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Evaluation of dual-energy X-ray absorptiometry compared to magnetic resonance imaging for collecting measurements of the human bony pelvis

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Abstract

Objectives: Imaging methods to measure the human pelvis in vivo provide opportunities to better understand pelvic variation and adaptation. Magnetic resonance imaging (MRI) provides high-resolution images, but is more expensive than dual-energy X-ray absorptiometry (DXA). We sought to compare pelvic breadth measurements collected from the same individuals using both methods, to investigate if there are systematic differences in pelvic measurement between these imaging methods.

Methods: Three pelvic breadth dimensions (bi-iliac breadth, bi-acetabular breadth, medio-lateral inlet breadth) were collected from MRI and DXA scans of a cross-sectional sample of healthy, nulliparous adult women of South Asian ancestry ($n = 63$). Measurements of MRI and DXA pelvic dimensions were collected four times in total, with one baseline data collection session and three replications. Data collected from these sessions were averaged, used to calculate technical error of measurement and entered into a Bland–Altman analysis. Linear regression models were fitted with a given MRI pelvic measurement regressed on the same measurement collected from DXA scans, as well as MRI mean bias regressed on DXA mean bias.

Results: Technical error of measurement was higher in DXA measurements of bi-iliac breadth and medio-lateral pelvic inlet breadth and higher for MRI measurements of bi-acetabular breadth. Bland Altman analyses showed no statistically significant relationship between the mean bias of MRI and DXA, and the differences between MRI and DXA pelvic measurements.

Conclusions: DXA measurements of pelvic breadth are comparable to MRI measurements of pelvic breadth. DXA is a less costly imaging technique than MRI and can be used to collect measurements of skeletal elements in living people.

1 | INTRODUCTION

There is growing interest in measuring the human pelvis in vivo to better understand its role in human variability and adaptation. For example, there is a growing interest in re-examining the obstetric dilemma (Washburn, 1960) with respect to anatomical variation and potential evolutionary influences on pelvic variation. Some researchers have suggested that early life programming and the ecological context in which women develop may impact on the development of the bony pelvis (Shirley et al., 2020; Wells, 2015, 2017; Wells et al., 2012). Other scholars have suggested that instead of pelvic morphology, maternal metabolism is the primary constraint on human gestation length and fetal growth (Dunsworth et al., 2012). Using a mathematical model, Mitteroecker et al. (2016) outlined that as a result of the evolutionary dynamics impacting the obstetric dilemma, weak directional selection favoring large neonates relative to maternal pelvic dimensions was sufficient to account for the high incidence of fetopelvic disproportion in human populations. In vivo measurements of the skeleton are made possible using medical imaging technology, including X-rays, dual-energy X-ray absorptiometry (DXA) or magnetic resonance imaging (MRI). A number of key studies have made us of medical imaging to evaluate pelvic variation in growing children and in adults.

Radiography was discovered by Wilhelm Conrad Roentgen in 1895, and used to visualize the human body from the early 20th century onwards (Reed, 2011). Early examinations of the pelvis in living people included collecting measurements from radiographs, using a method known as roentgen pelvimetry. Thoms (1933) outlined his use of this approach, where during the second exposure of X-ray wavelengths a technician would introduce a radio-opaque centimeter grid in the same plane as the X-ray film that was superimposed on the radiograph image, allowing collection of linear measurements. This method was used to collect pelvic measurements from adults and growing children, and was used in general practice by obstetricians to assess possible pelvic variability which could impact childbirth (Dippel, 1955).

Greulich and Thoms (1944) applied roentgen pelvimetry on radiographs of 107 girls ranging in age from 5 to 15 years. Results showed the pelvic canal was constricted in girls 3–4 years prior to menarche, and that during puberty the canal increased first in width and subsequently in anterior–posterior breadth. Moerman (1982) also collected pelvic measurements from radiographs of girls aged 8–18 years (also Fels Longitudinal Study participants) using a point digitizer and digital software, finding that when compared with stature, the bony pelvis grew more slowly and continuously into late adolescence.

Pelvic radiographs from adults were used to examine links between pelvic dimensions and biosocial factors. For example, Holland et al. (1982) collected pelvic measurements from the radiographs of 242 men and 314 women from Northern Ireland who were clinically referred for an intravenous pyelogram (an X-ray test which provides an image of the kidneys, bladder, ureter and the urinary tract). Their study aimed to quantify pelvic shape differences between the sexes and to examine if pelvic dimensions, height, and year of birth had statistical associations in both men and women. They collected linear measurements of the pelvis such as true conjugate diameter and widest transverse diameter, and calculated pelvic dimension indices, such as brim index (calculated as true conjugate diameter divided by widest transverse diameter and multiplied by 100). Height was significantly positively correlated with year of birth and with four of seven pelvic indices for men and women. To determine if any change occurred in pelvic indices over time, Holland and colleagues classified birth year and height, and calculated mean pelvic index value for men and women of a given height and completed trend tests. Trend tests indicated that the true conjugate, posterior sagittal, brim and the posterior-sagittal-transverse indices had at least one significant trend in men and women; two indices, the interspinous diameter and the sagittal diameter showed no significant trends. The exception to this correspondence was the widest transverse diameter, which showed no evidence of trend for men but a significantly decreasing trend in two of the height groups for women. Holland et al. (1982) found that pelvic dimensions for men and women of similar stature were significantly different. Furthermore, pelvic dimensions correlated with their year of birth, suggesting that common environmental factors such as nutrition were the most likely causes of variation in both men and women.

