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The contribution of hip geometry to the prediction of hip osteoarthritis

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SUMMARY

Objective: To determine how well measures of hip geometry can predict radiological incident hip osteoarthritis (HOA) compared to well known clinical risk factors.

Design: The study population is part of the Rotterdam Study, a prospective population-based cohort. Baseline pelvic radiographs were used to measure hip geometry by two methods: Statistical Shape Models (SSM) and predefined geometry parameters (PGPs). Incident HOA (Kellgren and Lawrence (KL) $\geq$ 2) was assessed in 688 participants after 6.5 years without radiographic HOA at baseline. The ability to predict HOA was quantified using the area under the Receiver Operating Characteristics (ROC) curve (AUC).

Results: Comparison of the two methods showed that both contain information that is not captured by the other method. At 6.5 years follow-up 132 hips had incident HOA. Five PGPs (Wiberg angle, Neck Width (NW), Pelvic Width (PW), Hip Axis Length (HAL) and Triangular Index (TI)) and two SSM (modes 5 and 9) were significant predictors of HOA ($P = 0.007$). Hip geometry added 7% to the prediction obtained by clinical risk factors (AUC = 0.67 (geometry), 0.66 (gender, age, Body Mass Index (BMI)) and combining both: AUC = 0.73, respectively). Mode 12 (associated with position of the femoral head in acetabulum) and Wiberg angle were predictors of HOA in participants without radiological signs at baseline (KL = 0). Although the strength of the prediction decreased for all variables at a longer follow-up, the contribution of hip geometry was still significant ($P = 0.01$).

Conclusions: Hip geometry has a moderate ability to predict HOA in participants with and without initial signs of osteoarthritis (OA), similar to and largely independent of the predictive value of clinical risk factors.

Introduction

Variations from what it is considered a “normal hip morphology” have been associated with hip osteoarthritis (HOA). The reason might be that certain morphologies of the hip joint result in mechanical loads that increase stress at the articular surface[1–3]. Certain extreme morphologies, such as congenital hip dysplasia can cause hip at a relatively young age[4,5]. For individuals with a less unfavourable morphology of the hips, osteoarthritis (OA) might only develop when other risk factors are present as well and consequently hip OA occurs at older age.

Different approaches to quantify hip geometry exist. Generally, many predefined geometry parameters (PGPs) applicable to radiographs have been described in literature that measure distinct traits of the hip joint (acetabulum, pelvis and proximal femur) in terms of distances, areas or angles. Within the group of PGPs, the Wiberg angle also known as Center Edge Angle (measuring acetabular dysplasia and position of the hip in relation to the acetabulum), femoral neck width (NW) and the triangular index (TI) (measuring asphericity of the femoral head) have been associated to the development and progression of hip OA[6–9]. Other parameters have also been associated to hip OA in small studies without conclusive evidence: neck shaft angle (NSA), hip axis length (HAL), spherical sector (SS), offset and pelvic width (PW)[9–13]. In general all

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these PGPs have been studied in small separate efforts and their contribution to the prediction of incident hip OA is not well known.

Alternatively, the geometry of the hip joint might be quantified in a more general sense using Statistical Shape Models (SSM). SSM offer a relatively new and conceptually different approach that captures the entire shape. Each of the SSM measures, which are called modes, describes a distinct pattern of variation present in a population[14]. SSM analysis has identified some distinct aspects of femoral shape that have been associated to clinical or radiological hip OA[15–17]. However, it is unknown whether these modes capture the same aspects of hip geometry as the predefined geometry measures. In addition, it is unknown if hip geometry can be used to identify subjects that will develop hip OA in the future.

The aim of this study was to compare these two approaches to quantify hip geometry (PGPs and SSM) with respect to predicting OA, and more specifically to determine the contribution of hip geometry to the prediction of incident radiographic hip OA.

Methods

Study population

We used data of the Rotterdam study, a large prospective population-based cohort study among men and women ≥55 years of age. The study design and rationale are described elsewhere in detail[18]. In summary, the objective of the study is to investigate the determinants, incidence and progression of chronic disabling diseases in the elderly. The medical ethics committee of Erasmus Medical Center approved the study and written informed consent was obtained from each participant.

