RESEARCH ARTICLE

Morphological Asymmetry of Pelvic Rings: A Study Based on Three-Dimensional Deviation Analysis

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Abstract

Objective: To evaluate the morphological asymmetry of pelvic rings existing in healthy individuals in terms of three-dimensional (3D) geometric shapes.

Methods: This study was a retrospective self-control study. CT images of healthy pelvises, scanned from Jan 2014 to Jan 2019, were taken from 159 subjects (88 males and 71 females) aged 20 to 59 years (39.1 ± 8.7 years). Digital pelvic ring models were reconstructed from CT images and then flipped over the corresponding sagittal planes to obtain their mirrored models. A 3D deviation analysis of a pelvic ring was conducted between the original model and its mirrored model *via* model registration and quantification of the geometric differences. Next, the pelvic rings were split to the left and right hipbones. The same flipping procedures as done by pelvic rings were performed for left hipbones to obtain their mirrored models. A 3D deviation analysis was also performed between the left and right hip bones. Quantitative variables representing deviation mainly included the average deviation (AD) and the maximum deviation (MD). MDs over 4 mm and 10 mm were deemed as critical levels for evaluating the severity of asymmetry as per Matta's scoring system. The quantitative assessments of the asymmetry covered pelvic rings, bilateral hip bones and the specific anatomic regions of a hip bone.

Results: 157 out of 159 pelvic rings (98.74%) had more than 4 mm of the MD and 27 (16.98%) of them exceeded 10 mm of the MD. The MD of pelvic rings was 1.23 times as high as that for the bilateral hip bones (7.46 mm vs. 6.08 mm, $P < 0.05$). The ADs of pelvic rings and bilateral hip bones were 1.28 mm and 0.94 mm, respectively ($P < 0.05$); 2.27% of the surface points of a pelvic ring had more than 4 mm geometric deviations compared with its mirrored model, while 0.59% ($P < 0.05$) of bilateral hip bones were on the same level of deviation. 119 out of 159 pelvic iliac crests (74.8%) had MDs more than 4 mm, and 15 (9.4%) reached 10 mm or more. Only 15 (9.4%) pelvises presented asymmetric features in the area of obturator foramen where the MDs exceeded 4 mm.

Conclusions: Pelvic asymmetry exists in the general population, but 3D geometric symmetry is present in specific anatomic regions. It implies that restoring the 3D symmetry of specific anatomic regions is more reliable than "restoring the symmetry of pelvic ring" in pelvic ring reduction or pelvic fixation design.

Key words: Deviation analysis; Pelvis; Surgical planning; Three-dimensional models

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Introduction

Pelvic ring injury is growing in incidence among the general population, and severe pelvic fractures are associated with high mortality in elderly people and high morbidity in young people.[1] Surgical techniques are used to rebuild the stabilization of an injured pelvis using a plate/screw fixation structure for pelvic bone reduction.[2,3] Pelvic symmetry is taken for granted as a surgical rule when creating a patient-specific repair model for the injured pelvic bone in terms of the contralateral geometric shape.[4–6] Due to the geometric and anatomic complexity of the pelvis, morphological symmetry might be clinically beneficial in the design and 3D-printing fabrication of a customized fixation plate.[7–9] Furthermore, several studies employed the concept of morphological symmetry of the pelvic ring to evaluate the reduction grade of injured pelvic bones, such as Sagi's inlet/outlet ratio[10] and Lefaivre's cross measurement.[11,12] These two evaluations have higher intra- and interobserver reliability than Matta's scoring system, which is commonly used for the assessment of morphological features of hip bone and joints after surgery.[13,14]

Despite the undoubted advantages of a pelvis being morphologically symmetrical when surgical technologies are applied, pelvic symmetry has not been demonstrated by published studies, and controversy exists in the application of the rule of symmetry in developing surgical protocols or assessing the clinical outcome. Pelvic asymmetry was found *via* measurements from 12 pairs of hip bone specimens.[15] Three-dimensional (3D) studies based on computed tomography (CT) images obtained from 14 normal pelvises revealed the symmetrical features of hip bones.[4] However, small sample sizes and relatively poor statistical characteristics of the sample (such as narrow age range) might not sufficiently conclude symmetrical features of hip bones. Most published studies addressed the geometric symmetry or asymmetry of hip bones. To date, no studies have investigated the symmetrical feature of a pelvic ring, which covers two hip bones and their alignments. Morphological symmetry of a pelvic ring refers to the geometric symmetry of hip bones as well as symmetrical alignments of bilateral hip bones, i.e., asymmetrical orientations of hip bones can cause the pelvic ring asymmetry even though exact geometrical symmetry of bilateral hip bones is present. Furthermore, Boulay *et al.*[15] performed 71 sets of anatomic parameter measurements on left and right hip bones, and found that 15 sets exhibited significant geometric differences between the bilateral hip bones. As a hip bone is composed of the ischium, pubic bone, and iliac bone, Boulay's finding demonstrates varying levels of asymmetry present in different anatomic sites of a hip bone. If any anatomic sites of bilateral hip bones are found to be asymmetric, the pelvic ring is certainly also asymmetric. But if a pelvic ring is asymmetric, it is also meaningful to determine the site of anatomic symmetry to be utilized as a geometric reference for pelvic ring reduction. To date, no studies have clearly confirmed the asymmetric or symmetric features in specific anatomic regions of a pelvic ring.

