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Original article

Archetype analysis of the spine-hip relationship identifies distinct spinopelvic profiles

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ABSTRACT

Introduction: The position of the pelvis in the sagittal plane can vary considerably between different functional positions. Adapting the position of the acetabular cup in relation to the alignment between the spine and the hip of each individual, prior to prosthesis placement, can prevent the risk of prosthetic impingement. Taken individually, risk factors for unfavorable spinopelvic kinematics can be difficult to interpret when trying to precisely predict which patients are at risk. Furthermore, the use of classifications or algorithms can be complex, most often associated with limited values and often difficult to apply in current practices of risk assessment.
Hypothesis: We hypothesized that the deconstruction of the data matrix including age and spinopelvic parameters (SPT, LL, PI, LF and PI-LL) correlated with the analysis of spinopelvic kinematics could be used to define an individualized hip-spine relationship.
Material and method: We applied archetypal analysis, which is a probabilistic, data-driven and unsupervised approach, to a complete phenotype cohort of 330 patients before total hip arthroplasty to define the spinopelvic profile of each individual using the spinopelvic parameters without threshold value. For each archetype, we analyzed the spinopelvic kinematics, not implemented in the creation of the archetypes.
Results: An unsupervised learning method revealed seven archetypes with distinct spinopelvic kinematic profiles ranging from −8.9 ° to 13.15 ° (p = 0.0001) from standing to sitting and −5. 35 ° to −10.81 ° (p = 0.0001) from supine to standing. Archetype 1 represents the "ideal" patient (A1); young patients without spinopelvic anomaly and the least at risk of mobility anomaly. Followed by 3 archetypes without sagittal imbalance according to their lumbar lordosis and pelvic incidence, from the highest to the lowest (archetypes 2–4), archetype 4 exposing a greater risk of spinopelvic kinematic anomaly compared to others. Then 2 archetypes with sagittal imbalance: archetype 5, with an immobile pelvis in the horizontal plane from standing to sitting position in anterior tilt and archetype A6, with significant posterior pelvic tilt standing, likely compensating for the imbalance and associated with the greatest anomaly of spinopelvic kinematics. Finally, archetype 7 with the stiffest lumbar spine without sagittal imbalance and significant unfavorable kinematics from standing to sitting.
Conclusion: An archetypal approach to patients before hip replacement can refine diagnostic and prognostic features associated with the hip-spine relationship and reduced heterogeneity, thereby improving spinopelvic characterization. This risk stratification of spinopelvic kinematic abnormalities could make it possible to target patients who require adapted positioning or types of implants before prosthetic surgery.
Level of evidence: IV retrospective study.

1. Introduction

The positioning of prosthetic implants is one of the most important variables for the success of total hip arthroplasty [1]. The systematic orientation at 40 ° inclination and 15 ° anteversion [2] does not avoid the risk of prosthetic impingement [3] or dislocation [4], which is why more personalized techniques allow for better adaptation to the patient's anatomy [5,6]. New techniques taking into account spinopelvic

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kinematics adapt the implant according to the individual relationship of the hip and spine in order to offer a specific orientation to the patient according to pelvic mobility [7,8]. Prosthetic impingement is a common cause of poor functional outcomes [9] including instability, premature wear, unexplained pain [10] and squeaking in the ceramic-on-ceramic bearings [11].

The position of the pelvis can vary significantly in the sagittal plane between functional positions with significant modifications in lumbar lordosis and the sacral slope depending on the positions adopted in daily life [12]. A significant proportion of the population presents an abnormality of spinopelvic kinematics represented either by an anterior rotation of the pelvis of more than 13 ° from the standing to sitting position with a risk of anterior prosthetic impingement [13]; i.e., a posterior rotation of more than 13 ° from a supine to standing position with a risk of posterior impingement.

Numerous risk factors for kinematic abnormalities have been described [14]: excessive pelvic retroversion, defined by a spinopelvic tilt (SPT) ≤ -10 °, sagittal imbalance, pelvic incidence (PI) – lumbar lordosis (LL) ≥ 10 °, lumbar stiffness, defined by lumbar flexion (LF) ≤ 20 °, as well as low PI associated with low LL and an apex at the L5-S1 disc level, or more distal [15]. Furthermore, functional acetabular anteversion seems to be correlated with pelvic incidence [16], as does anatomical acetabular anteversion [17]. Classifications of the hip-spine relationship have emerged to determine patients at risk of mobility abnormalities and define the orientation of the cup or the most suitable type of implant [7,8,18,19]. However, their uses can be complex, most often associated with limited values and difficult to apply in current risk assessment. If individualized biomechanical analysis systems allow a complete analysis with identification of a positioning target [20,21], their use most often requires CT scans and a fairly long time between the examinations and the final analysis.