DXA is a more recent medical imaging technology, and its potential for visualizing the pelvis in living people has only recently attracted attention. DXA was originally developed to measure bone mineral density via low-level X-ray beams, in order to assess osteoporosis risk (Mazess et al., 1990). The precursor of the DXA scanner was introduced in 1963 and known as single-photon absorptiometry (SPA), where a single-energy photon beam was directed through a peripheral skeletal site (such as the calcaneus) and a detector on the opposite side of the beam measured the attenuation of the photon energy passing through bone and soft tissue. When compared with a calibration standard, the amount of bone mineral could be quantified (Lewiecki & Binkley, 2017). Dual-photon absorptiometry (DPA) followed SPA, including two different radioisotopes which each emitted photon energy at different levels, enabling bone density to be

quantified at "central" skeletal sites in the body, such as the lumbar spine (Lewiecki & Binkley, 2017). By the 1980s, DPA had been mostly replaced by single-energy X-ray absorptiometry (SXA), where the photon source was produced by an X-ray tube, before the company Hologic introduced the first dual-energy X-ray absorptiometry (DXA) system in 1987 (Lewiecki & Binkley, 2017). Photon absorptiometry required a radioisotope source which had to be regularly replaced, whereas the use of an X-ray tube for a photo source in DXA did not require replacement and increased processing speed.

Use of two beams of different energy levels by DXA allows the differentiation of tissue types—thicker and denser tissues (e.g., bone) attenuate X-rays more than thinner or less dense tissues (e.g., muscle and fat). DXA systems can be used to estimate the density of bone and soft tissue simultaneously, resulting in whole body scans that capture fat mass, lean soft tissue, and bone mass.

Novotny, Davis, Wasnich, Biernacke, & Onaka (2000) collected pelvic breadth measurements from whole-body DXA scans of 326 healthy Hawaiian women between 45 and 59 years, as well as survey data on their birth weight, maternal and paternal anthropometry, milk consumption during adolescence, physical activity during adolescence and reproductive history. They developed maternal pelvic size measurements from DXA to use as predictors of infant birthweight. Their results showed that adolescent milk consumption and age at menarche were positively associated with the horizontal distance between the outermost points of the greater trochanters, which together with infant sex and gestational age predicted infant birthweight. Novotny and colleagues' work demonstrates the use of DXA scans in collecting linear skeletal measurements of the pelvis and the relevance of incorporating these data with growth and development indicators throughout the life course.

Building on Abrahamyan et al.'s (2008) work which created formulae for limb length assessment from DXA scans of children, Völgyi et al. (2010) used whole-body DXA scans to collect both length and width data from selected skeletal sites in living children. The aim of their study was to investigate the growth pattern of height and weight, and the width and length of various body segments (including the pelvis) in 396 Finnish girls between the ages of 10 and 18 years. Völgyi et al. (2010) also collected body measurement data from the mothers and maternal grandmothers of each girl in the study, to examine generational variation in limb length, height, and weight, and calculated peak growth velocity for height, weight, body mass index (BMI), two pelvic width measurements and shoulder breadth. Results of their study showed that growth velocity for lesser pelvis width (medio-lateral pelvic inlet breadth) peaked at 13.5 months, with the greater pelvis width (bi-iliac breadth) growth velocity peaking at 11.6 months prior to menarche. By the age of 18 years, the girls in the study had still not reached their mothers' shoulder, great pelvis and lesser pelvis widths despite reaching their mother's height. Völgyi and colleagues' study outlines the complexity of pelvic growth, as well as the value of DXA as a means of examining linear change during growth throughout the entire body.

Beyond X-ray techniques, pelvic shape and size in living people may also be estimated using MRI. MRI is a medical imaging technique based on nuclear magnetic resonance (Lauterbur, 1973), with each image produced from a scan representing multiple cross-sectional "slices" of the body. MRI is preferred in research and clinical settings as a non-invasive method of visualizing internal organs and skeletal structures in living people (Hu et al., 2012; Kwong et al., 1992), and has been used to collect pelvimetry data and visualize the female bony pelvis and reproductive organs (Berger et al., 2013; Handa, 2003; Hricak et al., 1983; Levine, 2006; Miller et al., 2010; Spörri et al., 1997; Stark et al., 1985). More recently, Shirley et al. (2020) examined pelvic dimensions in 68 nulliparous women of South Asian ancestry using MRI through the lens of the "developmental origins of health and disease" (DOHaD) hypothesis, to better understand the consequences of different components of growth variability. The study tested whether adult pelvic dimensions were associated with two components of height, each a proxy for either early postnatal or later growth, and whether adult pelvic dimensions were associated with birth weight, a marker of nutritional investment in utero. They found that when controlling for birth weight, height-residual (height statistically adjusted for tibia length) was associated with bi-acetabular breadth, bi-iliac breadth, and the pelvic inlet, while tibia length was significantly associated with all pelvic dimensions except interspinous diameter. Conversely, controlling for the linear growth variables, birth weight only correlated with bi-iliac breadth.

Both MRI and DXA imaging provide exciting research opportunities for examining bony skeletal dimensions in living humans, however each technique has limitations. MRI creates high-resolution images of both hard and soft tissues for the entirety of the patient's or study participant's body, allowing both trunk and limbs to be reconstructed in 3-D format. The gold standard for body composition analysis is cadaver analysis, meaning that no in vivo techniques can be considered to meet the same criteria of accuracy (Wells & Fewtrell, 2006). Instead, multicomponent methods of evaluating body composition (such as the four component model, which divides body weight in to water, minerals, proteins and fat),

which provide the opportunity to evaluate both fat and fat-free mass, are considered sufficiently accurate to warrant being termed reference methods (Wells & Fewtrell, 2006). The high-resolution images produced by MRI have led to MRI being considered a reference method in clinical studies of body composition. That is, MRI is the preferred method for estimating body composition (Heymsfield et al., 2005) and is often used as a reference for collecting the same body composition data when using DXA. However MRI is also expensive, and scanners do not currently accommodate the full range of body size (Bazzocchi et al., 2016). For instance, on the UK's National Health Service (NHS), an MRI scan with no contrast for a patient who is 19 years old and older costs £145 (NHS, 2017). DXA scans are lower in cost (£62 on the NHS [NHS, 2017]) and have low radiation exposure relative to other imaging technologies that emit radiation, and may be used with a greater range of physical variation in body size (Bazzocchi et al., 2016). Compared to MRI, however, DXA scans (depending on the scanner model) provide lower-resolution images, and do not give a cross-sectional view of the body, presenting instead an image of the prone patient's body in coronal plane. The high resolution of MR imaging is ideal for collecting in vivo measurements of the skeleton. DXA scanners may be lower in financial cost than MRI scanners, though are generally exclusive to Western, urbanized contexts and therefore likely to be non-representative of global populations. Novotny et al. (2000) and Völgyi et al. (2010) both used DXA scans to collect pelvic measurements from living people, however neither study validated the use of DXA compared to MRI or another reference method.