As performing 3D deviation analyses between original models and their mirrored models are recommended for the study of bone asymmetry,[4,16] the primary aim of this study is to investigate the 3D asymmetry or symmetry of pelvic rings based on appropriate sample size and characteristics. Moreover, a computer-aided 3D deviation analysis offers quantitative measurements and visual display of the morphological differences of pelvic rings as well as hip bones. Secondly, this study also aims to evaluate the effects of the alignment of bilateral hip bones on the asymmetry of a pelvic ring. The third objective of this study is to quantitively assess asymmetry or symmetry of specific anatomic sites of bilateral hip bones.

Methods

This retrospective self-control study was approved by the ethics committee of Foshan Sanshui District People's Hospital, and performed from March 2019 to October 2020.

Inclusion and Exclusion Criteria

Anonymous CT images of 159 healthy pelvises were randomly selected from a pelvis CT database containing 2300 subjects (Table 1).

Inclusion criteria were set as follows: (i) subjects aged from 20 to 59 years with healthy pelvises; (ii) CT scans were performed from Jan 2014 to Jan 2019 using a Discovery CT750 HD (GE Medical Systems, Chicago, IL, USA) CT scanner; (iii) CT images were obtained at a slice thickness of 1.25 mm with 512*512 pixels per slice.

TABLE 1 The baseline characteristics of the samples

			Age group (count)			
Gender	Count	Age (year)	20–29 years	30–39 years	40–49 years	50–59 years
Male	88	38.3 ± 8.0	17	32	29	10
Female	71	40.2 ± 9.5	12	18	30	11
Total	159	39.1 ± 8.7	29	50	59	21
P* value	-	0.172	0.382			

Note: $P < 0.05$ indicates statistical significance. *Male vs. Female

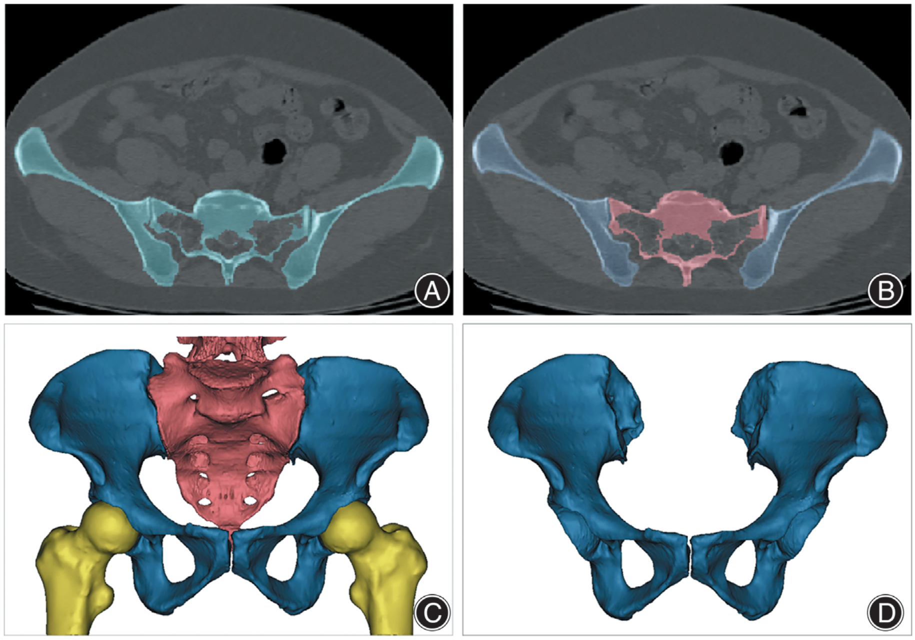

FIGURE 1 Three-dimensional reconstruction of a pelvic ring model: (A) the pelvic mask segmented from pelvic CT images; (B) the mask of bilateral hip bones and sacrum; (C) a three-dimensional model of bilateral bones and sacrum; (D) a pelvic ring model without covering the sacrum model.

Exclusion criteria were set as follows: (i) a large number of noise pixels or bad quality was present in a pelvic image; (ii) one or more slices of pelvic images were missed; (iii) the pelvis was with bone defects or malformations caused by hip dysplasia, osteoarthritis, osteohyperplasia, previous bone trauma, or tumor; (iv) the sacroiliac joint was partially fused due to bone hyperplasia which might lead to an inaccurate segmentation; (v) tumor or severe deformity was in the lower lumbar spine such as scoliosis or transitional vertebra; (vi) tumors, defects, or malformations were present on proximal femur.

Reconstruction of 3D Digital Pelvic Ring Model

CT images of 159 pelvises were imported into Mimics (Materialize, Leuven, Belgium) software using DICOM files. Image segmentation was performed using the bone automatically segmentation tool and split mask tool on Mimics.[17] Mimics then reconstructed 3D models of pelvises and saved them into STL file format for export into Geomagic Studio software (3D Systems, Rock Hill, SC, USA) for further smoothing those models for digital analysis. In this study, the pelvic ring model referred to two hip bones without covering the sacrum model since the morphological analysis targeted the symmetrical features of the alignment of hip bones (Figure 1).

