Osteoarthritis and Cartilage 21 (2013) 559–564

Osteoarthritis and Cartilage

Total hip replacement but not clinical osteoarthritis can be predicted by the shape of the hip: a prospective cohort study (CHECK)

R. Agricola †*, M. Reijman †, S.M.A. Bierma-Zeinstra †‡, J.A.N. Verhaar †, H. Weinans †§, J.H. Waarsing †

† Department of Orthopaedics, Erasmus MC University Medical Centre, Rotterdam, the Netherlands
‡ Department of General Practice, Erasmus MC University Medical Centre, Rotterdam, the Netherlands
§ Department of Biomechanical Engineering, Delft University of Technology, Delft, the Netherlands

ARTICLE INFO

Article history:
Received 7 September 2012
Accepted 8 January 2013

Keywords:
Osteoarthritis
Hip
Morphology
Shape
Risk factor

SUMMARY

Objective: To investigate the association between baseline hip shape and both clinical hip osteoarthritis (OA) and total hip replacement (THR) at 5-year follow-up.
Design: Individuals from the Cohort Hip and Cohort Knee (CHECK) study, with early symptomatic OA, having standardized anteroposterior pelvic radiographs at baseline and 5-year follow-up ($n = 723$) were included. Hip shape on the radiographs was assessed using statistical shape modeling (SSM). Hips fulfilling the American College of Rheumatology (ACR) criteria at follow-up were classified as clinical OA. The association between each mode of shape variation and both outcome measures was calculated by Generalized Estimating Equations (GEE).
Results: The included individuals comprised 575 females and 148 males (mean age 55.9 ± 5.2 years). At baseline, 8% fulfilled the ACR criteria, 76% had no radiographic hip OA [Kellgren & Lawrence (K&L) = 0] and 24% had doubtful OA (K&L = 1). At follow-up, 147 hips (10.4%) fulfilled the ACR criteria and 35 hips (2.5%) had received THR. Five shape variants (modes) at baseline associated significantly with THR within 5 years. When combined in one GEE model, these shape variants resulted in a predictive power indicated by an area under the curve of 0.81. No shape variants associated with the presence of clinical OA at follow-up.
Conclusion: The shape of the hip as quantified by an SSM has a good predictive value for THR, whereas variation in shape cannot predict clinical OA. Minor shape variants may be used as a radiographic biomarker to predict the future risk of THR.

Introduction

Osteoarthritis (OA) is often present in multiple joints, but hip OA frequently occurs in isolation, suggesting that local factors are important in its development[1]. There is growing evidence that morphology of the hip joint is one such risk factor. Morphological abnormalities of the hip probably predispose to OA by an altered biomechanical behavior of the hip[2]. This seems plausible for hips with an evident non-optimal shape as seen in (congenital) hip dysplasia, Perthes disease, and slipped capital femoral epiphysis[3,4]. Recently however, the more prevalent cam-type deformities have also been recognized as a causative factor for end-stage OA, with a positive predictive value as high as 52%[5]. Thus, the morphology of the hip appears promising for prediction of hip OA before the actual onset of OA[6,7].

Obvious shape abnormalities are usually quantified by predefined measures such as the center-edge angle for dysplasia and the alpha angle for cam-type deformity. However, subtle morphological variation might also play an important role, but these are difficult to capture by predefined measures.

By using statistical shape modeling (SSM), a sophisticated technique which identifies independent shape variants, it is possible to quantitatively describe the total morphology of the hip[8,9]. An SSM describes all variation in shape that exists in the study population, and is therefore a method which can identify shapes 'at risk' for OA without any assumptions.

Hip OA is usually defined by clinical symptoms such as pain and decreased function, or radiographically by structural alterations as seen on radiographs. However, a poor association between clinical

* Address correspondence and reprint requests to: R. Agricola, Department of Orthopaedics, Erasmus Medical Centre, Room Ee16-18, PO Box 2040, 3000 CA Rotterdam, the Netherlands. Tel: 31-10-7044627; Fax: 31-10-7044690.
E-mail addresses: r.agricola@erasmusmc.nl (R. Agricola), m.reijman@erasmusmc.nl (M. Reijman), s.bierma-zeinstra@erasmusmc.nl (S.M.A. Bierma-Zeinstra), j.verhaar@erasmusmc.nl (J.A.N. Verhaar), h.weinans@erasmusmc.nl (H. Weinans), e.waarsing@erasmusmc.nl (J.H. Waarsing).