The baseline measurements were conducted between 1,990 and 1,993. In total, 7,983 participants were examined. The present study used a randomly selected sample of 750 subjects from Rotterdam study I (RS-1) among participants with a Kellgren and Lawrence score (KL) at baseline ≤1 in both hips. Participants with hip fracture and participants with low quality radiographs or with artifacts on both hips were not included. Only subjects with completed follow-up were included. This resulted in a total of 1,283 hips from 688 participants.

Clinical evaluation and physical examination

At baseline, medical information and physical examination, including measurements of height and weight were obtained.

Radiographic assessment

Weight-bearing antero-posterior pelvic radiographs were taken with both of the patient's feet positioned in 10° internal rotation and the X-ray beam centred on the umbilicus. Both at baseline and at two follow-up visits (mean time to follow-up: 6.5 and 11 years) hip joints were scored using the KL-grading system, by two independent observers who were trained by an experienced physician in OA and advised by a radiologist[19]. The presence of OA features (osteophytes and joint space narrowing) was evaluated using as reference an atlas of individual radiographic features in OA. The final KL score was a composite score according to the presence of both features: narrowing of the joint space (superior, medial, axial) and superior osteophytes (femoral and/or acetabular) scored from 0 to 3 according to the atlas[20]. Incident hip OA, determined at each follow-up visit separately, was defined as a KL of two or more (Definite narrowing of the joint space and at least possible osteophytes; equivalent to grade 1 in the atlas for each feature) or a total hip replacement (THR). KL was scored for both hip joints. Kappa statistic for KL score was 0.68 (inter-rater reliability).

Statistical Shape Models (SSM)

A set of 67 points were placed by one observer (MC) and used to delineate the contours of proximal femur, pelvis and acetabulum to create the statistical shape model (Fig. 1). Using the freely available Active Shape Model (ASM) toolkit (Cootes *et al.* Manchester, UK), we constructed an SSM of the 1,283 hips [Fig. 1(a)]. The independent modes of variation in hip shape were extracted by Principal Component Analysis. The first 24 modes that were used in this study, explained 90% of the variance in hip shape (Supplementary Fig. 1).

Predefined Geometry Parameters (PGPs)

Using the contour points of the SSM, we automatically calculated 12 geometry parameters (PGPs) that describe different aspects of the femoral head, acetabulum, femoral neck and pelvis: TI, head radius (HR), NSA, head–neck ratio, SS, Wiberg angle, NW, neck length, HAL, Isquiopubic index (IPI), PW and offset [Fig. 1(b) and (c)]. Explanation about methods for calculating PGPs was included in the supplementary data (Supplementary Table I).

Intra and inter-observer agreement for shape modes and geometry parameters

A subset of 46 hips was used to measure within and between observer agreement in shape modes and predefined geometry measurements. Two observers (JW and MCC) placed the 67 points for each hip. Intraclass Correlation Coefficients (ICC) were used to analyse intra and inter-observers agreement.

Supplementary Fig. 2a and b shows the intra- and inter-observers agreement values for each of the modes and predefined geometry parameters, respectively. For the shape modes, we found a mean ICC value of 0.78 for intra- and 0.80 for inter-

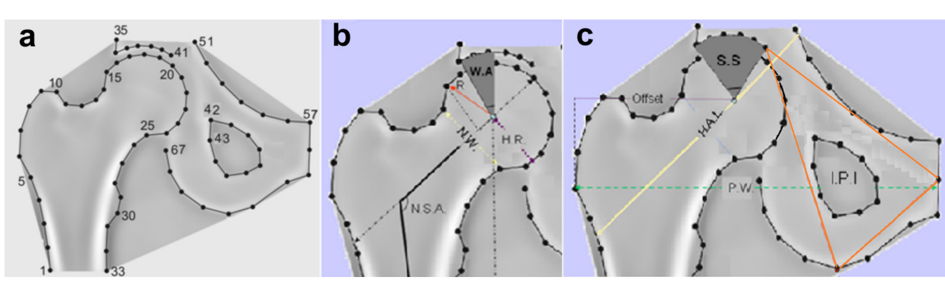

Fig. 1. (a) A set of 67 points were used to delineate the contours of proximal femur, pelvis and acetabulum to create the SSM. (b) and (c) Schematic representation of the predefined geometry parameters used in this study. (b) NW, HR, Wiberg angle (w) "in dark grey", NSA, TI, dotted line (red line shows resulting radius (R)). (c) Shows in dark grey: SS, PW, IPI "orange triangle", HAL and offset.

observer agreement. Some modes had an ICC below 0.7: mode 7, 9, 12 and 13 (Supplementary Fig. 2a).