It appears that traditional statistical models do not seem optimal for analyzing heterogeneity and risk stratification. Methods derived from machine learning have demonstrated improvement in the characterization of pathologies. The archetypal analysis derived from artificial intelligence, never before used in the field of hip surgery, introduced by Cutler and Breiman [22], addresses the heterogeneity of a study population by defining a limited set of extreme or pure phenotypes in the overall data set. This method describes each patient as a composite of the underlying archetypes which allows for probabilistic assessment while retaining the uniqueness of each patient. Our objective was to define spinopelvic profile archetypes using an unsupervised machine learning technique and to analyze the corresponding spinopelvic kinematics for each archetype.

We hypothesized that the deconstruction of the data matrix including age and spinopelvic parameters (SPT, LL, PI, LF and PI-LL), correlated with the analysis of spinopelvic kinematics, could be used to define an individualized hip-spine relationship and identify patients with an increased risk of spinopelvic kinematic abnormalities.

2. Material and method

2.1. Patients

We analyzed a consecutive retrospective cohort of 330 patients from January 2020 to April 2023 suffering from osteoarthritis or aseptic osteonecrosis operated on in the same department and having benefited from the Optimized Positioning System™ (OPS) preoperative planning technique (Corin, Cirencester, UK) for cementless prosthesis placement with a ceramic-on-ceramic or metal-on-polyethylene dual mobility bearing (Meije Dynacup or MobiliT, Corin, Cirencester, UK). Patients were included in the planning protocol randomly according to the limited number of OPS positioning instruments. The informed consent of patients was gained and validated by our research ethics committee to allow the use of patients' health data.

2.2. Spinopelvic parameter

In order to carry out the Optimized Positioning System™ preoperative planning technique, each patient had functional radiographs of the spine in profile: standing, sitting in maximum flexion. In addition to the radiological assessment, a CT scan including the pelvis and both lower limbs was necessary.

The parameters analyzed on the standing lateral radiographs were: LL and SPT. We calculated sagittal imbalance as the difference between PI and LL on standing radiographs. The pelvic incidence was measured on the CT scan and corresponded to the angle created by the intersection of a line drawn from the center of the femoral heads to the middle of the sacral plate and a line perpendicular to the middle of the sacral plate [23].

Lumbar flexion was measured as the difference in lumbar lordosis between standing and sitting positions. Pelvic mobility was measured as the difference between spinopelvic tilt in standing, supine and seated positions.

Each image was analyzed by two independent engineers, as part of the tailor-made programming for patients operated using the Optimized Positioning System™ (Corin, Cirencester, UK).

2.3. Judgment criterion

Our primary outcome measure was pelvic mobility determined by the change in pelvic tilt (ΔSPT) from standing to sitting and from supine to standing. These variables were not implemented during the creation of the unsupervised archetypes and made it possible to secondarily analyze the mobilities associated to each archetype.

2.4. Statistical analysis

To describe continuous variables, we used the mean and standard deviations (SD). For comparisons of percentages and means between groups, the Mann–Whitney, Kruskal–Wallis or Fischer test was used.

For Archetypal Analysis (AA), we first developed models with different numbers of archetypes and chose which one to use as the final model based on the residual sum of squares using the "elbow method". The optimal number of archetypes corresponds to the number of archetypes above with which no difference is observed in the residual sum of squares. The final model of seven archetypes assigned seven scores for each patient based on age and pelvic parameters; one for each archetype, whose scores add up to 1.0. Each patient was assigned to a single archetype based on the highest archetype score. Individual scores provide more detail than the majority cluster assigned to the patient. However, the latter is more practical for summarizing the results and the correlation to the analysis of spinopelvic kinematics. We used principal component analysis (PCA) to visualize the data matrix used to populate the AA.

We used STATA (version 14, Data Analysis and Statistical Software, StataCorp, Texas, USA) and R (version 4.0.0, R Foundation for Statistical Computing, Vienna, Austria) for analyses. Archetypes were assigned and created using the R "archetypes" package (version 4.0.0, R Foundation for Statistical Computing). All statistical analyzes were two-tailed, and probability values less than 0.05 were considered significant. No data was missing.

