (2.3)	0.185
S6 (Lesser trochanter)	5.5 (1.7)	5.0 (1.5)	0.064
S7	3.0 (1.0)	2.8 (0.7)	0.068
S8	1.7 (0.5)	1.6 (0.3)	0.010*
S9	1.3 (0.3)	1.2 (0.1)	0.023*

* indicating significance ($p < 0.05$)

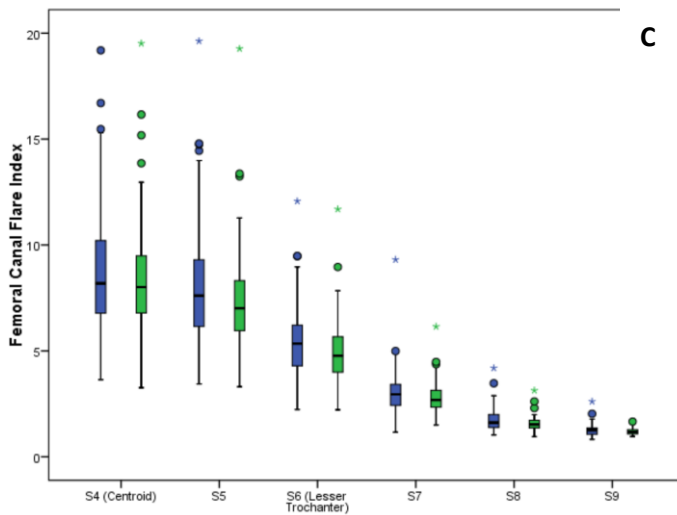
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197 Slices S4-9 in patients with mild DDH (blue) and Primary OA (green)



198 Slices S4-9 in patients with mild DDH (blue) and Primary OA (green)



Slices S4-9 in patients with mild DDH (blue) and Primary OA (green)

199
200 Figure 3: Boxplots illustrating A: Femoral Canal Torsion, B: Femoral Canal Size in cm² and C:
201 Femoral Canal Flare Index for the slices S4-9 in patients with mild DDH (blue) and Primary OA
202 (green).

203 **Discussion**

204 There an ongoing debate in which proportion of patients with advanced OA due to mild DDH
205 standard straight stems or short stems can be safely used to achieve secure endosteal stem
206 fit and joint geometry reconstruction. Therefore, knowledge of potential anatomical
207 differences of the proximal femur in patients with secondary osteoarthritis due to mild DDH
208 is of high clinical relevance, to achieve a high primary press-fit stability and to avoid
209 complications like instability, stem subsidence or intraoperative periprosthetic femoral
210 fractures^{19,20}.

211 Answering our research questions, our study found limited and rather small anatomical
212 differences of the proximal femur and the endosteal canal shape in patients with mild
213 dysplastic compared to those with primary hip osteoarthritis. However, a high inter-subject
214 variability for femoral canal torsion in both groups at the meta-diaphyseal level was observed.

215 There are several limitations of the present study that have to be acknowledged. Due to the
216 retrospective cohort study design, the first and most important limitation is a potential
217 selection bias. We tried to minimize this by including all patients with the diagnosis of
218 advanced secondary OA of the hip due to DDH Crowe type I/II, independent of prior hip
219 surgery from a consecutive series of patients. Our study cannot provide information on
220 anatomical differences of the proximal femur in severe DDH Crowe type III/IV, because these
221 patients were excluded from the present study. Furthermore, the inclusion of DDH patients
222 with prior hip surgery might have biased. However the fact that a substantial number of
223 patients with DDH have a history of prior surgery patients at the time of THA, this can also be
224 interpreted as a strength of the study.

225 Interpreting our results with regard to clinical relevance in context of the literature, the most
226 important limitation is that only two CT-data based studies exist and have investigated the
227 anatomy of the proximal femur in DDH patients compared to matched healthy controls but
228 excluded patients with osteoarthritis^{7,8}. In our study, we could not detect any differences
229 between DDH Crowe type I/II and primary OA patients for femoral version, endosteal isthmus
230 canal width and diameter in the 3D analysis^{7,8}. However, minor differences for the NSA in
231 males, and femoral head diameter, femoral offset, leg torsion and NSA in females were found.
232 Patients with DDH Crowe type I/II had significantly higher NSAs compared to primary OA
233 ($127.7 \pm 6.2^\circ$ vs. $123.1 \pm 3.5^\circ$; $p < 0.001$). The NSA angles for patients with DDH Crowe Type I
234 compare well to recent studies^{7,8}. We presume that the reported difference for the NSA angle
235 between DDH and control group patients may be attributable to the presence of advanced
236 OA, the difference between each study's control group (healthy vs. primary OA patients),
237 distribution of gender and study cohort size. In contrast to our study, two prior studies
238 reported a highly selected study population (only women from an Asian sub-population),
239 comparing the femoral anatomy of patients with all grades of DDH (Crowe I-IV) to a matched
240 healthy cohort without primary OA. The present study consisted of patients from a
241 European/white Caucasian population with 64% females and a matched control group with
242 primary OA. The fact that the present study only included patients with end-stage OA is a
243 particular strength and these differences in study populations should be acknowledged when
244 interpreting the present results.