Investigating the Asymmetry of a Pelvic Ring

The asymmetrical analysis of a pelvic ring was performed by quantitative comparison between original geometry of the pelvic ring and its flipped model. A pelvic model was flipped over the sagittal plane to obtain the geometric reflection using Geomagic's mirror function. Note that geometry of a mirrored model did not change whatever plane was applied as the axial plane of symmetry.[18] The two models were registered using an iterative least-square algorithm[4,16] (Figure 2). The registered models were saved into STL format and exported into 3-matics (Materialize) for conducting the 3D deviation analysis.

Investigating Morphological Differences of Right and Left Hip Bones

A pelvic ring model was firstly split into right and left hip bones. The left hip bone was flipped over the sagittal plane to obtain the geometry reflection, as shown in Figure 2. A 3D global registration between the mirrored left hip bone and original right hip bone was conducted to minimize the geometrical differences. A further assessment of 3D surface deviation was the same as for the pelvic ring mentioned above.

Outcome Measures

Results of 3D deviation analysis include quantitative variables and deviation color maps (DCMs). Quantitative variables include: the maximum 3D deviation (MD), the average 3D deviation (AD), the root mean square (RMS), the percentage of points over 2 mm deviation (PD > 2 mm), and the percentage of points over 4 mm deviation (PD > 4 mm).

Maximum 3D Deviation (MD)

The 3D deviation of a point is defined as the shortest distance from the test point to a reference surface point set.[19] For a model X and model Y, if all points on the surface of model X and Y are defined as $\{x_i\}_{i=1}^{n}$ and $\left\{y_j\right\}_{j=1}^{k}$, the 3D deviation of a point x on the model X to model Y is defined as:

$$d(x, \mathrm{Y}) = \min_{y\epsilon \mathrm{Y}} \|x - y\|_2 \tag{1}$$

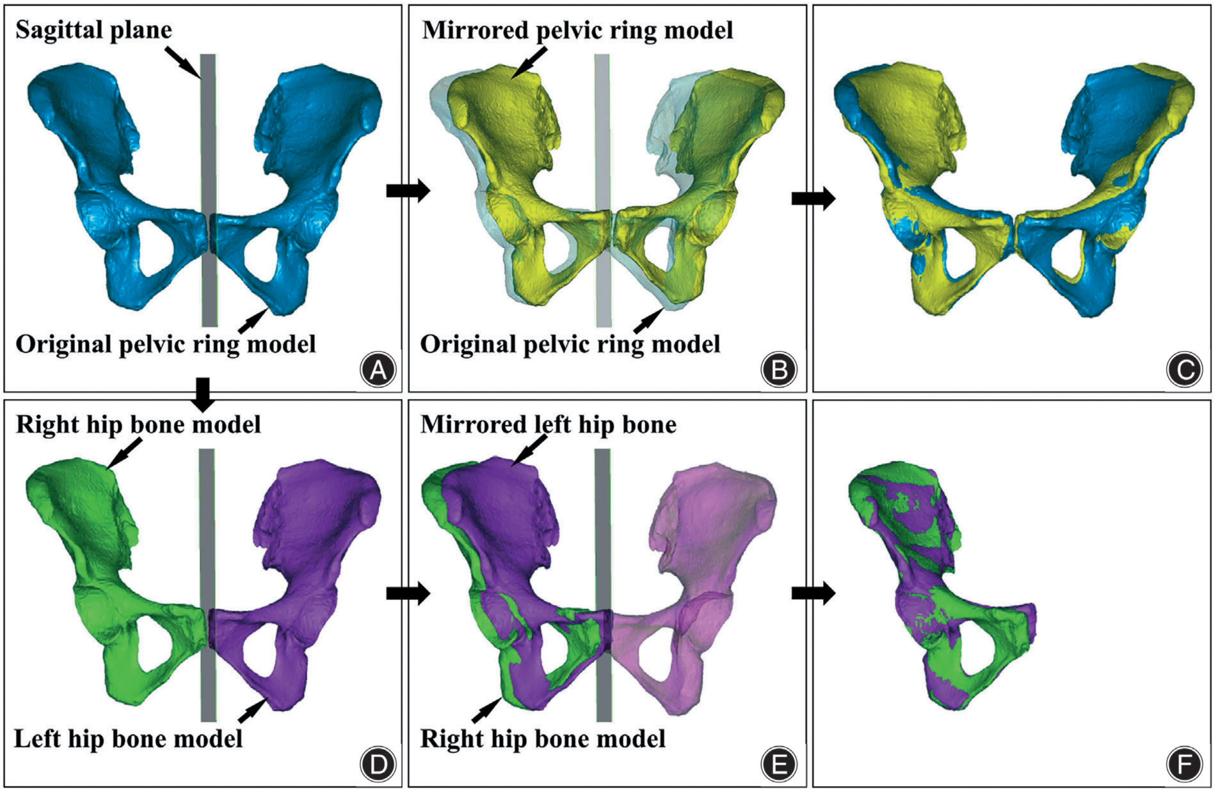

FIGURE 2 The deviation analysis of a pelvic ring (A, B, C) and bilateral hip bones (D, E, F): (A) the original model of a pelvic ring model and its sagittal plane; (B) flipping a pelvic ring over the sagittal plane to obtain the mirrored pelvic ring; (C) overlapping the mirrored model of a pelvic ring (yellow) and its original model (blue) using registration algorithms; (D) the right hip bone model (green) and left hip bone model (purple) split from the pelvic ring model shown in (A); (E) flipping the model of the left hip bone over the sagittal plane; (F) overlapping the mirrored model and the original model of the right hip bone using registration algorithm for 3D deviation analysis.