3. Results

3.1. Characteristics of the study population

The population included 330 patients, 196 women (59.4%) and 134 men (40.9%). The average age was 63.9 ± 10.94 years. The average LL of 58.6 ° ± 12.08 °, the average SPT of 0.04 ° ± 9.31 °, the average pelvic incidence of 55.28 ° ± 11.88 °, the average PI-LL of -2.88 ° ± 11.88 ° and the average LF of 50.93°±13.65 °.

3.2. Identification of archetypes

Based on the overlapping diagnoses and heterogeneity of spinopelvic parameters, we used unsupervised machine learning to identify distinct groups of patients. After integrating clinical characteristics and radiological criteria, seven distinct archetypes emerged (Fig. 1).

Fig. 2 presents the projection of patients in a principal component analysis (PCA) and the corresponding correlation circle according to the seven identified archetypes. The basic population parameters and spinopelvic factors according to the archetypes are presented in Table 1 and Fig. 3.

Archetype 1 (A1) (n = 51, 15.4%) was characterized by the youngest patients, moderate PI, normal LL and LF, low anterior SPT in standing position and no PI-LL imbalance.

Archetype 2 (A2) (n = 29, 8.8%) was characterized by high PI (mean 70 °), very high LL and LF, moderate posterior spinopelvic tilt and no PI-LL imbalance.

Archetype 3 (A3) (n = 91, 27.5%) was characterized by moderate PI, normal LL and LF, low anterior SPT and no PI-LL imbalance.

Archetype 4 (A4) (n = 63, 19.1%) was characterized by low PI, low LL and LF, weakly negative SPT with positive PI-LL ratio.

Archetype 5 (A5) (n = 36, 10.0%) was characterized by normal PI, normal lumbar lordosis and low LF, positive SPT and positive PI-LL ratio.

Archetype 6 (A6) (n = 39, 11.8%) was characterized by normal PI, low LL and LF associated with strongly negative STP and a large PI-LL imbalance.

Archetype 7 (A7) (n = 21, 6.4%) was characterized by normal PI, normal LL, and normal PI-LL ratio, negative SPT, and the lowest LF.

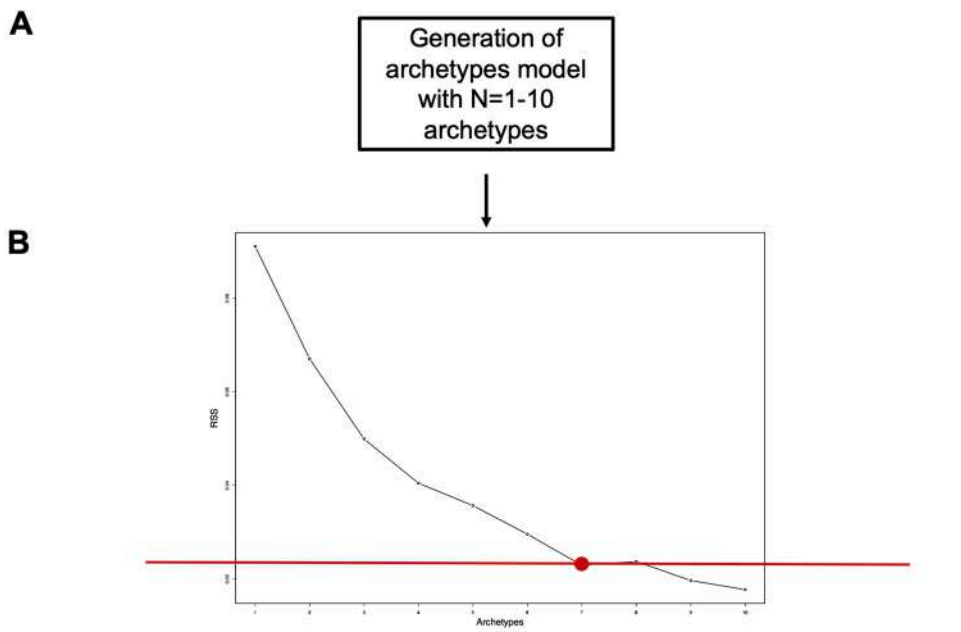
3.3. Archetypes and spinopelvic kinematics

The average mobility from standing to sitting was -8.9 ° ± 20.02 ° for A1, 2.45 ° ± 19.73 ° for A2, 3.12 ° ± 17.19 ° for A3, 6.01 ° ± 17.60 ° for A4, 0.30 ° ± 11.92 ° for A5, 13.15 ° ± 18.53 ° for A6 and 13.1 ° ± 11.14 ° for A7 (p = 0.0001) (Fig. 4).