1063-4584/$ – see front matter
http://dx.doi.org/10.1016/j.joca.2013.01.005

and radiographic definitions for hip OA has been reported[10]. Previously, it has been shown in cross-sectional and case-control studies that subtle shape variants of the proximal femur associate with radiographic OA[6,9,11–13]. However, it is unknown whether hip shape associates with OA as defined by clinical criteria. Possibly, 'at risk' shapes are different for both definitions, as it has been shown that those shape variants that associated with radiographic hip OA were different from those that associated with pain[13].

We investigated whether minor shape variants of hips without definite radiographic signs of OA at baseline, can be predictive in people with first onset hip or knee pain for the development of hip OA after 5 years, as classified either by the American College of Rheumatology (ACR) criteria for clinical OA or by total hip replacement (THR).

Methods

Study cohort

All individuals were participants of the Cohort Hip and Cohort Knee (CHECK) cohort. CHECK is a nationwide prospective cohort study of 1002 individuals with early symptomatic OA of knee or hip. On entry, all participants had pain or stiffness of knee or hip and were aged 45–65 years; they had not yet consulted their general practitioner (GP) for these symptoms, or the first consultation was within 6 months before entry. Participants with a pathological condition other than early OA that could explain the symptoms were not included in the cohort [for hip: trauma, rheumatoid arthritis, congenital dysplasia, Perthes disease, subluxation, osteochondritis dissecans, fracture, septic arthritis, Kellgren & Lawrence (K&L) grade 4 or THR, previous hip surgery, and individuals having only symptoms of bursitis or tendinitis][13].

Radiographs, serum samples, and clinical examination were obtained from 11 (general and university) hospitals at baseline and at 5-year follow-up. Individuals were recruited either by GPs who were invited to refer eligible persons to one of those centers and by advertisements in local newspapers. The 723 of the 1002 individuals who had anteroposterior (AP) pelvic radiographs of sufficient quality obtained both at baseline and at 5-year follow-up were included [the mean standard deviation (SD) follow-up was 5.06 (0.17) years]. Of the initial 1002 individuals, 137 subjects did not have pelvic radiographs at both baseline and follow-up, of the remaining individuals, 124 subjects had AP hip instead of AP pelvic radiographs at baseline, and 18 subjects did not have radiographs of sufficient quality at baseline to add them to the SSM. Excluded individuals did not differ on any baseline characteristic from the included individuals. The study was approved by the medical ethics committees of all participating centers, and written informed consent was obtained from all participants.

Radiographs and SSM

Weight bearing AP pelvic radiographs were obtained according to a standardized protocol. Feet were positioned such that the medial side of the distal part of the first phalanx touched and a wedge was used to assure 15° internal rotation. The tube to film distance was 120 cm, and the beam was centered on the superior part of the pubic symphysis.

From these radiographs at baseline the shape of the proximal femur and pelvis was outlined using SSM software (ASM tool kit, Manchester University, Manchester, UK)[8]. The shape model was created by a set of 75 landmark points that were positioned along the surface of the bone in the image by three investigators, who were unaware of any clinical or radiographic outcomes. Each point is always positioned on the same anatomical landmark (e.g., most lateral point of greater trochanter, most distal point of ischial bone etc.) of the outline, to allow comparison between the shapes (Fig. 1). Principal component analysis was used to transform the set of points into an SSM, which consists of a number of modes that together describe the total variation in shape in the study population. Shape variants which are correlated are captured in one mode such that each single mode represents independent shape variants. Each mode is quantitatively described as the mean, which corresponds with 0, and the positive or negative deviation from the mean as expressed in the number of SDs[8].

To examine the inter-observer reliability of the modes obtained, the point set was positioned by each investigator in 24 randomly