The 3D deviation of point y on the model Y to model X is defined as:

$$d(y, \mathrm{X}) = \min_{x e \mathrm{X}} \|y - x\|_2 \tag{2}$$

The MD is defined as the maximum deviation among the 3D deviations of all points, which is defined as the Hausdorff Distance.[19,20] For models X and Y, the MD is defined as[1920]:

$$\mathrm{MD}(\mathrm{X},\mathrm{Y}) = \max\left[\max_{x \in \mathrm{X}} d(x,\mathrm{Y}), \max_{y \in \mathrm{Y}} d(y,\mathrm{X})\right] \tag{3}$$

In this study, the MD represents one of the quantities of geometric differences between original and mirrored pelvic rings, or right and left hip bones.

Average 3D Deviation (AD)

The AD is the average value of 3D deviations of all points on a model compared to another model. In this study, AD is defined as[4,19]:

$$\mathrm{AD}(\mathrm{X},\mathrm{Y}) = \frac{1}{n+k}\left[\sum_{i=1}^{n} d(x_i, Y) + \sum_{j=1}^{k} d\left(y_j, X\right)\right] \tag{4}$$

In this study, the points are automatically sampled, and the ADs are calculated *via* 3-matic software (Materialize, Leuven, Belgium). The AD in this study represents the overall quantitative level of geometric differences between original and corresponding mirrored pelvic rings, or right and left hip bones. The greater the AD value, the higher the level of asymmetry.

Root Mean Square (RMS)

The RMS is the root mean square value defined as[4]:

$$\mathrm{RMS}(\mathrm{X},\mathrm{Y}) = \sqrt{\frac{1}{n+k}\left[\sum_{i=1}^{n} d^2(x_i, Y) + \sum_{j=1}^{k} d^2\left(y_j, X\right)\right]} \tag{5}$$

The RMS value in this study is another variable to evaluate the overall level of geometric difference of right and left hip

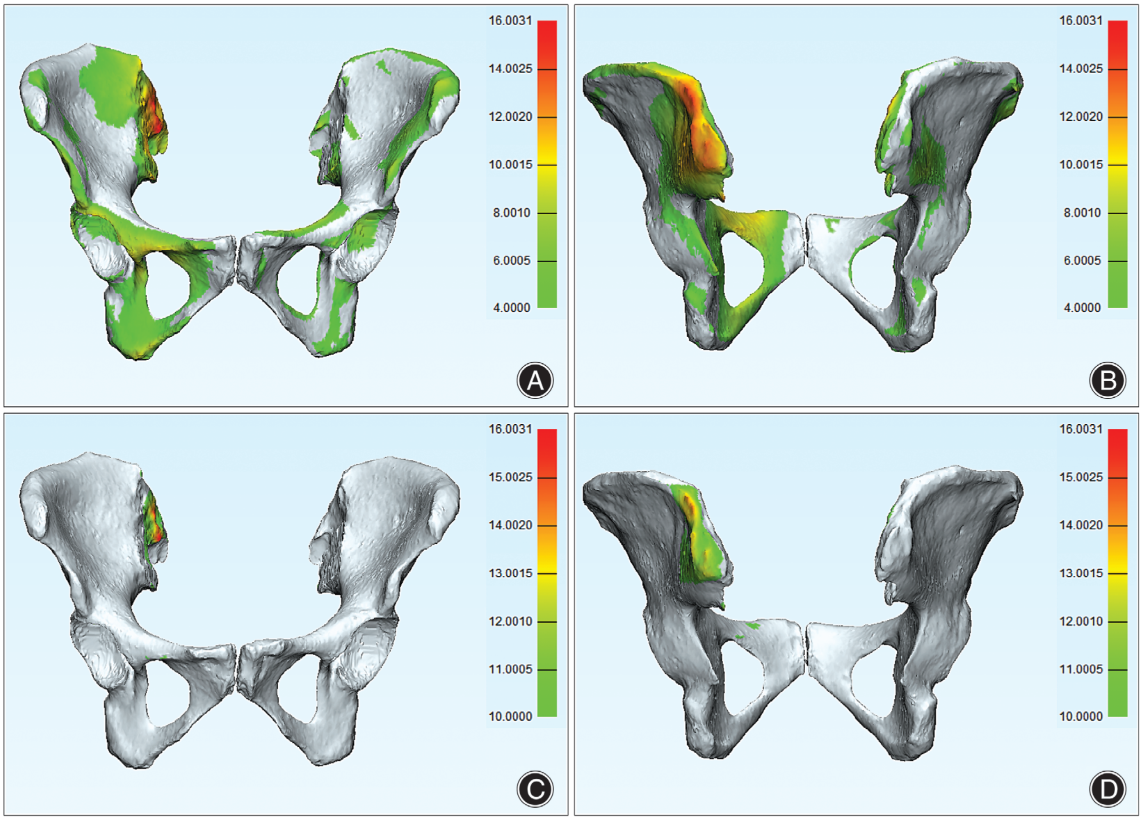

FIGURE 3 Deviation color maps (DCMs) of a pelvic ring with colored regions showing the deviation exceeding 4 mm (A, B) and 10 mm (C, D) threshold only: (A) anterior view; (B) posterior view; (C) anterior view; (D) posterior view.

bones. The greater the RMS value, the higher the level of asymmetry.