The average mobility from supine to standing was −3.25 ° ± 3.95 ° for A1, −6.13 ° ± 4.63 ° for A2, −5.35 ° ± 4.75 ° for A3, −6.73 ° ± 3.69 ° for A4, −10.35 ° ± 4.51 ° for A5, −10.81 ° ± 4.33 ° for A6, and −5.71 ° ± 4.24 ° for A7 (p = 0.0001) (Fig. 4).

3.4. Online application for surgeons

We created an online application that can be used by clinicians to determine a patient's archetype and corresponding spinopelvic kinematics (Supplemental Fig. S1, https://taubert.shinyapps.io/Archetype_



		Archetypes scores							Assigned Archetype Cluster
		Score A1	Score A2	Score A3	Score A4	Score A5	Score A6	Score A7	
Patients	#1	0	0	0	0	0	0.999	0	A6
	#2	0	0	0.0	0.28	0.11	0	0.61	A7
	#3	0.90	0	0	0	0	0	0.10	A1
	...	...	...	...	...	...	...	...	...
	#150	0	0	0.02	0.84	0	0	0.14	A4

Fig. 1. Flowchart of the archetypal algorithm.
We generated 10 archetype models using clinical and spinopelvic data from the dataset (Panel A). The "elbow method" was used to identify the point on the graph where adding more clusters did not significantly improve the intra-cluster variability, indicating the optimal number of clusters (Panel B). We selected 7 archetypes, comprising the final archetypal model. All patients were assigned a score for each of the 7 archetypes, and group assignments were based on the highest score for that patient. The table (Panel C) demonstrates the way typical data appears for real patients, and for each patient the proportion of matches with each archetype.
Abbreviations: A, Archetype.