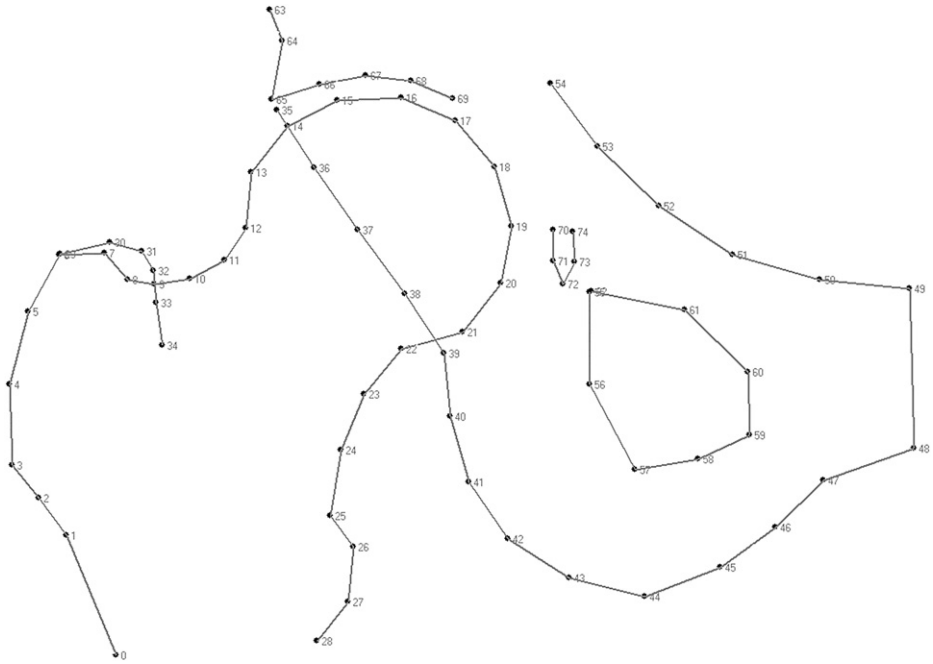

Fig. 1. The statistical shape model which consisted of 75 points.

selected radiographs. Intra-observer reliability was tested in 10 randomly selected radiographs with an interval of 2 months.

We retained enough modes to explain 90% of the variation in hip morphology of the included individuals. Further, all radiographs were scored for radiographic OA according to K&L classification at baseline and 5-year follow-up, independent of the positioning of the SSM point set[14].

Outcome measures

The primary outcome measures were meeting the clinical ACR criteria for hip OA at 5-year follow-up, and hips having received a THR within 5 years[15]. In short, a prerequisite for meeting the ACR criteria is hip pain, either together with internal hip rotation $<15^\circ$ and an erythrocyte sedimentation rate $\leq$45 mm/h, or together with hip internal rotation $\geq 15^\circ$, and pain on internal rotation, and morning stiffness of the hip $\leq$60 min, and age $>$50 years. Secondary outcome measures were two items of the ACR criteria separately; amount of hip pain and decreased internal hip rotation ($<15^\circ$) at 5-year follow-up. The severity of pain in the previous 48 h was assessed per hip using the Visual Analog Scale (VAS). This scale runs from 0 to 10, where 0 equals no pain and 10 very intense pain. Internal hip rotation was measured according to a standardized protocol in sitting position by a goniometer in 90° of flexion, which previously showed satisfactory reliability[16].

Statistical analysis

Reliability of positioning the point set was assessed using intra-class correlation coefficient (ICC). Univariable differences in baseline characteristics between hips that developed OA and normal hips were evaluated by the Mann–Whitney test for continuous variables, by chi-square test for sex, and by Generalized Estimating Equations (GEE) for K&L score.

To analyze whether a mode was predictive for the various outcome measures, regression models using GEE were constructed. All modes were corrected for age, gender, and BMI. In order to account for the many modes (24) tested, an effect was considered significant at a *P*-value smaller than 0.002 ($P = 0.05/24$ modes). From these predictive models, odds ratios (OR) were calculated for each mode to describe the strength for each independent predictive mode. The predictive power of the GEE model including all significant modes was tested by the area under the ROC curve (AUC). All statistical analyses were performed in SPSS version 17.0.

Results

Participants

Of the 723 individuals (1411 hips), 575 were women and 148 were men with a mean age of 55.9 years ($\pm$5.2 years). At baseline, 8% of the included hips fulfilled the ACR criteria whereas 92% did not meet the clinical criteria of hip OA. Radiographically, 76% of the included individuals had no signs of radiographic hip OA (K&L = 0) and 24% had doubtful radiographic hip OA (K&L = 1). Additional baseline characteristics are presented in Table I, stratified for the presence or absence of THR and clinical OA at follow-up.

Outcome measures

A total of 147 (10.4%) hips fulfilled the ACR criteria for clinical OA at 5-year follow-up and 35 hips (2.48%) underwent THR within 5-year follow-up. At follow-up, 23 hips (1.63%) had internal hip rotation less than 15°.

Predictive modes

A total of 24 modes were extracted from the SSM, which together explained 90% of the total variance in shape. We could not identify any mode at baseline, which was predictive for OA at 5-year follow-up ($P < 0.05$) as defined by the ACR criteria. When corrected for age, sex, and BMI, five modes (modes 7, 11, 12, 15, and 22) independent of each other associated significantly with THR within 5 years. The *P*-values, OR, and ICC scores of these modes are summarized in Table II. Modes with a *P*-value less than 0.05, but greater than 0.002 are also presented in Table II and illustrated in Supplemental Fig. 1. Although a mode does not represent only one single aspect of variation in shape, but is a combination of various correlated aspects of variation in shape, we described the most obvious patterns in shape variation that the predictive modes represent (Fig. 2). Combining the five significant modes in the GEE model for calculating the AUC, resulted in a predictive value of 0.81.