Mean ICC for the predefined geometry parameters were 0.92 for intra- and 0.86 for Inter-observer agreement. Almost all PGPs had an ICC above 0.7 (Supplementary Fig. 2b). Triangular index had a low inter-observer ICC but a high intra-observer ICC (Supplementary Fig. 2b. 0.54 and 0.90 respectively). For this parameter it is necessary to fix specific points around the femoral head, which apparently was done slightly different by the two independent readers.

Correlation among PGPs and among modes

We studied correlations between all predefined geometry measures using Pearson correlation test statistic (Supplementary Table II, *r*-squared). We observed a high number of significant correlations between the PGPs, most significant were the correlations (r-squared $\times$ 100) between hip axis length and head radius (72%), head radius and NW (69%), TI and NW (67%), NW and PW (55%), NW and hip axis length (54%), SS and Wiberg (52%), offset and hip axis length (45%). We defined moderate correlation as a $R^2 \geq 70\%$ and high correlation as a $R^2 > 80\%$ between two parameters.

Theoretically, all modes should be independent of each other. However, we found some significant correlations between some of the higher (explaining less variance in shape) modes, which could be due to mild non-linear correlation between variation in points.

Variation in geometry explained by modes

We examined how much of the variation in PGPs is captured by the modes. Using linear regression we found that all 24 modes together explain between 37% and 95% of the variation in each predefined geometry parameter (Supplementary Fig. 3a). These percentages are lower for parameters that represented angles or ratios like SS and head/neck ratio (Supplementary Fig. 3a, Neck shaft angle: 64%, Wiberg angle: 60% and TI: 57% and head/neck ratio: 37% respectively).

Variation in modes explained by PGPs

Similarly, we examined how much of the modes were explained by the PGPs (Supplementary Fig. 3b). A model for each mode was constructed, including the PGPs that were significant for that respective mode. Only significant PGPs contributed to explain the variation in modes. In general the PGPs explained only a small part of the total variation in hip shape as represented by SSM. The selected PGPs explained a high proportion of variation only for the two first modes (Supplementary Fig. 3a, R^2: 0.5 and 0.53 respectively). PGPs explained between 30% and 50% of the variation for modes between 4 and 8 and generally less than 30% after mode 9 (Supplementary Fig. 3b). For each mode a different set of geometry parameters was significant.

Statistical analysis

We calculated Pearson's correlation coefficients within the set of modes and within the set of geometry parameters. R^2 from linear regressions was used to estimate the proportion of variance in each mode of the SSM explained by PGPs and the percentage of variation in each PGP explained by the 24 modes of the SSM.

The associations between the modes and the PGPs with incident hip OA (defined as KL $\geq$ 2 or having had a THR at follow-up) were determined using Generalized Estimating Equations (GEE) which takes the correlation between left and right sides into account. The analyses were further adjusted for gender, age, height and BMI. When two PGPs were correlated ($R^2 \geq 0.7$) the most significant was included in the final model. To correct for multiple testing we set for significance a *P*-value of 0.05 divided by the number of parameters tested (Bonferroni adjustment). Testing the modes, we considered *P*-values lower than 0.0021 (=0.05/24) to be significant. Similarly, *P*-values lower than 0.0042 were considered significant for the analysis of the 12 PGPs. All *P*-values lower than 0.05 were reported.

To assess the contribution of PGPs and modes to the prediction of incident hip OA, multivariable GEE models were constructed using the significant PGPs and modes. These models were compared using DeLong's method[21] on the area under the receiver operating characteristics (ROC) curves [area under curve (AUC)]. SPSS v.15 (SPSS Inc., Chicago, IL, USA) and MedCalc v12.2.1.0 (MedCalc Software bvba, Belgium) were used for the statistical analyses.