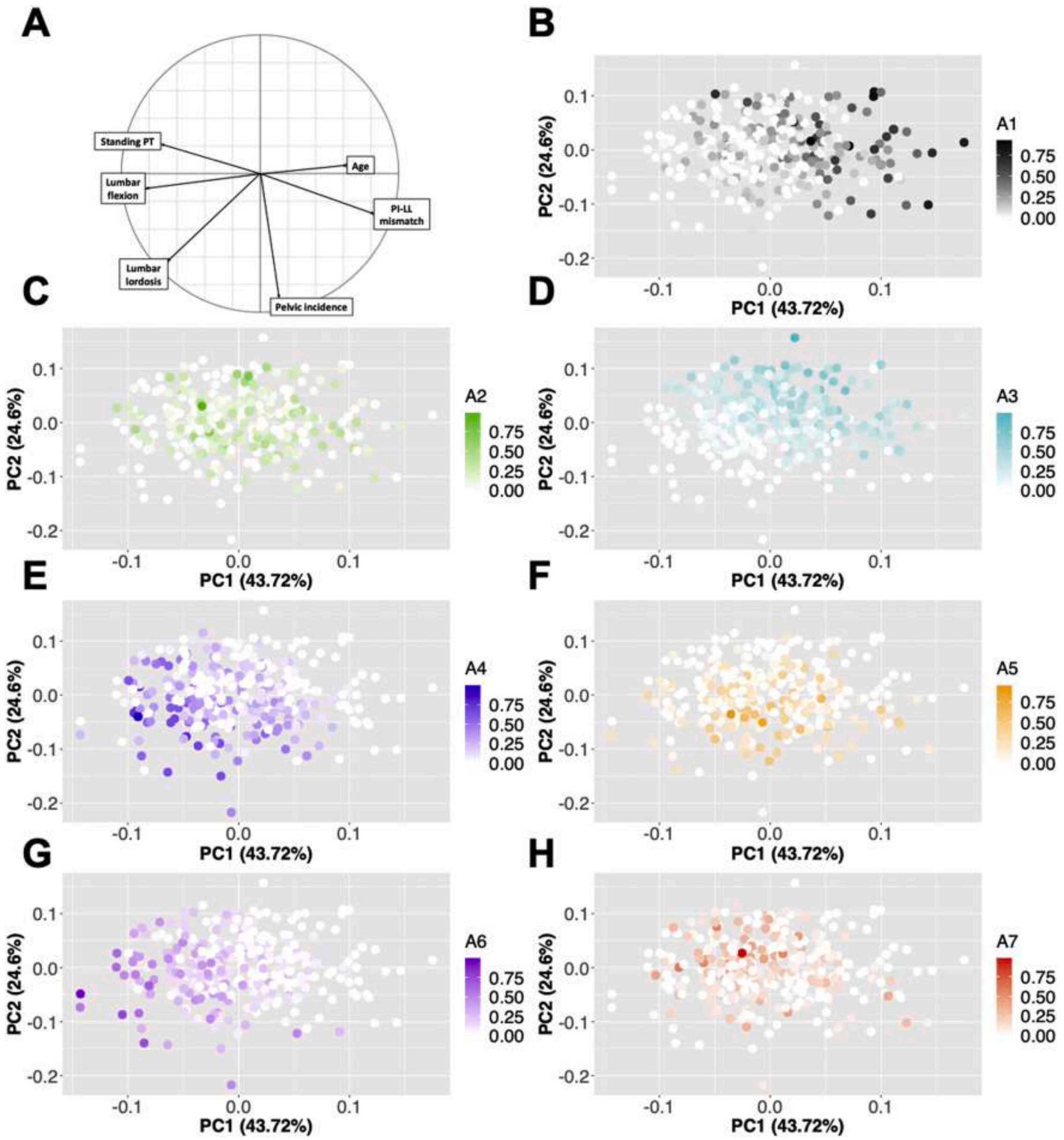


Fig. 2. Correlation circle and principal component analysis graphs of the 330 patients according to the 7 archetypes.
Panel A shows the correlation circle. Each figure (Panels B to H) corresponds to an archetype and its principal component analysis (PCA). The final 7-archetype model assigns 7 scores to each patient using age and spinopelvic data, one for each archetype, with scores totaling 1.0. Each point corresponds to a patient, and its intensity corresponds to the score for a given archetype (score from 0 to 1). Panel B corresponds to the PCA of Archetype 1, Panel C to Archetype 2, Panel D to Archetype 3, Panel E to Archetype 4, Panel F to archetype 5, Panel G to Archetype 6 and Panel H to Archetype 7.
Abbreviations: A, Archetype.

Table 1
Characteristics of patients according to their archetype.

	Archetype 1 n = 51	Archetype 2 n = 29	Archetype 3 n = 91	Archetype 4 n = 63	Archetype 5 n = 36	Archetype 6 n = 39	Archetype 7 n = 21	p value
Basic characteristics								
Age (years), mean (SD)	46.23 (9.58)	66.55 (5.39)	66.51 (7.39)	66.89 (7.06)	67.53 (5.67)	69.28 (6.62)	67.24 (6.62)	**<0.0001**
Male gender, No. (%)	21 (44.44)	13 (44.82)	38 (41.76)	23 (36.51)	13 (36.11)	15 (38.46)	11 (52.38)	**<0.0001**
Spinopelvic parameters								
Pelvic incidence, mean (SD)	55.12 (8.52)	70.41 (9.23)	49.68 (8.18)	45.73 (7.60)	63.78 (7.77)	64.48 (9.52)	56.71 (7.65)	**<0.0001**
Standing spinopelvic tilt, mean (SD)	3.11 (5.51)	−2.41 (5.51)	2.38 (7.01)	−1.87 (7.25)	5.55 (5.59)	−13.38 (5.75)	−0.48 (5.09)	**<0.0001**
Lumbar lordosis, mean (SD)	64.22 (10.02)	70.69 (9.33)	63.21 (7.25)	42.31 (7.80)	59.03 (6.88)	54.56 (8.73)	63.90 (9.55)	**<0.0001**
Lumbar flexion, mean (SD)	63.1 (12.45)	57.20 (6.98)	58.09 (9.57)	45.09 (10.03)	45.11 (8.71)	37.05 (10.16)	35 (8.80)	**<0.0001**
PI-LL, mean (SD)	−7.96 (8.49)	0.52 (10.32)	−13.57 (7.88)	3.4 (8.08)	5.11 (8.06)	10.41 (9.37)	−6.19 (5.72)	**<0.0001**

Abbreviations: SD: standard deviation, PI-LL: pelvic incidence – lumbar lordosis.