Although no modes were found to be significantly predictive for the ACR criteria at follow-up, we found modes, which could predict severity of pain and limited internal rotation at follow-up when analyzed separately. For pain, mode 9 was nearly significantly associated with the VAS scores (*P*-value of 0.007). Higher values of mode 7 were almost significantly predictive for internal rotation $<15^\circ$ (*P*-value of 0.003). The association between all modes and the secondary outcome measures is given in Supplementary Table I.

Discussion

In this prospective study we showed that the shape of the hip at baseline, as quantified using SSM, can predict THR after 5 years but not clinical OA after 5 years as defined by the ACR criteria. By using SSM in individuals that consulted their GP for the first time with knee or hip pain, it was possible to identify shape variants that increased the risk of requiring THR, before the actual radiographic onset of OA. At baseline, especially a broad and short femoral neck, and a retroverted acetabulum together with a non-spherical femoral head were predictive of fast progressing OA. In addition, hip

Table I
Baseline characteristics of the participants stratified by the absence or presence of clinical OA and THR at 5-year follow-up

	Total (1411 hips)	Absence of THR (1376 hips)	Presence of THR (35 hips)	*P*-value absence vs presence of THR	Absence of clinical OA (1264 hips)	Presence of clinical OA (147 hips)	*P*-Value absence vs presence of clinical OA
Age in years: mean (SD)	55.9 (5.20)	55.9 (5.2)	57.7 (4.1)	0.052	56.0 (5.2)	55.1 (5.4)	0.041
Women, No. (%)	1120 (79)	1097 (80)	23 (66)	0.030	1001 (79)	119 (81)	0.67
BMI, kg/m^2: mean (SD)	26.1 (4.1)	26.1 (4.2)	25.7 (4.1)	0.56	26.1 (4.2)	26.3 (3.6)	0.16
Height in cm: mean (SD)	169.9 (8.2)	169.8 (8.2)	170.2 (8.5)	0.88	169.8 (8.2)	170.4 (7.9)	0.42
Weight in kg: mean (SD)	75.3 (13.6)	75.3 (13.7)	74.6 (13.3)	0.99	75.1 (13.7)	76.6 (13.4)	0.19
K&L grade				<0.001			0.006
Grade 0, No (%)	1058 (76)	1048 (77)	10 (29)		964 (77)	94 (65)	
Grade 1, No (%)	331 (24)	306 (23)	25 (71)		280 (23)	51 (35)	

Abbreviation: BMI, body mass index.

Table II
The strength of the relation, reliability, and reproducibility of the modes which significantly associated with THR within 5 years

	Relation with THR at follow-up				Relation with clinical OA				Reliability and reproducibility (ICC)	
Modes	OR (95% CI)	*P*-value	aOR (95% CI)	*P*-value	OR (95% CI)	*P*-value	aOR (95% CI)	*P*-value	Range intra-observer	Inter-observer
Mode 2	**1.78 (1.27–2.47)**	**0.001**	1.73 (1.19–2.51)	0.004	1.00 (0.84–1.19)	0.99	1.03 (0.85–1.25)	0.77	0.96–0.98	0.97
Mode 4	**1.98 (1.32–2.98)**	**0.001**	2.01 (1.27–3.16)	0.003	1.06 (0.87–1.30)	0.55	1.08 (0.88–1.31)	0.47	0.74–0.96	0.81
Mode 5	0.69 (0.50–0.97)	0.033	0.64 (0.45–0.91)	0.012	1.10 (0.91–1.32)	0.33	1.08 (0.90–1.30)	0.41	0.88–0.93	0.82
Mode 6	0.75 (0.54–1.03)	0.072	0.69 (0.49–0.97)	0.034	1.16 (0.96–1.41)	0.12	1.17 (0.97–1.41)	0.11	0.61–0.87	0.43
Mode 7	**0.52 (0.37–0.74)**	**<0.001**	**0.54 (0.38–0.78)**	**0.001**	0.95 (0.78–1.15)	0.60	0.94 (0.77–1.14)	0.52	**0.62–0.87**	**0.76**
Mode 11	**1.71 (1.23–2.36)**	**0.001**	**1.78 (1.28–2.47)**	**0.001**	0.97 (0.83–1.13)	0.68	0.95 (0.82–1.11)	0.54	**0.74–0.92**	**0.76**
Mode 12	**2.01 (1.42–2.85)**	**<0.001**	**2.10 (1.46–3.04)**	**<0.001**	1.03 (0.87–1.22)	0.72	1.05 (0.88–1.25)	0.59	**0.63–0.91**	**0.84**
Mode 13	0.58 (0.40–0.84)	0.004	0.58 (0.40–0.84)	0.003	0.99 (0.84–1.17)	0.91	1.00 (0.84–1.18)	0.98	0.01–0.87	0.83
Mode 15	**1.95 (1.41–2.71)**	**<0.001**	**1.90 (1.39–2.59)**	**<0.001**	1.09 (0.91–1.30)	0.35	1.11 (0.93–1.33)	0.26	**0.59–0.93**	**0.86**
Mode 16	0.58 (0.39–0.85)	0.005	0.63 (0.44–0.91)	0.014	0.99 (0.82–1.20)	0.92	0.97 (0.80–1.18)	0.77	0.42–0.93	0.68
Mode 22	**0.56 (0.40–0.77)**	**<0.001**	**0.59 (0.42–0.81)**	**0.001**	0.88 (0.74–1.04)	0.13	0.88 (0.74–1.05)	0.14	**0.67–0.92**	**0.84**