Results

Baseline characteristics

Baseline characteristics of the study population are described in Table I. The mean age of the population was 65.6 years. At first follow-up, 119 subjects (132 affected hips) had incident hip OA. At second follow-up only 56 new incident cases were registered (comprising 65 new incident hips with OA). Participants with incident OA (KL $\geq$ 2) at follow-up were at baseline older, taller and more often females (Table I). Results for intra- and inter-observer agreements for the assessment of the geometry parameters of both SSM and PGP methods, correlation between variables of each method and percentage of variation explained of the measures of one method by the measures of the other method are presented as Supplementary material.

Statistical shape modes

Mode 5 and mode 9 were significantly associated with incident hip OA after Bonferroni adjustment for multiple testing ($P_{threshold} \leq 0.0021$, Table II). We used the graphic tool of the ASM toolkit to visually interpret the shape variations that each mode represented. Mode 5 appeared to represent internal and external rotation of the femur and corresponding variation in the pelvis, such that the femur is placed slightly in and out of the acetabulum (Fig. 2). Higher risk of incident OA appears to be associated with less covering of the femoral head by the acetabulum (Odds Ratio (OR) per standard deviation in mode 5 (OR): 1.54, and 95% Confidence Interval (CI): 1.30–1.85). Mode 5 was the variable more significantly associated with narrowing of the joint space at follow-up (P = 0.001), positively associated to the Wiberg angle and

Table I
Baseline characteristics of the study subjects

Baseline characteristics	No-OA (n = 569)	OA (n = 119)	P value
Age (years)	65 (0.27)	68 (0.58)	<0.0001
Female (%)	315 (55.4)	84 (70.6)	0.002
Height (cm)	168.6 (0.55)	170.3 (0.20)	0.03
Weight (kg)	74.7 (0.4)	75.9 (0.89)	0.24
BMI (kg/m^2)	26.4 (0.29)	26.7 (0.10)	0.37
KL 0 (%)	280 (49.2%)	13 (10.9%)	<0.0001
KL 1 (%)	289 (50.8%)	106 (89.1%)	

No-OA: subjects without HOA after 6.5 years follow-up. OA = cases with radiological osteoarthritis (KL $\geq$ 2) at first follow-up. N = 688 individuals, 1,283 hips. Presented values are means with Standard Deviation (SD) between brackets for continuous variables and numbers with percentages (%) between brackets for categorical variables.

Table II
Association between hip geometry (shape modes and predefined geometry parameters) and incident hip OA at first follow-up

Parameters	6.5 Years incidence hip OA n. cases = 119 (132 hips)	
	*OR (CI)	*P* value
SSM		
Mode 5	0.65 (0.54–0.77)	<0.0001
Mode 6	0.80 (0.66–0.97)	0.026
Mode 7	1.23 (1.02–1.50)	0.034
Mode 8	1.31 (1.08–1.58)	0.005
Mode 9	1.40 (1.14–1.72)	0.001
Mode 10	1.35 (1.11–1.64)	0.003
Mode 12	1.22 (1.02–1.45)	0.026
PGPs		
Wiberg	0.76 (0.63–0.92)	0.004
Spherical sector	1.26 (1.06–1.50)	0.011
Head radius	1.41 (1.09–1.82)	0.01
Neck width	1.60 (1.24–2.05)	2.45×10^{-4}
Hip axis length	1.49 (1.18–1.90)	0.001
Pelvic width	1.43 (1.16–1.75)	0.001
Triangular index	1.93 (1.54–2.43)	<0.0001

*OR and CI are presented for Standard Deviation (SD) change in each parameter. All modes derived from Statistical Shape Models (SSM) and Predefined Geometry Parameters (PGPs) with $p \leq 0.05$ are presented. Each parameter was analysed in relation with incidence of HOA at first follow-up after adjustment for gender, age and BMI.

negatively to the triangular index ($P < 0.01$, not in table). Visually, mode 9 mainly represents variation in length of the femoral neck, due to variation in the superior neck (Fig. 2). Mode 9 was negatively associated to the Wiberg angle and positively to the triangular index. A higher risk for incident hip OA corresponded to mode 9 values that represent a shorter neck (OR: 1.40, CI: 1.14–1.72).