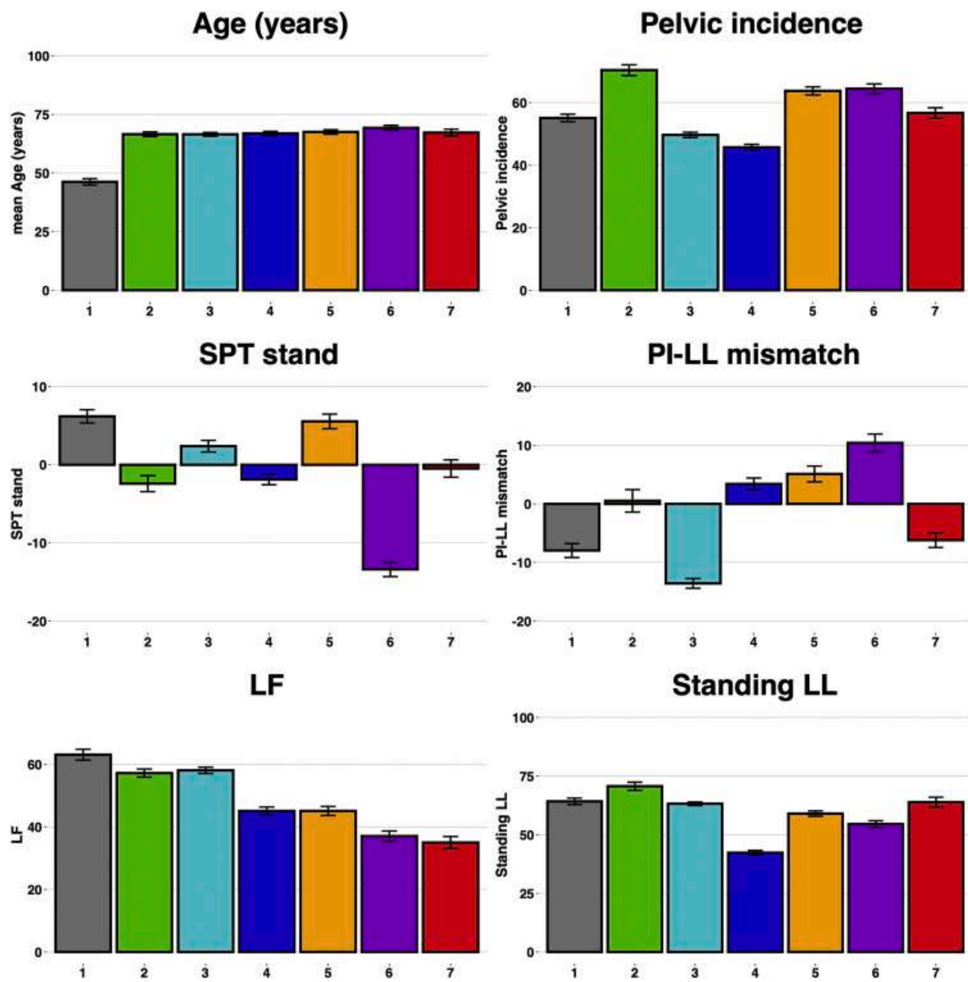


Fig. 3. Basic parameters and spinopelvic parameters according to archetypes.
Abbreviations: PI: pelvic incidence, LL: lumbar lordosis, SPT: spinopelvic tilt, LF: lumbar flexion.

analysis/).

4. Discussion

By applying the unsupervised probabilistic archetypal approach (AA) to the current cohort, we were able to reduce patient heterogeneity and form meaningful groups in terms of age and spinopelvic parameters.

4.1. Analysis of the seven archetypes

These archetypes describe the population before total hip replacement, between patients without sagittal imbalance or lumbar stiffness (A1-4) representing 71% of our population (273 patients) and patients with sagittal imbalance (A5 and A6) or with lumbar stiffness isolated (A7).

Archetype A1 concerns young patients, with normal PI without sagittal imbalance and better lumbar flexion probably explained by the increase in spinal stiffness with age [24].

A2 represents patients with a high pelvic incidence (average 70 °) and therefore a high, ample lordosis, described as "spine users" [7]; A3 a moderate pelvic incidence (mean 49.7 °) associated with moderate lumbar lordosis, the most common type in the asymptomatic population [25]; A4 represents patients with the lowest pelvic incidence (mean 45.7 °), lowest lumbar lordosis and low lumbar flexion without sagittal imbalance (mean PI-LL 3 °), described as "hip users" with flat backs [7].