Percentage of Points over 2 Mm Deviation (PD > 2 mm)
The PD > 2 mm is the percentage of points, $\{x_i\}_{i=1}^{n}$ and $\left\{y_j\right\}_{j=1}^{k}$, with 3D deviation over 2 mm. PD > 2 mm values indicate the proportion of pelvic surface area where geometric differences go beyond 2 mm.

Percentage of Points over 4mm Deviation (PD > 4 mm)
The PD > 4 mm is the percentage of points, $\{x_i\}_{i=1}^{n}$ and $\left\{y_j\right\}_{j=1}^{k}$, with 3D deviation over 4mm. PD > 4 mm values indicate the proportion of pelvic surface area where geometric differences go beyond 4 mm.

Post-Processing of DCMs
The results of the 3D deviation analysis were also visually displayed as DCMs for showing the distribution of deviations in the global surface of a pelvis and their anatomic regions. Maximum deviations over 4 and 10 mm were deemed as critical levels for evaluating the severity of asymmetry as per Matta's scoring system.[13] Figure 3 shown DCMs of a pelvic ring with the deviation exceeding 4 mm (A, B) and 10 mm (C, D). Figure 4 shows DCMs of a hip bone with the deviation exceeding 4 mm (A, B) and 10 mm (C, D).

Based on processed DCMs of pelvic rings, the quantitative asymmetry in specific anatomical regions of bilateral hip bones was evaluated. A hip bone was spilt into 15 anatomic regions as shown in: 1. iliac crest, 2. anterior superior iliac spine, 3. anterior inferior iliac spine, 4. acetabular rim, 5. articular surface of acetabulum, 6. contour of obturator foramen, 7. surface of iliac fossa, 8. surface of sacroiliac joint (including iliac tuberosity), 9. sciatic spine, 10. iliopectineal crest, 11. gluteal surface of ilium (between inferior gluteal line and external lip of iliac crest), 12. posterior anterior iliac spine, 13. posterior inferior iliac spine, 14. greater sciatic notch, and 15. ischial tuberosity (Figure 5).

Data Analysis
Statistical analysis was conducted using the Statistical Package for the Social Science software (SPSS, version 19.00, IBM, NY, USA). The one-sample Kolmogorov–Smirnov test was used to determine whether the data had normal distributions. Medians and interquartile range (IQR) were employed to summarize the data characteristics with non-normal distributions. The Wilcoxon rank-sum test was used to compare

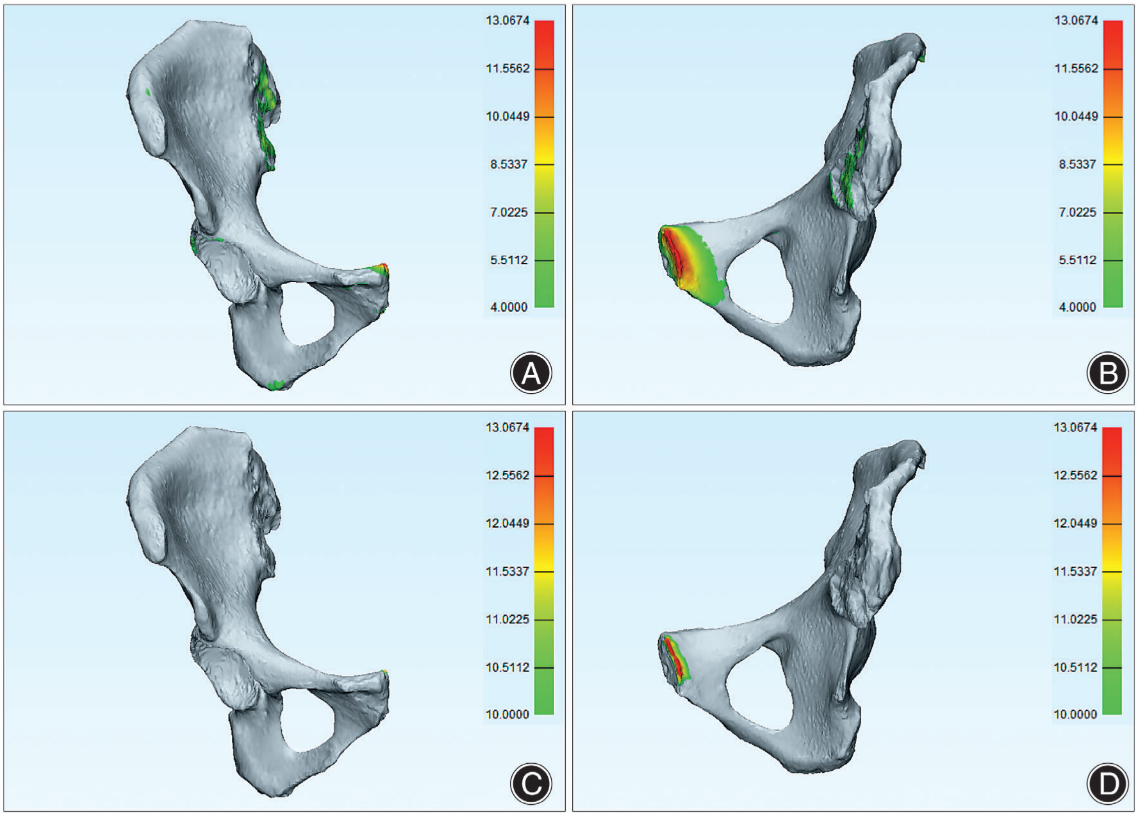

FIGURE 4 Deviation color maps (DCMs) of a hip bone with colored regions showing the deviation exceeding 4 mm (A, B) and 10 mm (C, D) threshold only: (A) anterior view; (B) posterior view; (C) anterior view; (D) posterior view.