aOR were adjusted for age, sex, and BMI at baseline. The presented OR represent every increase in one SD.
(a)OR: (adjusted) odds ratio, CI: confidence interval.

shape at baseline might predict hip pain and decreased internal rotation at 5-year follow-up.

This study confirmed the important role of hip shape on development of OA. In previous cross-sectional and case control studies, the importance of hip morphology as a risk factor of radiographic hip OA was already shown[4,8,10]. In these studies, shape variants of the femoral head and femoral neck appeared to pose the highest risk for end-stage OA. Recently, Barr *et al.* retrospectively

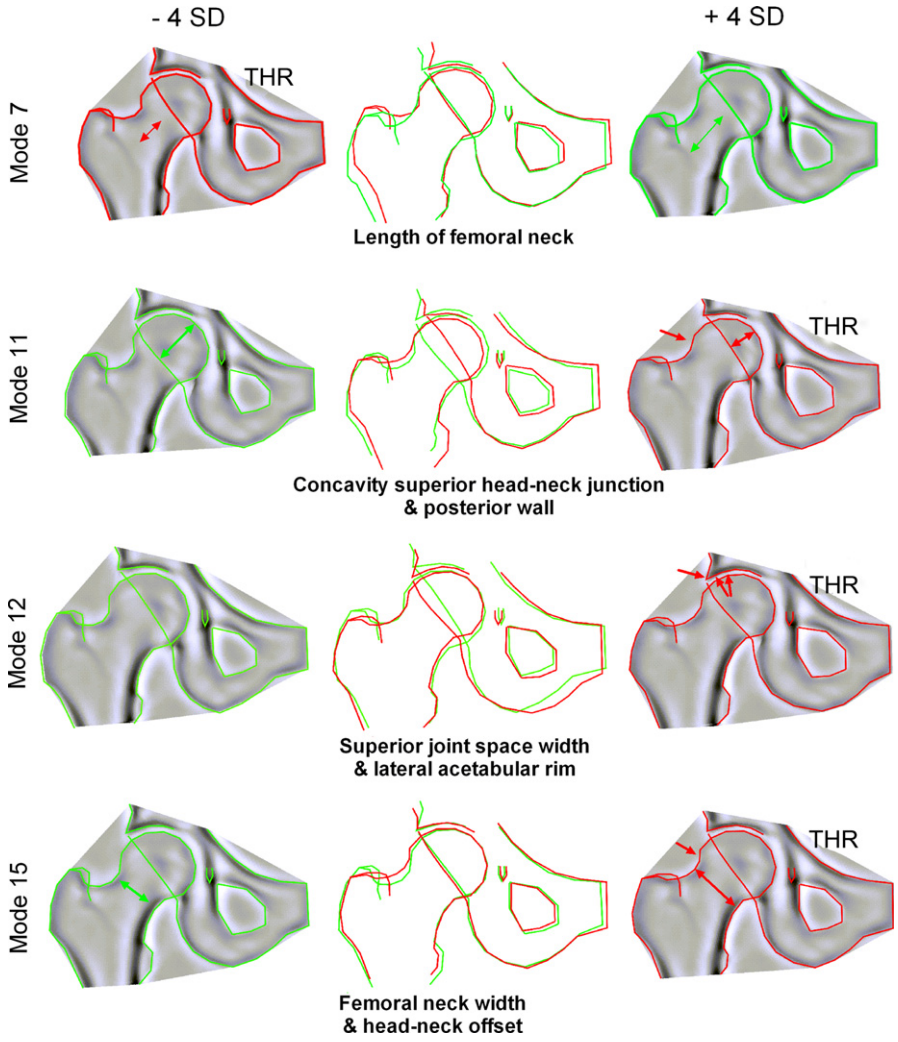

Fig. 2. Modes which were significantly predictive for THR are shown. The shapes corresponding with the −4 and +4 SDs of the mean are illustrated on the left and right side respectively. The middle column shows the overlapping shapes of the −4 and +4 SDs; the extremes which are predictive for THR are shown in red. Mode 7 represents variation in the length of the femoral neck, mode 11 represents variation in the concavity of the superior head–neck junction together with variation of the posterior wall, mode 12 represents variation in the superior joint space width together with the femoral head coverage by the lateral acetabular rim, and mode 15 represents variation in the femoral neck width, together with the resulting variation in head–neck offset.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article)