245 With regard to the implantation of cementless stems, the present data suggest that in women
246 with secondary OA due to DDH Crowe type I/II with a mean femoral offset of 36.0 mm and a
247 neck shaft angle of 127.9° hip anatomy can be restored using standard cementless stems that
248 offer a low offset stem design. As there were no clinically relevant rotational differences in
249 patients with DDH compared to those with primary OA, off the shelf implants appear to be a
250 suitable option for most patients with mild DDH. However, surgeons need to be aware of the
251 high inter-individual variability for femoral canal torsion in both groups of patients at the
252 meta-diaphyseal level and slightly less pronounced narrowing of the distal femoral canal in
253 DDH patients in order to decrease the risk for intraoperative periprosthetic femoral fractures
254 or under-sizing of the femoral stem as this has been reported to be a risk factor for late aseptic
255 loosening^{21,22}. This finding highlights the importance of preoperative planning in all cases to
256 identify potential outliers in advance. Moreover, conical or modular stem designs need to be
257 available as back-up option in case a sufficient fixation or restoration of offset and leg length
258 cannot be achieved, especially when a secure press-fit cannot be obtained or an excessive
259 alteration of the center of rotation is necessary during cup preparation.

260 **Conclusion**

261 The present study demonstrates that gender specific subtle anatomical differences of the
262 proximal femur between patients with end stage primary OA and secondary OA due to Crowe
263 type I/II DDH exist. The reported anatomical variation and the gender specific differences are
264 of clinical relevance for the choice of the femoral implant in cementless primary hip
265 arthroplasty to achieve optimal endosteal stem fit and simultaneous accurate reconstruction
266 of hip geometry. The findings of the present study are of clinical relevance, as they suggest
267 that patients with both primary OA and dysplastic OA with mild dysplasia demonstrate a highly
268 variable joint geometry and proximal femoral canal shape. However, most patients with mild
269 DDH seem appropriate for cementless femoral reconstruction with off the shelf implants when
270 multiple offset and size options are available. Outliers need to be identified during
271 preoperative planning.