Mode 12 was the only geometry parameter associated to incident OA in participants that had KL = 0 at baseline (Table IV, OR: 1.69, CI: 1.24–2.30). It appears to represent variation in acetabular version with corresponding rotation of the femur (Fig. 2). Mode 12 was positively associated to the SS, triangular index and PW (more covering of the femoral head and wider pelvis) ($P \leq 0.01$) and to a higher risk for OA in subjects without initial osteoarthritic changes (OR: 1.69, CI: 1.24–2.30).

Predefined geometry parameters

After Bonferroni adjustment, higher values for NW, PW, HAL and TI and lower values for the Wiberg angle corresponded to a higher risk for incident hip OA at first follow-up (Table II, $P < 0.0042$). Adjustment for pelvic rotation: Foramen Obturator Index (FOI) and hip size (scaling factor) did not influence the association with incident hip OA for these parameters. Gender was negatively correlated to scaling factor ($r^2 = -0.56$) and influenced the association of PGPs, especially those “bone size related parameters” and OA.

Prediction models of incident hip OA

Hip geometry alone (PGPs + modes) demonstrated moderate discriminative value for incident hip OA at first follow-up (Table III, AUC: 0.67). This value was similar to the predictive value based on demographic parameters that are known to associate with hip OA (age, gender, height, BMI; AUC: 0.66). Addition of PGPs and modes increased the predictive value of demographic risk factors by 5% and 6% respectively (Table III, $P = 0.014$ for PGPs and $P = 0.002$ for modes). Inclusion of the combination of PGPs and modes did not further increase the predictive power. The inclusion of all modes and PGPs that are associated to incident hip OA at $P < 0.05$ (from Table II), increased the area under the ROC only 2% (N.S.)

Additionally, we analysed the contribution of the selected SSM modes and PGPs to the prediction of the incident cases at second follow-up ($n = 56$) compared also to the demographic risk factors. In general, predictive values decreased at second follow-up for all variables. Prediction given by baseline characteristics was 10% lower. The contribution of the selected PGPs (Wiberg angle, neck and PW, HAL and TI) compared to baseline characteristics was