studied hip morphology of individuals, which presented with hip pain 5 years before, also using THR as an outcome measure[17]. Consistent with their findings, we found a predictive mode which represented femoral head flattening and superior neck broadening (mode 15, Fig. 2). The predictive role of bone shape on clinical OA remains poorly studied, as most other studies defined the presence of OA by radiographic criteria. Only one study by Waarsing *et al.*, using dual-energy X-ray absorptiometry (DXA) images, indicated that subtle shape aspects of the proximal femur not captured by common radiological measures contain information about clinical status[13]. However, in the present study, we found that baseline hip shape could not predict development of clinical OA as determined by the ACR criteria. This might be explained by the fact that in this study, the ACR clinical criteria were not stable in participants with early symptomatic OA. For instance, 103 out of 116 (89%) individuals which fulfilled the ACR criteria at baseline did not have OA anymore at 5-year follow-up when determined by the same criteria. An explanation of the discrepancy between hips fulfilling the ACR criteria at baseline and at follow-up might be the presence or absence of pain at both time points. For example, if an individual met the ACR criteria at baseline, he or she might not necessarily experience hip pain during the follow-up visit because the presence and severity of pain in hip OA is highly variable, especially in the early stage[18]. When analyzing those hips that fulfilled the ACR criteria either at baseline or at follow-up as an outcome measure, no predictive modes were found either. Another explanation of this discrepancy might be the variability in the measured internal hip rotation[19].

Although hip shape was not predictive for OA as determined by the combination of the ACR criteria, it could predict two clinical criteria independently; hip pain and decreased internal rotation. For pain, higher values of mode 9 at baseline associated with more pain at 5-year follow-up. The thicker and shorter femoral neck as represented by higher values of mode 9 shows striking similarities with mode 3 of the study by Waarsing *et al.*, who also found a broad and short femoral neck to be the most significant predictor for VAS pain score[13]. For internal rotation, a higher value of mode 7, which corresponds with a straight and longer femoral neck (Fig. 2), was predictive for internal rotation $<15^\circ$ at 5-year follow-up. Remarkable in this respect is that the opposite of mode 7 (lower values), representing a short femoral neck, was predictive for THR.

As decreased internal rotation is a clinical sign for cam impingement, we assumed a mode describing a non-spherical femoral head to be predictive for decreased internal rotation[20]. However, we did not find such a mode when applying a threshold value of 15°, but for limited internal rotation of 20° or less, mode 4, describing a non-spherical femoral head together with a shallow acetabulum, became highly significant (Supplementary Fig. 1). Interestingly, this mode was a predictor for THR as well (*P*-value of 0.003), but did not remain significant when corrected for multiple testing (*P*-value threshold of 0.002).

A larger statistical shape model might be more powerful for predicting OA[17]. Previous studies using SSM mostly included the proximal femur only, and despite the importance of the interaction between the proximal femur and acetabulum, only two studies additionally included the acetabular roof or a portion of the pelvis[9,13,17,21]. In order to quantify this interaction, we created a shape model of the complete hip joint by including both the proximal femur and the pelvis. The advantage of this model is that it can describe both the position of the proximal femur relative to the pelvis, and it can describe morphological variation of the femur, which is correlated with morphological variation of the pelvis. The importance of the interaction between proximal femur and pelvis for predicting OA was reflected in the significant modes. For example, higher values of mode 11 describe a flat head–neck junction, resulting in a broad femoral neck. Interestingly, the same mode also described a retroverted acetabulum as seen by a posterior wall located medially with respect to the center of the femoral head (see Fig. 2). Acetabular retroversion has previously been described as a risk factor for hip OA, but the evidence is conflicting[22–24]. Our results from the SSM indicate that acetabular retroversion only when combined with a flattened head poses a higher risk for THR.