Direct relationships between pelvic morphology, maternal and fetal growth and childbirth difficulties are challenging to test, as there are few studies that have examined the growth of the pelvis throughout life and inter-generationally. Studies of pelvic morphology are often hampered by a lack of diversity. For example, the description of "normal" childbirth in many midwifery and obstetric textbooks are modeled solely on studies focusing on the pelvic morphology common in European women (Betti, 2021). Previous research has also shown that pelvic morphology varies across populations (Betti & Manica, 2018; Kurki, 2013). Some of the obstacles in completing studies that examine in vivo pelvic growth are a lack of awareness of the use of DXA scans in collecting skeletal linear measurements, and a concern that pelvic measurements collected from DXA scans and MRI scans may have systematic differences that impact pelvic measurement data. In this study, we measured the bony pelvis of women using both MRI and DXA in order to test for systematic differences between DXA and MRI measurements of linear skeletal data.

2 | MATERIALS & METHODS

2.1 | Study sample

The sample used for this study was selected based on the availability of both magnetic resonance imaging (MRI) and dual energy X-ray absorptiometry (DXA) scans for each individual in the sample, as well as available data on body composition. The sample is from a cross-sectional study of healthy South Asian women ($n = 70$) (Shirley et al., 2018, 2020). Shirley et al. (2018, 2020) sought to explore associations between metabolic rate, organs, tissues and markers of growth and development, including scans of the pelvis using both DXA and MRI (Shirley et al., 2018, 2020). Shirley and colleagues recruited healthy individuals of South Asian ethnicity to test for somatic trade-offs. The decreased skeletal muscle mass and potentially decreased visceral organ mass recognized in the "thin-fat" phenotype is suggestive of somatic trade-offs, and therefore evidence of competition between tissues may be more readily observable in a South Asian cohort (Shirley, 2018). Recruiting South Asian participants also adds to the literature on variability in South Asian body composition, which is recognized to contribute to their heightened chronic disease susceptibility (Shirley, 2018). All data collection procedures were performed at the University College London (UCL) Great Ormond Street Institute of Child Health (GOSICH) and Great Ormond Street Hospital for Children NHS Foundation Trust (GOSH) from March 2015 to May 2016. Ethical approval for this study was granted by the Camden and Kings Cross NHS Research Ethics Committee of the Health Research Authority. All participants in the study gave written, informed consent (Shirley et al., 2018, 2020).

2.2 | Sample recruitment

The study recruited participants of South Asian (Indian, Pakistani, Bangladeshi and Sri Lankan) ethnicity between the ages of 20 and 28 years. Inclusion criteria were nulliparous, term-born women with BMI in the range of 17–28 kg/m^2. Participants self-reported their ethnicity as defined by categories used in Shirley et al. (2018, 2020), and is included here due to its potential relevance to the variability exhibited by pelvic measures. South Asian ethnicity was based on the participants' self-identification and confirmed by maternal and paternal grandparents also being Indian, Pakistani, Bangladeshi or Sri Lankan. The restricted age range was selected in order to minimize phenotypic variability associated with pubertal growth or aging, and the study was restricted to women in order to improve understanding of metabolic/

growth traits relevant to female reproductive investment. Individuals were excluded if they reported health conditions with the potential to affect growth or metabolism. The sample was recruited using flyers, posters and online advertisements displayed in UCL and surrounding universities.

2.2.1 | Imaging

Bone mineral and soft tissue data was collected using a GE Lunar Prodigy whole-body DXA scanner (GE Medical Systems, UK) and scans were visualized using enCORE 2002 software. Ionizing radiation is a concern in medical imaging and in the use of imaging for research, however exposure from DXA scans is relatively low. Effective radiation dose is expressed in sieverts (Sv) and is calculated from information about absorbed doses to the organ or tissue exposed to the X-rays and the relative radiation risk assigned to each of these organs or tissues. On average, the UK population is exposed to external photon radiation from natural background of the order of 1 mSv (1000 μSv) per year (COMARE, 2019). An adult undergoing a whole-body DXA scan is exposed to approximately 4.7 μSv (Bazzocchi et al., 2016).

Each subject was also scanned using magnetic resonance imaging (MRI; 3 T MAGNETOM, Siemens, Germany). MRI uses different types of magnetic fields to generate three dimensional images of the body, meaning that the primary risks associated with this scan relate to the presence of ferromagnetic devices, including biomedical implants (Hartwig et al., 2009). Volumetric 3D T2-weighted acquisition of the pelvis was performed using 144 contiguous coronal slices (TR 15.5 ms, TE 5.1 ms, flip angle 25, voxel size 1.2 × 1.2 × 1.2 mm, 1 average; scan duration ~5 min). The scanner was operated by trained radiographers.