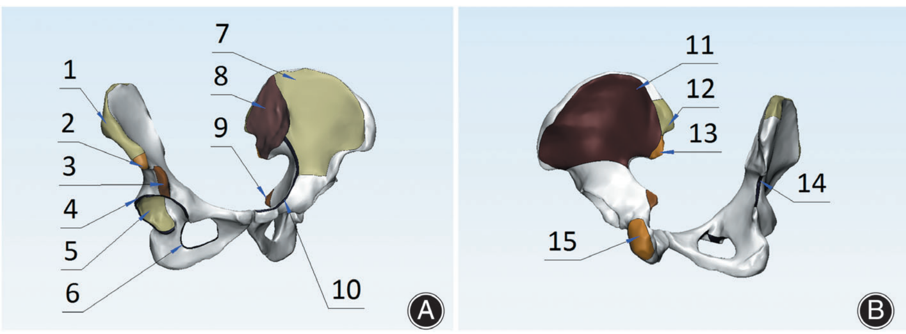

FIGURE 5 The anatomical sites (regions) of a pelvic ring: (A) 1. iliaca crest, 2. anterior superior iliac spine, 3. anterior inferior iliac spine, 4. acetabular rim, 5. articular surface of acetabulum, 6. contour of obturator foramen, 7. surface of iliac fossa, 8. surface of sacroiliac joint (including iliac tuberosity), 9. sciatic spine, 10. iliopectineal crest. (B) 11. gluteal surface of ilium (between inferior gluteal line and external lip of iliac crest), 12. posterior anterior iliac spine, 13.posterior inferior iliac spine, 14. greater sciatic notch, 15. ischial tuberosity.

TABLE 2 Median (IQR) on the further assessments of pelvic rings and hip bones

	MD (mm)	AD (mm)	RMS (mm)	PD > 2mm (%)	PD > 4mm (%)
Pelvic rings	7.46 (3.27)	1.28 (0.57)	1.69 (0.73)	20.62 (17.30)	2.27 (4.95)
Hip bones	6.08 (2.23)	0.94 (0.30)	1.23 (0.39)	9.78 (9.47)	0.59 (1.31)
P **value**	0.000	0.000	0.000	0.000	0.000

Note: $P < 0.05$ indicates statistical significance. MD, maximum 3D deviation; AD, average 3D deviation; RMS, root mean square; PD > 2 mm, percentage of points above 2 mm deviation; PD > 4 mm, percentage of points above 4 mm deviation

TABLE 3 Median (IQR) on the further assessments of pelvic rings between male and female subgroups

	Count	MD (mm)	AD (mm)	RMS (mm)	PD > 2 mm (%)	PD > 4 mm (%)
Male	88	7.20 (3.11)	1.24 (0.57)	1.65 (0.73)	20.10 (17.89)	2.22 (4.38)
Female	71	7.90 (4.32)	1.36 (0.59)	1.75 (0.82)	24.20 (15.08)	3.20 (6.43)
P **value**	-	0.031	0.209	0.228	0.346	0.187

Note: $P < 0.05$ indicates statistical significance. MD, maximum 3D deviation; AD, average 3D deviation; RMS, root mean square; PD > 2 mm, percentage of points above 2 mm deviation; PD > 4 mm, percentage of points above 4 mm deviation

TABLE 4 MD of Pelvic rings in different ages [median (IQR)] (mm)

	Age group			
Gender	20–29 years	30–39 years	40–49 years	50–59 years
Male	5.49 (3.38)	7.22 (3.11)	7.08 (2.49)	8.82 (2.51)
Female	6.64 (2.96)	7.01 (2.05)	8.58 (4.52)	9.06 (4.80)
Total	5.94 (2.71)	7.01 (2.56)	7.66 (4.94)	9.06 (2.71)

TABLE 5 The number of pelvises with deviation (asymmetry) above 4 mm and 10 mm occurring in specific anatomic regions

Anatomic regions with deviations[†]		Number of pelvises with deviations over 4 mm	Number of pelvises with deviations over 10 mm
1.	Iliac crest	119	15
2.	Anterior superior iliac spine	78	6
3.	Anterior inferior iliac spine	49	1
4.	Acetabular rim	72	2
5.	Articular surface of acetabulum	35	1
6.	Contour of obturator foramen	15	0
7.	Surface of iliac fossa	90	3
8.	Surface of sacroiliac joint[‡]	104	5
9.	Sciatic spine	30	0
10.	Iliopectineal crest of pelvis	28	2
11.	Gluteal surface of ilium[§]	105	6
12.	Posterior superior iliac spine	42	2
13.	Posterior inferior iliac spine	64	7
14.	Greater sciatic notch	21	0
15.	Ischial tuberosity	19	0

[†] Anatomic regions listed in this table are consistent with Figure 3A and B; [‡] Including iliac tuberosity and auricular surface of ilium in this study; [§] The surface between the inferior gluteal line and external lip of the iliac crest.

outcomes from the two sample groups: pelvic rings and hip bones. Gender-related statistical characteristics of pelvic rings between male and female subgroups were evaluated *via* the Mann–Whitney U test. A two-tailed p-value less than 0.05 indicated statistical significance.