Strengths of this study are the large number of hips assuring a robust statistical shape model, the prospective design, and the large statistical shape model. Also, the shape of the hips at baseline was not influenced by the arthritic process, as no hips showed definite radiographic OA at baseline. This was confirmed when the analysis was corrected for K&L grade at baseline. The same modes became significant without change in OR, assuring that the found shapes were true OA predisposing shapes. There are however some limitations. The hip joint is a complex three-dimensional structure and variants of shape might not be visible on the AP radiographs. Still, SSM is able to quantify variation in orientation of bone structures from the projection of the radiographs. Another issue concerns variation in orientation of the bones, which will influence the projected shape. Variation in position was minimized by using a standardized protocol. Since remaining positional variation is often dictated by variation in anatomy, the effect on the projected shape cannot be separated from true anatomical shape variants. Still, both effects might contain valuable information with regards to OA development. We aimed to use clinical outcomes of OA, although THR could be considered not to be a pure clinical outcome, but is rather a combination between radiographic signs of OA and symptoms. The significant modes for THR might therefore also be predictive for radiographic OA. However, when analyzing the five predictive THR modes for those hips with radiographic OA as defined by a K&L grade of 2, 3, or 4 at follow-up ($n = 64$), only mode 15 (a broader femoral neck) could predict radiographic OA. Further, THR is a validated and clinically relevant outcome measure[25].

In conclusion, the morphology of the hip at baseline could not predict which hips fulfilled the ACR criteria at 5-year follow-up, probably due to the instability of those criteria in these participants, likely related to variability in pain. However, receiving a THR within 5 years was predicted well by the shape of the hip. In particular, before the presence of definite radiographic OA as defined by the K&L score, shape variants can be identified that pose a higher risk for THR during the 5-year follow-up. Hip morphology might therefore be used as a radiographic biomarker to predict the future risk of THR.

Contributions

RA, MR, SB-Z, JV, HW, and JW contributed to conception and design of this study; RA, MR, SMAB-Z, and JW performed data collection; RA and JW conducted data analysis; RA, MR, SB-Z, JV, HW, and JW contributed to data interpretation and preparation of the manuscript. The final version of the article was approved by all the authors. RA takes responsibility for the integrity of the work as a whole.

Role of the funding source

Grants: The CHECK study was funded by the Dutch Arthritis Association.

The sponsor of the study, the Dutch Arthritis Association, had no role in study design, data collection, data analysis, data interpretation, writing of the report, or decision to submit the paper for publication. The corresponding author had full access to the study data and had final responsibility for the decision to submit for publication.

Conflict of interest

None.

Acknowledgments

The authors thank CF Vermeulen and J van Egmond for their involvement in positioning the landmark points on the radiographs for the SSM, as well as all the participants of the CHECK cohort. CHECK-cohort study is initiated by the Dutch Arthritis Association and performed within; Erasmus Medical Center Rotterdam; Kennemer Gasthuis Haarlem; Leiden University Medical Center; Maastricht University Medical Center; Martini Hospital Groningen/ Allied Health Care Center for Rheum. and Rehabilitation Groningen; Medical Spectrum Twente Enschede/Ziekenhuisgroep Twente Almelo; Reade, formerly Jan van Breemen Institute/VU Medical Center Amsterdam; St. Maartens-kliniek Nijmegen; University Medical Center Utrecht and Wilhelmina Hospital Assen.

Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.joca.2013.01.005.