2.3 | Pelvimetry measurements

Pelvic measurements were extracted from the MRI and DXA scans of each participant by a single researcher (SLD). Measurements included bi-iliac breadth (BIIB), medio-lateral pelvic inlet breadth (INML), and bi-acetabular breadth (BIAC), and are detailed in Table 1. They were selected based on the visibility of specific bony landmarks on both MRI and DXA scans, and also to reflect changing breadths of the pelvis moving from superior to inferior aspects of the bony girdle. Pelvic measurement locations are shown in illustration in Figure 1 and examples of these measurements as collected on both MRI and DXA scans are shown in Figure 2. MRI scans were visualized and measurements were collected digitally using open-source OsiriX DICOM software (Rosset et al., 2004). DXA scans were visualized using enCORE 2002 software, and measurements were collected using the Line ROI measurement tool available on the Custom Analysis toolbar (G.E. Healthcare, 2012). Previous studies collecting skeletal measurements from DXA scans have also made use of the Line ROI tool to collect linear measurements from the skeleton (Völgyiet al. 2010; Abrahamyan et al., 2008).

All measurement sets were repeated four times to assess intra-observer variability. The first replication was completed 24 hours after the baseline data collection. The second and third replications took place approximately 4 and 5 months after baseline data collection, respectively.

TABLE 1 Descriptions of linear measurements of pelvic dimensions used in this study

Pelvimetric measurement	Description for MRI measurement (viewed in coronal plane)	Description for DXA measurement
Bi-iliac breadth	Maximum distance between the right and left iliac blades, defined by the outermost edge of the iliac crest	Maximum distance between the right and left iliac blades, defined by the outermost edge of the iliac crest
Medio-lateral inlet breadth	Maximum distance between linea terminalis of the right and left iliac blades	Maximum distance between linea terminalis of right and left iliac blades
Bi-acetabular breadth	Distance between most anterior meeting point of fovea capitis of the right and left femora and acetabular notch of the right and left iliac blade, taken at tissue depth that clearly displays the entry point of the ligament of the head of the femur in to the fovea of the femur	Distance between most anterior meeting point of fovea capitis of the right and left femora and acetabular notch of the right and left iliac blade

Abbreviations: DXA, dual energy X-ray absorptiometry; MRI, magnetic resonance imaging.

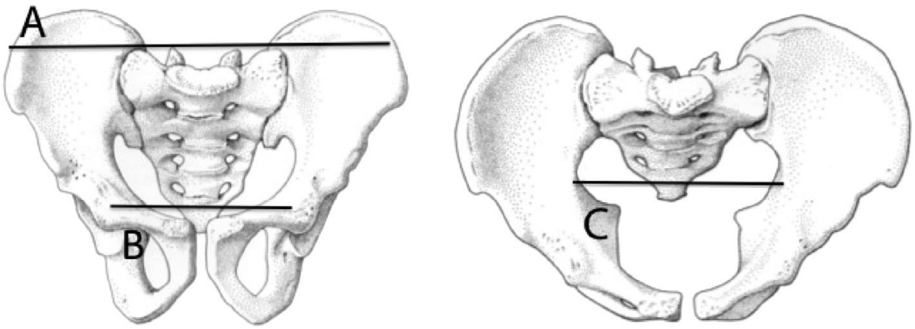

FIGURE 1 Diagram of pelvic variables measured using magnetic resonance imaging (MRI) and dual energy absorptiometry X-ray (DXA) scans; (A) bi-iliac breadth (BIIB); (B) bi-acetabular breadth (BIAC); (C) mediolateral inlet breadth (INML). Image produced by Decrausaz

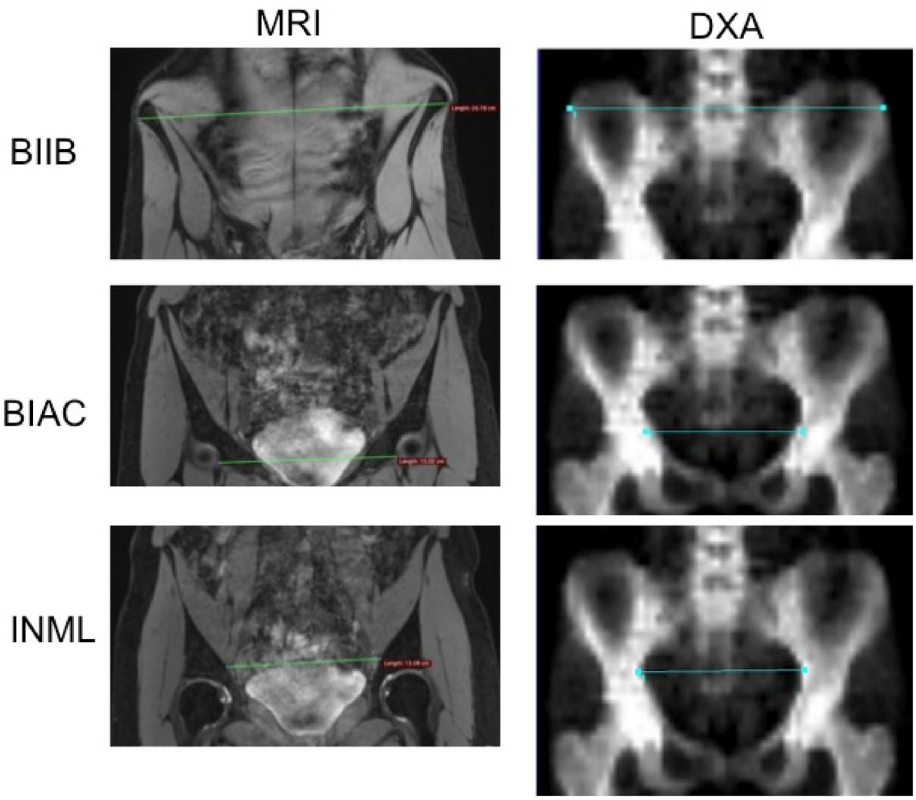

FIGURE 2 Examples of magnetic resonance imaging (MRI) on left and dual energy absorptiometry X-ray (DXA) on right scans used to collect bi-iliac breadth (BIIB), bi-acetabular breadth (BIAC) and medio-lateral pelvic inlet breadth (INML). The green line on the MRI image shows the line tool used in OsiriX DICOM software to collect pelvic measurements, and the blue line on the DXA image shows the line ROI measurement tool used in enCORE 2002 software to collect pelvic measurements