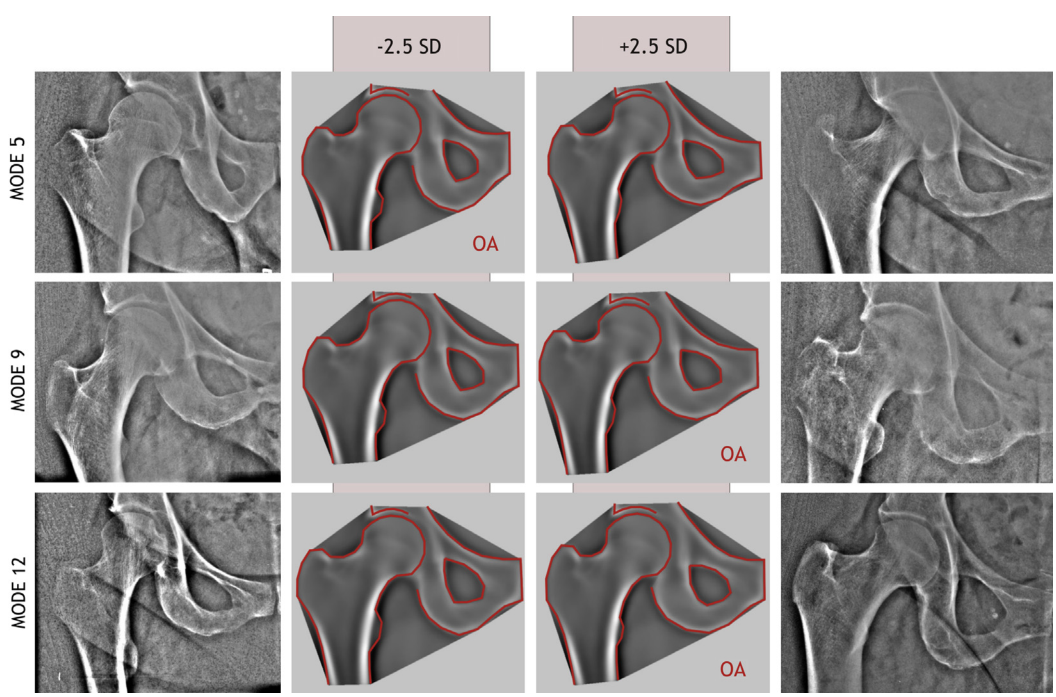

Fig. 2. A visual representation of the extremes of the range of variation of SSM modes 5, 9 and 12 (−2.5 and +2.5 times the population standard deviation). The left and right columns contain true radiographs of subjects with extreme scores on the specific modes.

Table III
Area under ROC curves for models to predict hip OA at 6.5 and 11 years follow-up

Models	First follow-up 6.5 years		Second follow-up 11 years	
	AUC-ROC (95%CI)	*P* value	AUC-ROC (95%CI)	*P* value
Baseline characteristics	0.66 (0.64–0.69)	Ref.	0.56 (0.53–0.59)	Ref.
1) PGPs + modes	0.67 (0.64–0.69)	0.88*	0.66 (0. 63–0.69)	0.06*
2) Base + modes	0.72 (0.67–0.76)	0.002*	0.59 (0.56–0.62)	0.27*
3) Base + PGPs	0.71 (0.68–0.73)	0.014*	0.67 (0.64–0.70)	0.016*
4) Base + PGPs + modes	0.73 (0.71–0.76)	0.007*	0.68 (0.65–0.71)	0.011*
5) Base + KL	0.83 (0.81–0.85)	<0.0001*	0.57 (0.54–0.60)	0.72*
6) Base + KL + PGPs + modes	0.82 (0.80–0.84)	0.42**	0.68 (0.65–0.71)	0.014**

AUC-ROC = Areas under the receiving operator characteristics curve and 95% confidence interval (95% CI). **P* values are given for AUC comparison between baseline characteristics (gender, age, BMI and height) and the following models: 1) Only geometry parameters; PGP: Wiberg, NW, PW, HAL, TI and modes: 5 and 9, 2) Baseline characteristics and modes (5 and 9), 3) Baseline characteristics and the Predefined Geometry Parameters (PGP, 4) Baseline characteristics and geometry: Predefined Geometry Parameters (PGP and modes, 5) Baseline characteristics and KL score. ***P* value for comparison of the full model with model 5 (Baseline characteristics and KL score).

around 11% (Table III, $P = 0.016$ for ROC' curves comparison with baseline characteristics). The two selected SSM modes did not add to the prediction at second follow-up.

Since many of the KL = 1 cases probably have early OA and thus do not represent true incident OA, we stratified the group according to KL at baseline. For the KL = 0 cases, mode 5 and 9 still showed association with incident hip OA, albeit not significant anymore for mode 9 (Table IV). In these subjects, mode 12 also gave a significant association to incident hip OA. Mode 12 contributed around 9% to the prediction of OA given by baseline characteristics in individuals with KL = 0 at baseline (Not in table, ROC: 0.61, CI: 0.54–0.67). Of the PGPs, only Wiberg angle reached significance when hips with KL = 0 were selected (Table IV), though the effects of the other PGPs did not disappear.

Predictions based on hip geometry for OA were of very low specificity for incidence OA using the first follow-up the sensitivity was 0.998 while specificity was very low, around 0.05. Thus, the probability that a positive prediction was a true positive is around 0.104 while the probability that it was a false positive is 0.896 for any particular positive result (+OA). On the other hand, the probability that a negative prediction was a true negative was around 0.995 while the probability that it was a false negative is very low: 0.0047.