Results

3D Deviation of Pelvic Rings and Hip Bones

157 out of 159 pelvic rings (98.74%) had more than 4 mm maximum deviation (MD) and 27 (16.98%) of them exceeded 10 mm MD. The surface 3D deviation analysis of bilateral hip bones identified 150 pelvises (94.34%) with more than 4 mm MD and 4 (2.51%) of over 10 mm MD. The MD of pelvic rings reached a peak value of 16 mm.

Median and IQR values after using the Wilcoxon rank-sum test for the further assessment items (MD, AD, RMS, PD) revealed statistical differences between the two sample groups, pelvic rings and hip bones (Table 2). The MD of pelvic rings was 1.23 times higher than for the bilateral hip bones (7.46 mm vs. 6.08 mm, $P < 0.05$). The AD of pelvic rings was 1.36 times higher than for the bilateral hip bones (1.28 mm vs. 0.94 mm, $P < 0.05$). RMS in the pelvic rings was 1.37 times greater than in the bilateral hip bones (1.69 mm vs. 1.23 mm, $P < 0.05$). Around 21% of the surface area of a pelvic ring had more than 2 mm geometric deviation compared with its mirrored model, while the percentage of the surface points of bilateral hip bones on the same level of deviation was 9.78% ($P < 0.05$), around half the proportion of a pelvic ring. Moreover, 2.27% of the surface area of a pelvic ring had more than 4 mm geometric deviations compared with its mirrored model, while the percentage of the surface points of bilateral hip bones on the same level of deviation was 0.59% ($P < 0.05$), around one-fourth as low as that of a pelvic ring.

3D Deviation of Pelvic Rings in Different Genders and Ages

Regarding the assessment items of AD, RMS and PD of gender-related pelvic rings, no statistical significances were found in male and female groups as shown in Table 3. The MD of pelvic rings in the female group was 10% higher than the male group (7.90 mm vs. 7.20 mm, $P < 0.05$).

The MDs of the pelvic rings rose with increased age as shown in Table 4. The MD of female pelvic rings in the older group aged 50–59 years was 36% greater than the younger group aged 20–29 years, especially in the male group (60% greater) (Table 4).

Statistical Analysis of Anatomical Regions with High Deviations

The DCMs highlighted the regions with over 4 and 10 mm of the maximum deviation as shown in Figure 3. Table 5 listed the number of pelvic rings (159 in total) whose specific anatomic regions (Figure 5) had deviations over 4 mm and 10 mm. The pelvic iliac crest led all anatomic regions (15 in total) either on the 4 mm or 10 mm setting, as shown in Table 5, followed by surface of sacroiliac joint and gluteal surface of ilium. 119 out of 159 pelvic iliac crests (74.8%) had deviations over 4 mm. The higher deviation group with 10 mm included 15 pelvic iliac crests, while the other 14 regions presented single digit deviations.

Discussion

3D Asymmetry of a Pelvic Ring

In this study, 3D morphological analysis using medical imaging technology quantitatively depicted the asymmetrical features of pelvic rings and bilateral hip bones. Measurements and statistical analysis demonstrated the high incidence of asymmetry of healthy pelvic rings. Over 95% (98.74%) of subjects had more than 4 mm of maximum surface deviation of pelvic rings compared with their flipped models. More than 15% (16.98%) of them exceeded 10 mm of maximum deviation. Those outcomes suggested a high popularity of asymmetric pelvic rings existing in the general population. Geometrical asymmetry of bilateral hip bones also generally existed in subjects. 94.34% of subjects had high maximum surface deviation (over 4 mm) between the two hip bones. Indeed, a pair of asymmetric bilateral hip bones undoubtedly resulted in an asymmetric pelvic ring. However, the asymmetry of pelvic rings was not fully determined by the asymmetry of bilateral hip bones. A much high deviation in each assessment item was present in a pelvic ring compared with its hip bones (as shown in Table 2), suggesting a higher level of asymmetry of a pelvic ring than its components. Measurement results supported the notion that asymmetrical alignment of bilateral hip bones played an important role in triggering the asymmetry of a pelvic ring. Lubovsky *et al.*[21,22] reported asymmetric alignments of the acetabular rim. This study also found that nearly half of the pelvises had high deviations on the acetabular rims (MD > 4 mm). Consequently, the exact symmetry of a pair of bilateral hip bones did not guarantee pelvic symmetry due to the asymmetrical positioning of the two hip bones.