2.4 | Analytical methods

2.4.1 | Measurement precision

Measurement precision is defined as the magnitude of difference between repeated measures using the same technique by the same observer (Wong et al., 2008). Calculating measurement precision of MRI and DXA pelvic breadth measurements is a means of testing the repeatability of data collection, i.e., the extent to which each replication of measurement collection results in the same data value. In this study, measurement precision was examined using the technical error of measurement (TEM), using a variant which allows anthropometrists to confirm the exactness of repeated measurements performed by a single researcher (Ulijaszek & Kerr, 1999). Broadly, TEM is calculated by carrying out a number of repeat measurements on the same subject, either by the same observer, or by two or more observers, taking the differences and entering them into an equation formulated for one or multiple observers (Ulijaszek & Kerr, 1999). The composite TEM used in this study was calculated using the methods outlined in Ulijaszek and Kerr (1999), where TEM was calculated for both DXA and MRI repeated measurements performed by a single researcher over four data collection sessions.

2.4.2 | Measurement technique agreement

Bland Altman plots were used to examine the agreement between MRI and DXA pelvic measurements (Bland & Altman, 1986). These plots present a scatter of difference values between measurement techniques on the y-axis against mean values on the *x*-axis, with horizontal lines representing mean bias and limits of agreement

calculated as twice the standard deviation of the bias (i.e., 95% confidence intervals [CI]). The distance of all values in the plot from the line of mean bias represents the magnitude of the difference between methods. If the differences are normally distributed, 95% of differences will lie between these limits (Bland & Altman, 1986). The limits of agreement (or 95% CI) between the methods can be expressed in absolute units (centimeters) and also as a percentage of the mean value once the values have been log-transformed. The correlation between the bias and the mean is also calculated, to test whether the magnitude of the bias varies according to the size of the trait. Linear regression analyses were also performed to examine the association between MRI and DXA pelvic measurements, where MRI pelvic measurements was entered as the dependent variable and DXA pelvic measurements as the independent variable. All statistical analyses and plots were conducted in SPSS (IBM Statistical Package for the Social Sciences, Version 20.0).

TABLE 2 Descriptive statistics of the sample used in this study ($n = 63$), including pelvic variables measured using MRI (magnetic resonance imaging) and DXA (dual-energy X-ray absorptiometry)

	Minimum	Maximum	Mean	SD
MRI BIIB (cm)	20.47	28.24	25.08	1.74
MRI INML (cm)	10.69	13.64	12.21	0.65
MRI BIAC (cm)	11.58	14.91	13.16	0.72
DXA BIIB (cm)	20.46	28.21	25.20	1.66
DXA INML(cm)	11.12	13.84	12.61	0.59
DXA BIAC (cm)	11.52	14.83	13.26	0.68

Note: Pelvic variables are bi-iliac breadth (BIIB), medio-lateral inlet breadth (INML) and bi-acetabular breadth (BIAC).
Abbreviations: DXA, dual energy X-ray absorptiometry; MRI, magnetic resonance imaging.

TABLE 3 Results of composite technical error of measurement (TEM) calculation for pelvic measurements using MRI (magnetic resonance imaging) and DXA (dual absorptiometry X-ray)

	Composite TEM (cm)
MRI BIIB	0.17
DXA BIIB	0.55
MRI INML	0.33
DXA INML	0.43
MRI BIAC	0.59
DXA BIAC	0.56

Note: Pelvic variables are bi-iliac breadth (BIIB), medio-lateral inlet breadth (INML) and bi-acetabular breadth (BIAC).
Abbreviations: DXA, dual energy X-ray absorptiometry; MRI, magnetic resonance imaging.

3 | RESULTS

3.1 | Study sample and measurement precision

The sample collected by Shirley et al. (2018, 2020) included 70 women. Fifty-one percent of the participants reported Indian ethnicity, 11% Pakistani, 11% Bangladeshi, and 11% Sri Lankan, while 13% reported mixed ancestry among the four represented countries. One participant's ancestors had immigrated to Mauritius from India. Forty-seven percent of the sample was born in South Asia, while the majority of subjects born outside of South Asia were born in the United Kingdom (Shirley et al., 2020). Descriptive statistics of the study sample and measurement variables are available in Table 2. The sample size for this study was reduced from 70 to 63 as there were occasional missing MRI scans. The results of the composite TEM calculation are presented in Table 3. TEM was higher in DXA measurements of bi-iliac breadth and medio-lateral pelvic inlet breadth and higher for MRI measurements of bi-acetabular breadth. MRI and DXA measurements of bi-iliac breadth showed the greatest difference in TEM and MRI and DXA measurements of bi-acetabular breadth showed the smallest difference in TEM.

3.2 | Measurement variation

DXA and MRI pelvic measurements collected over four sessions were averaged for analysis. DXA measurement bias and MRI measurement bias are expressed in

TABLE 4 Results of bias and Bland–Altman analysis, including mean bias and limits of agreement and results of linear regression of mean bias regressed on mean of pelvic variables measured using MRI (magnetic resonance imaging) and DXA (dual absorptiometry X-ray)

	Mean bias (cm)	Mean bias (%)	Limits of agreement (cm)	Limits of agreement %	R^2	p*
BIIB	−0.12	−0.22	±0.65	7.59	.055	.063
INML	−0.41	−1.43	±0.62	5.42	.017	.157
BIAC	−0.10	−0.33	±0.59	4.51	.024	.223

Note: Pelvic variables include bi-iliac breadth (BIIB), medio-lateral inlet breadth (INML) and bi-acetabular breadth (BIAC). *Values are significant at $p < .05$.
Abbreviations: DXA, dual energy X-ray absorptiometry; MRI, magnetic resonance imaging.