References

1. Cushnaghan J, Dieppe P. Study of 500 patients with limb joint osteoarthritis. I. Analysis by age, sex, and distribution of symptomatic joint sites. Ann Rheum Dis 1991 Jan;50(1):8–13.
2. Ganz R, Parvizi J, Beck M, Leunig M, Notzli H, Siebenrock KA. Femoroacetabular impingement: a cause for osteoarthritis of the hip. Clin Orthop Relat Res 2003 Dec;(417):112–20.
3. Stulberg SD, Cooperman DR, Wallensten R. The natural history of Legg-Calve-Perthes disease. J Bone Joint Surg Am 1981 Sep;63(7):1095–108.
4. Reijman M, Hazes JM, Pols HA, Koes BW, Bierma-Zeinstra SM. Acetabular dysplasia predicts incident osteoarthritis of the hip: the Rotterdam study. Arthritis Rheum 2005 Mar;52(3):787–93.
5. Agricola R, Heijboer MP, Bierma-Zeinstra SM, Verhaar JA, Weinans H, Waarsing JH. Cam impingement causes osteoarthritis of the hip: a nationwide prospective cohort study (CHECK). Ann Rheum Dis 2012 Jun 23, http://dx.doi.org/10.1136/annrheumdis-2012-201643.
6. Weinans H, Siebelt M, Agricola R, Botter SM, Piscaer TM, Waarsing JH. Pathophysiology of peri-articular bone changes in osteoarthritis. Bone 2012 Aug;51(2):190–6.
7. Baker-LePain JC, Lane NE. Relationship between joint shape and the development of osteoarthritis. Curr Opin Rheumatol 2010 Sep;22(5):538–43.
8. Cootes TF, Taylor CJ, Cooper DH, Graham J. Active shape models – their training and application. Comput Vis Image Und 1995 Jan;61(1):38–59.
9. Gregory JS, Waarsing JH, Day J, Pols HA, Reijman M, Weinans H, *et al*. Early identification of radiographic osteoarthritis of the hip using an active shape model to quantify changes in bone morphometric features: can hip shape tell us anything about the progression of osteoarthritis? Arthritis Rheum 2007 Nov;56(11):3634–43.
10. Kinds MB, Welsing PM, Vignon EP, Bijlsma JW, Viergever MA, Marijnissen AC, *et al*. A systematic review of the association between radiographic and clinical osteoarthritis of hip and knee. Osteoarthritis Cartilage 2011 Jul;19(7):768–78.
11. Doherty M, Courtney P, Doherty S, Jenkins W, Maciewicz RA, Muir K, *et al*. Nonspherical femoral head shape (pistol grip deformity), neck shaft angle, and risk of hip osteoarthritis: a case-control study. Arthritis Rheum 2008 Oct;58(10):3172–82.
12. Nicholls AS, Kiran A, Pollard TC, Hart DJ, Arden CP, Spector T, *et al*. The association between hip morphology parameters and nineteen-year risk of end-stage osteoarthritis of the hip: a nested case-control study. Arthritis Rheum 2011 Nov;63(11):3392–400.
13. Waarsing JH, Rozendaal RM, Verhaar JA, Bierma-Zeinstra SM, Weinans H. A statistical model of shape and density of the proximal femur in relation to radiological and clinical OA of the hip. Osteoarthritis Cartilage 2010 Jun;18(6):787–94.
14. Kellgren JH, Lawrence JS. Radiological assessment of osteo-arthrosis. Ann Rheum Dis 1957 Dec;16(4):494–502.
15. Altman R, Alarcon G, Appelrouth D, Bloch D, Borenstein D, Brandt K, *et al*. The American College of Rheumatology criteria for the classification and reporting of osteoarthritis of the hip. Arthritis Rheum 1991 May;34(5):505–14.
16. Bierma-Zeinstra SM, Bohnen AM, Ramlal R, Ridderikhoff J, Verhaar JA, Prins A. Comparison between two devices for measuring hip joint motions. Clin Rehabil 1998 Dec;12(6):497–505.
17. Barr RJ, Gregory JS, Reid DM, Aspden RM, Yoshida K, Hosie G, *et al*. Predicting OA progression to total hip replacement: can we do better than risk factors alone using active shape modelling as an imaging biomarker? Rheumatology (Oxford) 2012 Mar;51(3):562–70.
18. Verkleij SP, Hoekstra T, Rozendaal RM, Waarsing JH, Koes BW, Luijsterburg PA, *et al*. Defining discriminative pain trajectories in hip osteoarthritis over a 2-year time period. Ann Rheum Dis 2012 Apr 4, http://dx.doi.org/10.1136/annrheumdis-2011-200687.
19. Reichenbach S, Juni P, Nuesch E, Frey F, Ganz R, Leunig M. An examination chair to measure internal rotation of the hip in routine settings: a validation study. Osteoarthritis Cartilage 2010 Mar;18(3):365–71.
20. Wyss TF, Clark JM, Weishaupt D, Notzli HP. Correlation between internal rotation and bony anatomy in the hip. Clin Orthop Relat Res 2007 Jul;460:152–8.
21. Waarsing JH, Kloppenburg M, Slagboom PE, Kroon HM, Houwing-Duistermaat JJ, Weinans H, *et al*. Osteoarthritis susceptibility genes influence the association between hip morphology and osteoarthritis. Arthritis Rheum 2011 May;63(5):1349–54.
22. Giori NJ, Trousdale RT. Acetabular retroversion is associated with osteoarthritis of the hip. Clin Orthop Relat Res 2003 Dec;(417):263–9.
23. Kim WY, Hutchinson CE, Andrew JG, Allen PD. The relationship between acetabular retroversion and osteoarthritis of the hip. J Bone Joint Surg Br 2006 Jun;88(6):727–9.
24. Ezoe M, Naito M, Inoue T. The prevalence of acetabular retroversion among various disorders of the hip. J Bone Joint Surg Am 2006 Feb;88(2):372–9.
25. Dougados M, Gueguen A, Nguyen M, Berdah L, Lequesne M, Mazieres B, *et al*. Requirement for total hip arthroplasty: an outcome measure of hip osteoarthritis? J Rheumatol 1999 Apr;26(4):855–61.