Table IV
Incident hip OA at first follow-up and modes based on selection of KL = 0 or KL = 1 at baseline

	KL = 0		KL = 1	
	OR (CI)	*P* value	OR(CI)	*P* value
SSM				
Mode 5	0.43 (0.26–0.70)	6.6×10^{-4}	0.71 (0.58–0.87)	8.0×10^{-4}
Mode 6	1.04 (0.65–1.67)	0.86	0.80 (0.64–1.00)	0.05
Mode 7	1.52 (0.88–2.61)	0.13	1.19 (0.93–1.51)	0.17
Mode 8	0.94 (0.59–1.50)	0.80	1.41 (1.12–1.78)	0.003
Mode 9	1.41 (0.83–2.34)	0.20	1.30 (1.04–1.64)	0.023
Mode 10	1.10 (0.74–1.63)	0.64	1.36 (1.09–1.69)	0.007
Mode 12	1.69 (1.24–2.30)	9.4×10^{-4}	1.01 (0.80–1.28)	0.94
PGPs				
Wiberg	0.44 (0.26–0.73	0.001	0.74 (0.59–0.93)	0.009
Spherical sector	0.93 (0.66–1.32)	0.70	1.33 (1.07–1.64)	0.010
Head radius	1.54 (0.93–2.56)	0.09	1.37 (1.02–1.84)	0.039
Neck width	1.31 (0.76–2.27)	0.33	1.57 (1.06–2.33)	0.025
Hip axis length	1.70 (1.11–2.62)	0.015	1.47 (1.14–1.90)	0.003
Pelvic width	1.42 (0.91–2.21)	0.12	1.26 (0.99–1.60)	0.06
Triangular index	1.26 (0.60–2.62)	0.54	1.69 (1.32–2.17)	<0.0001

Association of SSM = Statistical Shape Modes, PGPs = Predefined Geometry Parameters and incident hip OA at first follow-up was evaluated according with the KL score at baseline (KL = 0 or KL = 1). Values presented are OR and 95% CI per Standard Deviation (SD) change in the respective parameter.

Discussion

In this study we investigated the extent to which hip geometry contributes to the prediction of radiological incident hip OA. In line with previous studies, we showed that distinct aspects of hip shape are clearly associated to incident hip OA. Additionally, we demonstrated that hip geometry can improve the prediction given by clinical risk factors in subjects with or without initial signs of OA (KL = 0/1). Ability of hip shape to predict incident hip OA was similar and slightly better than the common demographic risk factors age, gender, height and BMI. Hip geometry contributes between 8% and 12% to the prediction given by clinical risk factors for participants with or without initial radiographic changes respectively.

Two different approaches were used to quantify hip geometry: predefined measures and a Statistical Shape Model (SSM). In the first approach, we selected specific geometry measures from literature, which have been shown to be related to mechanical load on the hip or to OA. The second hypothesis-free approach used a SSM to find measures of hip shape that represent distinct patterns of correlated aspects of hip geometry within the total variation of hip shape in our cohort. In theory, the SSM represents the most complete information on hip shape. Indeed, the predefined geometry measures could only partly explain the variation in the SSM modes. Vice versa, the modes explained well the measures of size, but could not fully describe those measures that represented angles and ratios. Both methods appear to contain information that is not captured well by the other method; since they describe different aspects of hip geometry we consider that depending of the study subject they might complement each other.

Since the OA process alters the shape of the bones in the affected joint, the question arises whether the geometry aspects associated with OA represent a cause or consequence of OA. The strength of the association for many measures was similar in subjects with KL = 0 at baseline when compared to the overall association, suggesting that these measures might represent shape variants that predate radiological OA. Exceptions were NW, TI, SS and a few modes that showed a lower association with OA and thus might reflect changes in shape related to bone remodelling during early OA. Interestingly, Wiberg angle and mode 12 were predictors of OA in subjects without initial signs of OA (KL = 0), and also contributed to the prediction of incident OA at second follow-up. These measures might thus represent shape aspects that are a causing factor for OA. However, these statements remain only as tentative explanations, since we had low power in the group with KL = 0 to derive conclusions on the differences between the groups (KL = 0/1). On the other hand, for many of the association with hip geometry parameters the relation was stronger or only present for those with KL = 1. This indicates that at least part of the observed associations might actually represent active bone remodelling that it is known to occur at early stages of OA and that might be considered as an important components of the pathogenic process that leads to OA[22]. Alternatively, bone adaptation in OA can be mechano-regulated with structural changes that might occur independent of cartilage degeneration[23].