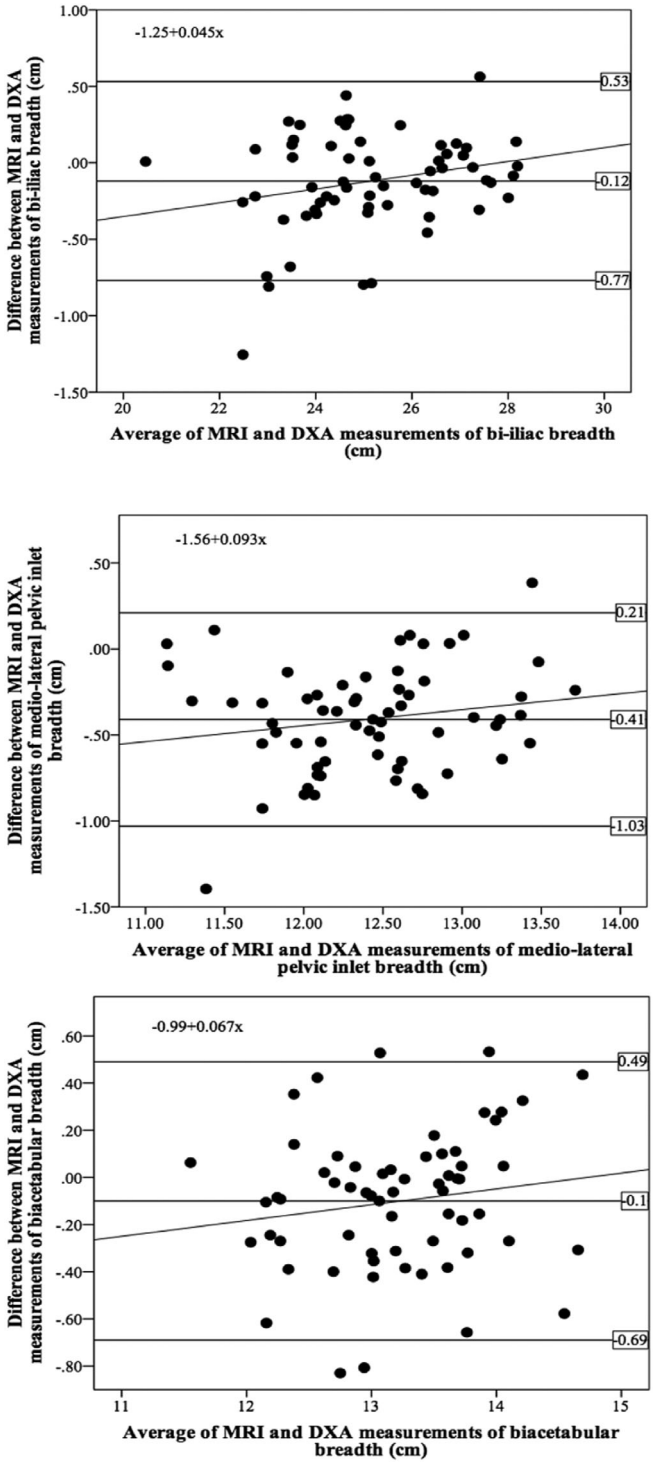

FIGURE 3 Bland–Altman analysis of agreement between magnetic resonance imaging (MRI) and dual energy X-ray absorptiometry (DXA) measurements of bi-iliac breadth, medio-lateral pelvic inlet breadth and bi-acetabular breadth in a sample of 63 women. The horizontal line on the upper portion of the graph shows the upper limit, the horizontal line in the middle of the graph shows the mean difference between MRI and DXA values and the horizontal line on the lower part of the graph shows the lower limit. The bias is calculated as MRI values minus DXA values. The regression line equations are shown in the top left of the plots

percentages in Table 4. DXA measurements were consistently smaller than MRI measurements of the same pelvic dimensions (e.g., DXA measurements of bi-iliac breadth were 0.22% smaller than MRI measurements of bi-iliac breadth), with the average magnitude of the difference below 2% for all pelvic measures. Bi-acetabular breadth measurements demonstrated the smallest difference between MRI and DXA (0.10 cm), while the largest difference between methods was observed formedio-lateral pelvic breadth (−0.41 cm).

3.3 | Measurement technique agreement

Table 4 displays results of a Bland–Altman analysis and linear regression of mean bias and differences between MRI and DXA measurements. Figure 3 shows Bland–Altman plots for bi-iliac breadth, medio-lateral pelvic inlet breadth and bi-acetabular breadth. Results of linear regression analyses of mean bias showed no statistically significant relationship between mean bias and the differences between MRI and DXA pelvic measurements, suggesting that there is no proportional bias for any of the pelvic measurements examined in this study. Bi-iliac breadth measurements had the highest correlation between mean bias and differences between MRI and DXA measurements, though this correlation (R^2 .055, p .063) was not statistically significant. Bi-iliac breadth measurements had the largest limits of agreement at 7.6% followed by medio-lateral inlet breadth and bi-acetabular breadth. Bi-iliac breadth and bi-acetabular breadth measurements had a bias below 1%.

Results of linear regression analyses between MRI and DXA pelvic measurements are presented in Table 5 and Figure 4, showing MRI pelvic measurements regressed on DXA pelvic measurements. Relationships between all MRI and DXA measurements of all pelvic variables were statistically significant. MRI and DXA measurements of bi-iliac breadth had the highest correlation (R^2 .96), followed by bi-acetabular breadth (R^2 .83) and medio-lateral inlet breadth (R^2 .77).