A5 includes patients with sagittal imbalance and anterior standing spinopelvic tilt and A6 includes patients with sagittal imbalance and, likely compensatory, significant pelvic retroversion [7]. Finally, archetype A7 patients can be described as having a stiff lumbar spine without sagittal imbalance or pelvic retroversion.

The AA therefore found 7 spinopelvic archetypes including an "ideal" patient archetype (A1), young patients without spinopelvic anomaly, representing a sixth of patients, with the least risk of mobility anomaly. Comparing patients without sagittal imbalance, A4 exposes them to a greater risk of spinopelvic kinematic abnormalities [26–28] compared to A2/A3 and corresponds to the distal apices of lumbar lordosis, described as a risk factor [15]. A3, comprising half of these patients without lumbar anomaly, presents a normal pelvic incidence and the lowest PI-LL. This can be explained by the presence of relatively low pelvic incidence but without hypolordosis, described as anteverted Roussouly type 3 [25], and without increased risk of spinopelvic kinematic abnormality [29,30].

In patients with sagittal imbalance, the presence of an anterior tilt of the pelvis in the standing position for A5 is associated with the absence of pelvic mobility when moving to the sitting position, such as an immobile pelvis in the horizontal plane. If there is no pelvic mobility abnormality, it has been described as a risk of anterior prosthetic impingement in the seated position with risk of posterior dislocation and should therefore require additional investigations, particularly if associated with hip hypermobility [10]. Patients in group A6 appear to have the most risk factors for abnormal spinopelvic kinematics [6,14,31]: the most significant sagittal imbalance, the greatest spinopelvic retroversion and low lumbar flexion. Consequently, this archetype presents the most significant anterior rotation of the pelvis from the standing to sitting