272

273 **References**

- 274 **1. Merle C, Waldstein W, Gregory JS, Goodyear SR, Aspden RM, Aldinger PR, Murray DW, Gill**
 275 **HS.** How many different types of femora are there in primary hip osteoarthritis? An active shape
 276 modeling study. *J Orthop Res* 2014;32-3:413-22.
- 277 **2. Pagnano W, Hanssen AD, Lewallen DG, Shaughnessy WJ.** The effect of superior placement of
 278 the acetabular component on the rate of loosening after total hip arthroplasty. *J Bone Joint Surg Am*
 279 *1996;78-7:1004-14.*
- 280 **3. Hartofilakidis G, Stamos K, Karachalios T, Ioannidis TT, Zacharakis N.** Congenital hip disease
 281 in adults. Classification of acetabular deficiencies and operative treatment with acetabuloplasty
 282 combined with total hip arthroplasty. *J Bone Joint Surg Am* 1996;78-5:683-92.
- 283 **4. Innmann MM, Maier MW, Streit MR, Grammatopoulos G, Bruckner T, Gotterbarm T, Merle C.**
 284 Additive Influence of Hip Offset and Leg Length Reconstruction on Postoperative Improvement in
 285 Clinical Outcome After Total Hip Arthroplasty. *J Arthroplasty* 2017.
- 286 **5. Mahmood SS, Mukka SS, Crnalic S, Sayed-Noor AS.** The Influence of Leg Length Discrepancy
 287 after Total Hip Arthroplasty on Function and Quality of Life: A Prospective Cohort Study. *J Arthroplasty*
 288 *2015.*
- 289 **6. Mahmood SS, Mukka SS, Crnalic S, Wretenberg P, Sayed-Noor AS.** Association between
 290 changes in global femoral offset after total hip arthroplasty and function, quality of life, and abductor
 291 muscle strength. *Acta Orthop* 2016;87-1:36-41.
- 292 **7. Noble PC, Kamaric E, Sugano N, Matsubara M, Harada Y, Ohzono K, Paravic V.** Three-
 293 dimensional shape of the dysplastic femur: implications for THR. *Clin Orthop Relat Res* 2003-417:27-
 294 40.
- 295 **8. Sugano N, Noble PC, Kamaric E, Salama JK, Ochi T, Tullos HS.** The morphology of the femur in
 296 developmental dysplasia of the hip. *J Bone Joint Surg Br* 1998;80-4:711-9.
- 297 **9. Crowe JF, Mani VJ, Ranawat CS.** Total hip replacement in congenital dislocation and dysplasia of
 298 the hip. *J Bone Joint Surg Am* 1979;61-1:15-23.
- 299 **10. Tannast M, Hanke MS, Zheng G, Steppacher SD, Siebenrock KA.** What are the radiographic
 300 reference values for acetabular under- and overcoverage? *Clin Orthop Relat Res* 2015;473-4:1234-46.
- 301 **11. Merle C, Grammatopoulos G, Waldstein W, Pegg E, Pandit H, Aldinger PR, Gill HS, Murray**
 302 **DW.** Comparison of native anatomy with recommended safe component orientation in total hip
 303 arthroplasty for primary osteoarthritis. *J Bone Joint Surg Am* 2013;95-22:e172.
- 304 **12. Kumar PG, Kirmani SJ, Humberg H, Kavarthapu V, Li P.** Reproducibility and accuracy of
 305 templating uncemented THA with digital radiographic and digital TraumaCad templating software.
 306 *Orthopedics* 2009;32-11:815.
- 307 **13. Hallgren KA.** Computing Inter-Rater Reliability for Observational Data: An Overview and Tutorial.
 308 *Tutor Quant Methods Psychol* 2012;8-1:23-34.
- 309 **14. Lehil MS, Bozic KJ.** Trends in total hip arthroplasty implant utilization in the United States. *J*
 310 *Arthroplasty* 2014;29-10:1915-8.
- 311 **15. National Joint Registry of E.** National Joint Registry 14th Annual Report 2017.
 312 [http://www.njrreports.org.uk/Portals/0/PDFdownloads/NJR%2014th%20Annual%20Report%202017.p](http://www.njrreports.org.uk/Portals/0/PDFdownloads/NJR%2014th%20Annual%20Report%202017.pdf)
 313 [df](http://www.njrreports.org.uk/Portals/0/PDFdownloads/NJR%2014th%20Annual%20Report%202017.pdf) [Last Access: Dec 27 2017] 2017:43-4.
- 314 **16. Kärrholm J, Lindahl H, Malchau H, Mohaddes M, Rogmark C, Nemes S, Rolfson O.** The
 315 Swedish Hip Arthroplasty Register Annual Report 2016.
 316 [https://registercentrum.blob.core.windows.net/shpr/ir-rsrapport-2016-](https://registercentrum.blob.core.windows.net/shpr/ir-rsrapport-2016-SJirXXUsb.pdf)
 317 [SJirXXUsb.pdf](https://registercentrum.blob.core.windows.net/shpr/ir-rsrapport-2016-SJirXXUsb.pdf) [last access: Dec 27 2017] 2016:37.
- 318 **17. Lopez-Lopez JA, Humphriss RL, Beswick AD, Thom HHZ, Hunt LP, Burston A, Fawsitt CG,**
 319 **Hollingworth W, Higgins JPT, Welton NJ, Blom AW, Marques EMR.** Choice of implant combinations
 320 in total hip replacement: systematic review and network meta-analysis. *BMJ* 2017;359:j4651.
- 321 **18. Akiyama K, Shibuya T.** Influence of femoral bowing on range of motion after total hip arthroplasty.
 322 *Int Orthop* 2017.
- 323 **19. Albrektsson T, Linder L.** A method for short- and long-term in vivo study of the bone-implant
 324 interface. *Clin Orthop Relat Res* 1981-159:269-73.
- 325 **20. Albrektsson T, Branemark PI, Hansson HA, Lindstrom J.** Osseointegrated titanium implants.
 326 Requirements for ensuring a long-lasting, direct bone-to-implant anchorage in man. *Acta Orthop Scand*
 327 *1981;52-2:155-70.*
- 328 **21. Streit MR, Haeussler D, Bruckner T, Proctor T, Innmann MM, Merle C, Gotterbarm T, Weiss S.**
 329 Early Migration Predicts Aseptic Loosening of Cementless Femoral Stems: A Long-term Study. *Clin*
 330 *Orthop Relat Res* 2016;474-7:1697-706.

331 **22. Streit MR, Innmann MM, Merle C, Bruckner T, Aldinger PR, Gotterbarm T.** Long-term (20- to 25-
332 year) Results of an Uncemented Tapered Titanium Femoral Component and Factors Affecting
333 Survivorship. *Clin Orthop Relat Res* 2013;471-10:3262-9.

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