4 | DISCUSSION

This study addresses the applicability of medical imaging in collecting skeletal measurements from living women, with the aim of examining systematic differences between DXA and MRI measurements of linear skeletal data. The same measurements of pelvic breadth were collected from MRI and DXA scans of a sample of living women and the two techniques were compared. Tests demonstrated that DXA measurements of pelvic breadth

TABLE 5 Results of the linear regression of pelvic variables measured using magnetic resonance imaging (MRI) regressed on the same variables measured using dual-energy X-ray absorptiometry (DXA)

	SE	Beta	*t*	R^2	*p**	95% CI lower	95% CI upper
BIIB	0.03	0.98	41.69	.96	.000*	0.98	1.08
INML	0.07	0.88	14.37	.77	.000*	0.83	1.09
BIAC	0.06	0.91	17.43	.83	.000*	0.86	1.09

Note: Pelvic variables include bi-iliac breadth (BIIB), medio-lateral inlet breadth (INML) and bi-acetabular breadth (BIAC). *Values are significant at $p < .05$.

are less technically precise over four replications than MRI measurements of the same variables. DXA measurements were also consistently lower than MRI pelvic trait measurements by 1.5%. Overall, bi-iliac breadth measurements were closest in agreement across imaging methods, while bi-acetabular breadth and medio-lateral inlet breadth demonstrated lower measurement agreement. Bland–Altman analyses did not show systematic differences between different methods of collecting pelvic skeletal from the scans of living women.

The MRI scans of the pelvis in this study are higher in resolution and clarity than the DXA scans, making for easier visualization of the anatomical landmarks used to collect pelvic breadth measurements. This suggests that between MRI and DXA imaging methods, MRI would be the preferred option. However, the higher financial cost of MRI, alongside the relatively low radiation dose of DXA when compared to other radiation-emitting medical imaging methods (Bazzocchi et al., 2016), presents DXA as a viable option for collecting in vivo measurements of the bony pelvis. It is, however, important to note that neither the MRI nor DXA pelvic trait measurements collected in this study should be assumed to be a "correct" or "true" set of values. That is, there is no gold standard method against which to compare either imaging method when collecting linear skeletal measurements from living people. Collecting measurement data from medical imaging does not yield the same accuracy as collecting measurements directly from the human body, however collecting in vivo measurements of the pelvis is only possible and ethical through medical imaging. Measurement error and bias exist in data collected from both MRI and DXA. Bias in quantitative analysis of MRI scans may result from partial volume effects, head tilt, plane of view, use of noncontiguous slices, contrast or intensity manipulations, and magnetic inhomogeneities (Plante & Turkstra, 1991). Similar sources of bias may also exist in DXA scans. Previous studies collecting linear measurements from DXA scans found variation in interobserver reliability. For instance, Abrahamyan et al. (2008) found, in terms of coefficient of variation, ±1.21% for humeral measurements, ±1.45% for radial measurements, ±0.77% for femoral measurements, and ±0.98% for tibial measurements.

One of the major challenges of collecting pelvic breadth data from MRI and DXA scans is the nature of the image of the pelvis produced by these methods. This is primarily a result of the differing visual perspectives in which the pelvis is presented. The bony pelvis is a three-dimensional structure, however in this study MRI and DXA scans were handled in two-dimensions. A two-dimensional view limits the types of measurements that can be collected from these images. MRI scans are built from multiple image slices moving from anterior to the posterior aspect of the body. In this study, these image slices could not be collated to create three-dimensional models of the pelvis, meaning that linear measures of pelvic depth (e.g., depth from the posterior aspect of the pubis to the anterior aspect of the coccyx) could not be collected. DXA scans produce a single image of the pelvis from an anterior perspective, meaning that pelvic depth measurements are similarly unavailable. It should be noted that Novotny et al. (2000) collected a pelvic depth measurement from DXA scans (vertical distance between the pubic symphysis and the promontory of the sacrum). This may be accurate when collecting osteometrics from a Hologic DXA scanner (as Novotny and colleagues did), however given variation in buttock adipose tissue in participants that could tilt the pelvic girdle, pelvic depth measurements were not collected in this study. It should also be noted that Novotny et al. (2000) collected their scan data using a Hologic Model 200 (Hologic USA) scanner in fan-beam mode. In the present study, scan data were collected on a GE Lunar Prodigy whole-body DXA scanner (GE Medical Systems, UK), which includes a narrow fan-beam, increasing the resolution and image quality (Bazzocchi et al., 2016).

Pelvic *breadth* measurements can be collected from both MRI and DXA scans. The manner in which breadth measurements are collected differs between MRI and DXA scans. Pelvic breadth measurements collected from MRI scans are collected at slightly different points of scan depth and the researcher must identify the depth that contains the anatomical landmark of interest. It is recommended that the researcher initially work with a radiographer or similarly experienced technician to recognize key pelvic anatomical structures in MRI scan images. Pelvic breadth measurements collected from DXA scans are