According with our results, subjects with OA had higher values of bone size-related parameters and gender adjustment increased the strength of the associations between geometry and OA. It was not the case for adjustment of the scaling factor. Association between bone size, geometry and OA might share common etiological factors; It has been recently discussed that genes implicated in bone formation and growth have also a role in OA (pleiotropic effects), what could be part of the explanation.

Prediction of OA decreased for all variables using a longer follow-up. The demographic risk factors for OA, gender, age, height and BMI lost their predictive value for the 11 years follow-up. The predictive power of geometry also decreased to a value between 6% and 16%. The decrease in predictive value of geometry at second follow-up was not exclusive for shapes but, it was more pronounced for them. It might be explained by the sensitivity of shapes to detect early OA-changes, including bone remodelling. On the other hand, larger variations in geometry might cause OA earlier in life as is the case for subjects with severe dysplasia and impingement where OA develops several years earlier than for subjects without these large geometrical differences[24,25].

Many shape aspects that were found to be relevant for hip OA, appear to be related to the congruency between femur and acetabulum determined by asphericity of the femoral head, more specifically the shape of the superior head–neck junction, and the shape of the acetabular socket (acetabular dysplasia). Asphericity of the femoral head results in impingement of the head against the labrum, eventually resulting in damage which might trigger the development of OA. Typical is the anterolateral prominence or cam deformity which is thought to be formed during adolescence as a result of physical activity[26,27]. Also less severe forms of asphericity like a flattening of the head–neck junction (pistol grip deformity) have been associated to OA[9]. These shape aspects are generally measured by the alpha angle or the TI, while other measures like the width of the neck or the head–neck ratio are also influenced. This study further supports these findings, with significant associations of the TI, NW.

Our results corroborate earlier publications on mild dysplasia as a risk factor for hip OA[7], in the current study indicated by the effects of the Wiberg angle and mode 5. Besides, the association of high values of the SS with increased OA-risk supports the idea that deep placement of the femoral head predisposes for OA as in cases of protrusion acetabuli where there is a progressive migration of the femoral head into the pelvic cavity[28,29].

The conclusions of this study extend only to cases of radiographic OA since we did not consider information on clinical OA symptoms. Other limitation derives from the interpretation of geometry from 2D X-ray images that might be simultaneously influenced by true changes in geometry and by positional variation in the bones. Thus, we cannot be certain whether the found association with OA is due to true geometry variants or due to differences in bone position, especially since variation in position of the bones could reflect hip pain and OA-related limitations in internal rotation of the hip. Visual inspection of the modes of the SSM, however subjective, does give some indication of whether positional variation plays a role[30]. In the same manner, interpretation of what modes represent is subjective of nature. Thus the diagnostic value of SSM is rather limited. Further, although reproducibility of the predefined geometry measures was good, we did not validate these measures with the same geometry parameters measured by hand using the original protocols. Finally, in spite of the significant predictive value of geometry for hip OA in general, predictions based on hip geometry were of very low specificity. Clinical utility of hip geometry need to be tested in groups at higher risk, for example in groups at higher genetic risk for OA.

The advantage of the use of predefined geometry measures is that it seems simple and intuitive. However, some measures correlate hampering statistical analysis and interpretation of findings. This drawback is absent when SSM is used, since all modes are theoretically independent, although we found some mild correlations in the higher modes. When we combined the two methods in a predictive model for OA, we observed that the PGPs did not contribute additionally to the prediction of incident hip OA made by the shape modes, indicating that the majority of relevant geometry information for OA is contained in the modes of the SSM.

In conclusion, this study confirms that hip geometry is strongly associated with OA and it is able to predict OA similar to known risk factors. Some variations in hip geometry are associated with early osteoarthritic changes but others might precede radiologic OA contributing to the prediction of incident OA in subjects without radiological evidence of OA.

Author contributions

All authors contributed to the research project's design and conception; data analysis and interpretation; and in the writing, revising and final approval of the manuscript. Castaño Betancourt M, Waarsing JH and Van Meurs JBJ take responsibility for the integrity of the work presented to the Journal.

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Conflict of interest

None of the authors have conflicts of interest related to the manuscript.

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Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.joca.2013.06.012.

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