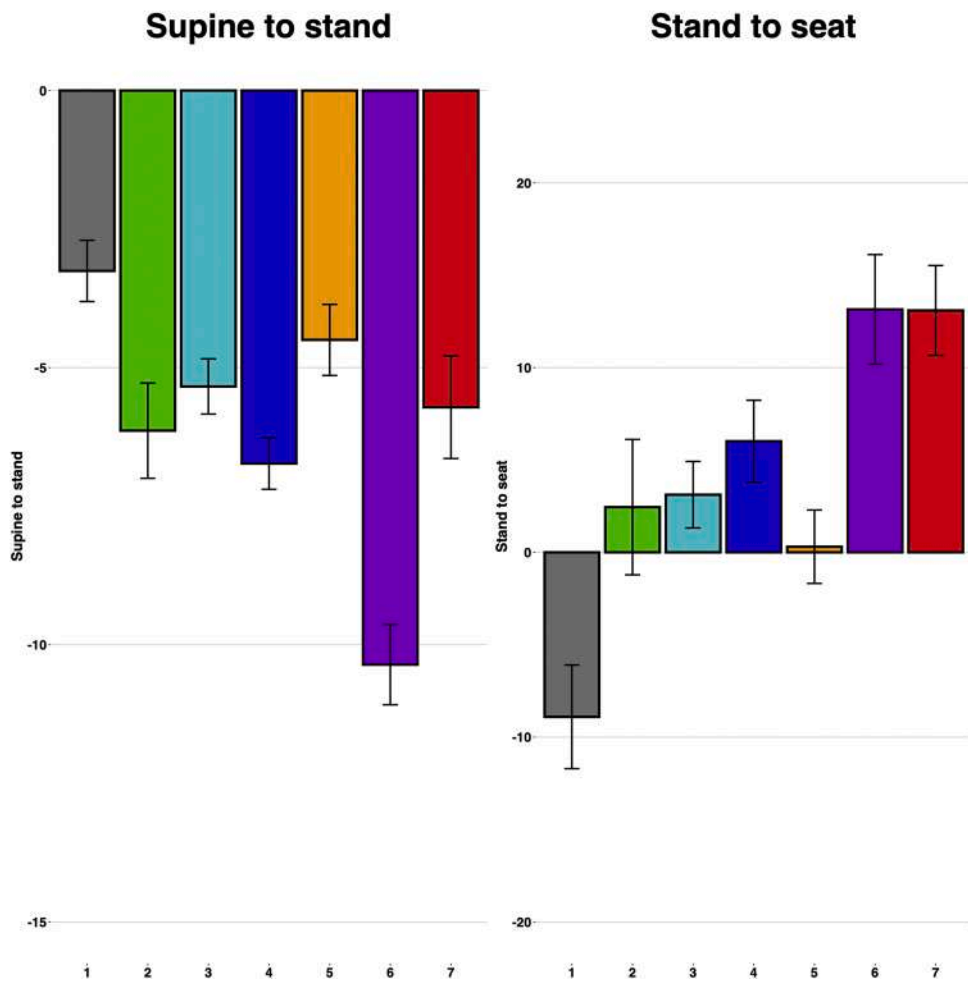


Fig. 4. Standing-sitting mobility and supine-standing mobility according to the archetypes.
Each archetype, from 1 to 7 according to the analysis of spinopelvic mobility from the supine position to standing and standing to flexed sitting, are represented on the abscissa.

position (13.15 °) and in addition the most significant posterior rotation of the pelvis in extension, which may explain the risk of prosthetic impingement simultaneously posterior in extension and anterior in seated position.

The presence of a stiff spine, as in A7, with the lowest lumbar flexion (average of 35 °) represents one of the most unfavorable spinopelvic kinematics from standing to sitting (13.1 °), as already described [8,14], leading to a high risk of anterior impingement but without abnormality from a supine to standing position and therefore probably a lower risk of posterior prosthetic impingement.

The identification of patients associated with archetypes 5–7 could require additional explorations to adapt implant positioning with possible custom-made guides [32] and/or the type of implant used, corresponding to profiles at high-risk of impingement or dislocation as per the Bordeaux classification [7]. In these patients, the use of dual mobility cups has also demonstrated effectiveness in reducing the risk of instability with very good results in terms of survival and safety [33–36].

4.2. *Strengths and limits*

The strength of the present analysis is that it addresses archetypes without preconceived hypotheses, using unsupervised analyzes to obtain distinct phenotypes, not just based on clinicians' beliefs or classifications. The use of archetypes makes it possible to easily assess the risk of abnormal spinopelvic kinematics by using continuous variables without limits, whose threshold values differ depending on the classifications (from −10 to −19 ° for spinopelvic tilt [6,14,37] and from 10 to 20 ° for the PI-LL ratio) [14,31,38]. In addition, the individualized analysis of the different risk factors in the same patient can make their interpretation difficult, emphasizing the utility of this technique, preserving the uniqueness of each patient with individualized scores associated to each archetype (Fig. 1 and Supplementary Fig. S1). An application has also been created to provide surgeons with a simple and reproducible individualized risk prediction tool.

The use of prognostic algorithms is limited by the need to perform multiple radiographs and scans. Using radiographs to analyze pelvic mobility can be error-prone [39]. This new approach could be useful in clinical practice, as it only requires 2 radiographs.

Spinopelvic mobility seems to change after THA [40], and we did not include hip flexion in this analysis because it is a variable which seems to be restored after hip prosthesis placement [6] while possibly playing a role in changes in postoperative pelvic mobility [41]. By using independent archetypes of spinopelvic mobility, it could prove interesting to analyze the sensitivity of these clusters in predicting changes in mobility and the risk of postoperative dislocation [31,42].

Further research using a large prospective cohort of patients remains to be carried out and future trials are necessary to analyze the impingements and dislocations associated with each archetype.

5. Conclusion

An archetypal probabilistic approach based on patient data before prosthesis placement can help refine diagnostic and prognostic features associated with the hip-spine relationship and reduced heterogeneity, thereby improving characterization and risk stratification for kinematic abnormalities spinopelvic in patients. This approach could allow selection of patients requiring adaptation of the position of the cup, or the type of implant.

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None.

Author contributions

TA and OA designed the study. TA interpreted the data. TA and OA performed the analyses. TA wrote the manuscript. AH, GR, MB, GA, and WG participated in data interpretation and critically reviewed the manuscript. All authors critically revised the manuscript for important intellectual content.

Conflicts of interest

TA is a consultant for the companies Corin, Depuy, Amplitude and Lape Medical. WG is a consultant for the companies Corin, Amplitude and Lape Medical. GR is a consultant for the Corin company.

Use of artificial intelligence

We used a system derived from artificial intelligence to create the archetypes (R, version 4.0.0, R Foundation for Statistical Computing, Vienna, Austria). No artificial intelligence system was used for the interpretation of the results or the writing of the article.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.otsr.2024.103944.

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