Anatomic Region with High Incidence of Asymmetry

The iliac crest is an anatomic region with a high incidence of asymmetry. This study found that 119 out of 159 pelvic iliac crests (74.8%) had relatively high degree of asymmetry with more than 4 mm maximum deviation, and 15 (9.4%) reached 10 mm or more (Table 3). The morphological assessment revealed that either the deviation value or the number of subjects with asymmetric iliac crest topped all other regions of a pelvic ring. Those findings were consistent with published studies. Boulay *et al.*[15] concluded the asymmetry of the iliac crest in terms of the anatomic measurements of the pelvis. Furthermore, Ead *et al.*[4] reported that the highest level of asymmetry was present on the iliac crest. As the load-bearing site, the ilia could have an active mechanobiology-related bone modeling and remodeling process. Mechanical loading triggered the mechanoregulation of bone to reach mechnostat with optimal structure to react the surrounding mechanical environment.[23] The substantial asymmetry between left and right femurs revealed by Laumonerie's study[24] suggested unbalanced mechanical loads to be transferred to bilateral ilia *via* the acetabulum and sacroiliac joint.[25,26] Moreover, muscles and ligaments surrounding the ilia engage in a gait pattern, which may present asymmetrical features.[15,27] Those unbalanced mechanical loads may induce the mechanobiological bone remodeling of the ilia to an asymmetrical pattern.

Clinic Significance and New Directions

Asymmetry of the pelvic ring is a common morphological feature that should have a clinical impact for the evaluation of the reduction grade of an injured pelvis. Three major techniques have been used to assess the reduction grade. The Matta's scoring system[13] assumes a symmetric pelvic ring to be the target geometry for restoring and evaluating reduction grade based on postoperative radiography. The restored pelvic ring certainly has different morphological features compared with the original shape with asymmetric geometry. Relatively inexact assessments would be made due to the poor investigation of asymmetry in a pelvic ring. Sagi's inlet and outlet ratio technique highly depends on a reference axis symmetrically splitting a pelvic ring,[10] which may not exist due to the asymmetry shape of the pelvis. The cross measurement method developed by Lefaivre[11] and Keshishyan[12] employs a reference line running through the buttress above the acetabular dome where a high level of asymmetry was found in this study. Some published studies state that those three techniques might not be fully correlated with the functional outcomes of an injured pelvis measured by Majeed score after surgery.[14] A quantitative assessment of asymmetry in a pelvic ring may provide a technical benefit to increase the accuracy of the evaluation of reduction grade.

The in-depth assessment of pelvic asymmetry covering geometry and alignments of bilateral hip bones would have clinical implications on the design of a patient-specific implant for a pelvic surgery. A tailor-made pelvic fixation plate offers a custom fitted feature that would have biomechanical benefits for restoring the stability of an injured pelvis[7] and significant advantages in pelvic fixation under laparoscopy.[28] It is taken for granted that the contralateral hip bone is the best template to rebuild the patient-specific geometry of the injured side due to absence of the original shape.[7–9] It is problematic to employ contralateral technology to restore stability of the pelvis and accommodate biomechanical balance in a patient with a severe asymmetrical pelvic ring possibly due to the unbalanced skeletomuscular structure. A well assessed morphological asymmetry incorporated into the contralateral technique provides a technical means to reduce the risk of design weakness in a patient-specific surgical implant.

Despite a high level of asymmetry existing in some anatomic regions in a pelvic ring, some anatomic regions such as the obturator foramen, greater sciatic notch, and sciatic spine (see Table 5) are regarded as symmetric in 3D space due to the marginal difference between bilateral features present in those areas. As pelvic reductions under preoperative or intraoperative 3D imaging gaining traction, 3D asymmetrical or symmetrical regions could be important references for assessing the reduction quality, especially closed reduction under CT imaging.[29,30] For example, in the navigated reduction of unilateral sacroiliac joint dislocation with intraoperative CT, 3D symmetrical regions being restored symmetry can be regarded as a sign of the sacroiliac joint with good articulation,[29] and it is probably not so good if we find only several 3D asymmetrical regions being symmetrical. However, in the pelvic ring surgery with conventional intraoperative 2D imaging, 2D projections of 3D symmetrical regions can be asymmetrical if the radiographic projection deviate from symmetry-oriented direction. Therefore, seeking the best projection and defining the best reference from radiographic signs is a critical issue that should be addressed in future studies.

Limitations

This study includes three limitations. First, all subjects were taken from a single-center rehabilitation hospital where population-related morphological differences were not fully taken into account. Second, the absence of patients' physical data, such as height and body weight, as well as demographic data, may yield statistical bias due to the underlying biological correlation between those data and pelvic asymmetry. Third, lumbar degeneration and/or mild herniated discs were detected in 13 subjects *via* CT imaging. The correlation between lumbar degeneration and pelvic asymmetry was not investigated in this study. Lumbar degeneration and herniated disc are common in adult and elderly populations, so the exclusion criteria should not include this item.

Conclusion

Asymmetry of a pelvic ring is a common morphological feature covering geometric asymmetry of bilateral hip bones and their alignments. Specific anatomic regions such as the iliac crest present a relatively high severity of asymmetry. It implies that both asymmetric and symmetric features can be set as reference signs for the reduction of pelvic ring injury or fixation design.

Quantitative assessments of the asymmetry of a pelvic ring have clinical implications in precisely evaluating the reduction grade of an injured pelvis after surgery as well as in developing a patient-specific surgical implant for the pelvis.

Compliance with Ethical Standards

This study was performed at the People's Hospital of Sanshui District of Foshan City, and approved by the Ethics Committee of the Hospital (Approval 201913).

Authors' Contributions

Xianhua Cai, Fan Zhang contributed to the conception of the study; Fan Zhang performed the experiment and wrote the manuscript; Dengming Zhang, Zhizhong Wang contributed significantly to harvest and check all data of the experiment; Zhou Huang administrated CT images; All authors discussed the results and revised the manuscript.

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