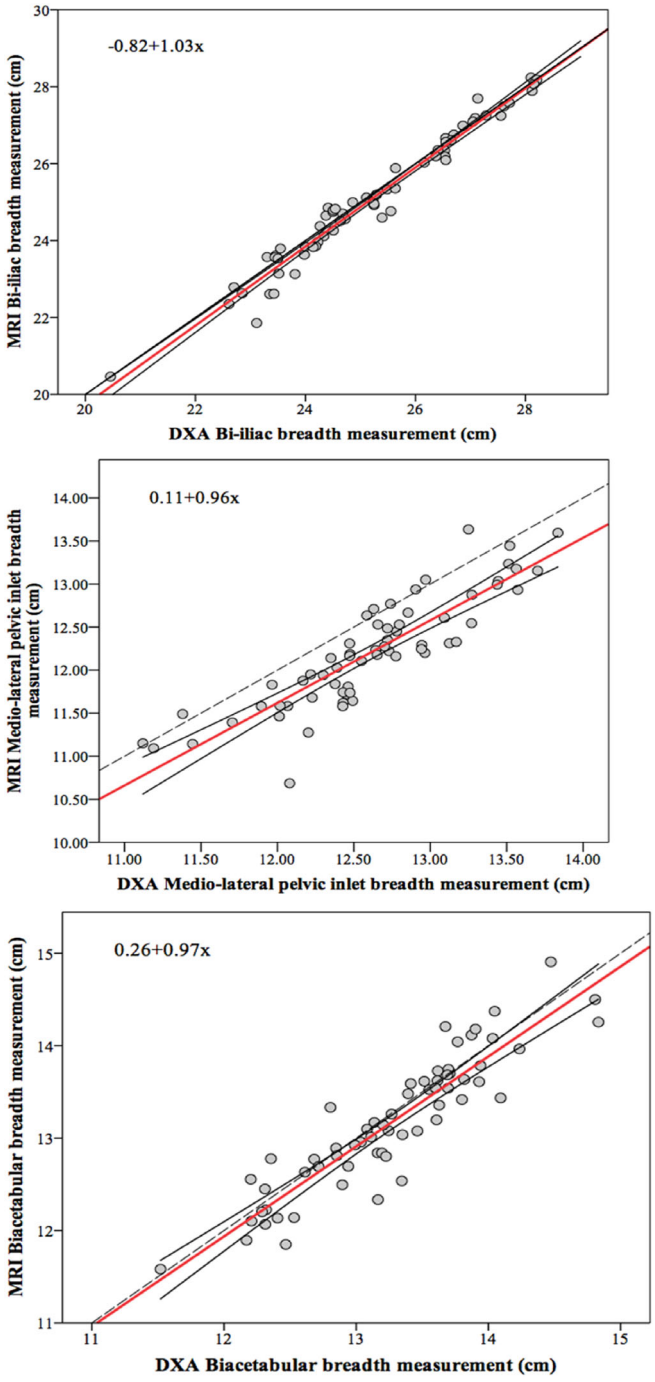

FIGURE 4 Linear regression plots of pelvic variables measured using magnetic resonance imaging (MRI) and dual energy X-ray absorptiometry (DXA) including bi-iliac breadth, medio-lateral pelvic inlet breadth and bi-acetabular breadth. Regression line equations are shown in the top left of the plots. Regression line is shown in red and dashed line represents line of identity

collected from a static image, with the researcher simply increasing the magnification of the image to identify the anatomical landmark for a specific measurement. While DXA and MRI scans give a detailed image of the pelvis, there is a marked difference in identifying bony anatomical landmarks digitally compared to pinpointing them on dry bone. This study suggests the feasibility of using imaging to measure skeletal dimensions, however it should be noted that these methods are distinctly different from tactile osteometric data collection from dry bone.

Anatomical landmarks for the bi-acetabular breadth and medio-lateral inlet breadth measurements proved more challenging to locate in both MRI and DXA scans, which may explain why measurement agreement was poorer than for bi-iliac breadth. It is likely that issues of locating the necessary anatomical landmark notably affected the medio-lateral inlet breadth measurement. The midpoint of the arcuate line was sometimes difficult to isolate on the DXA scans due to poor image quality once the DXA scan image was maximized. Image quality may differ between models of DXA scanner. For example, the GE Lunar iDXA, a narrow fan-beam densitometer with a greater number of detectors, provides improved resolution (1.05 mm longitudinally, 0.6 mm laterally) and image quality compared to other GE DXA models (Bazzocchi et al., 2016). Both medio-lateral inlet breadth and bi-acetabular breadth measurements necessitated different visualizations of anatomical landmarks on MRI compared to DXA. This was necessary for the different methods, though likely contributed to significant differences between measurement sessions. The position of the participant during initial scanning may also affect ability to visualize anatomical landmarks. Lambrinoudaki et al. (1998) have reported significant differences in DXA calculation of body mass from scans of patients lying in supine vs. prone positions on the examination table. Participants in this study were all in supine position for MRI and DXA scanning procedures.

Generalizability of our findings is limited to some extent by sample characteristics and measurement procedure. The sample used for this study is relatively homogenous in ancestry (as all participants were of South Asian ancestry) and tightly clustered in age—this allows for clear interpretation of results but may not be directly applicable to other living populations. Measurement procedure could be improved by including an inter-observer error study to better quantify error in measurement procedure between researchers, including making use of the extra replications used in this study to examine error rate with time intervals between replications. This would be especially instructive for osteological researchers making use of these types of imaging methods for the first time.

This study builds on Shirley et al.'s (2020) work examining pelvic size variation from a developmental origins perspective by demonstrating the applicability of DXA imaging for collecting skeletal measurement in vivo, as

DXA imaging is more financially accessible, has lower radiation exposure and is more frequently used in clinical studies than MRI. This study also adds to the paucity of studies on the use of DXA scans for examining change in body size and skeletal linear measurements throughout growth (Völgyi et al., 2010). Decrausaz and Cameron (2022) have recently outlined the value of using clinical studies of child growth, specifically those including medical imaging, to address palaeopathological investigations of child health. The combination of detailed lifestyle data (such as dietary intake or hours of physical activity) and medical imaging data (such as MRI or DXA) that are included in clinical studies of child growth or clinical studies examining variation in adults allows for clarification of the factors that shape bone growth and variation in humans. The results of this work suggest that the collection of skeletal dimension data from medical imaging such as DXA and MRI scans is biologically representative and a fruitful area for creating multidisciplinary collaborations and generating evolutionarily-relevant research questions.

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AUTHOR CONTRIBUTIONS

Sarah-Louise Decrausaz: Conceptualization (lead); data curation (equal); formal analysis (lead); investigation (lead); methodology (equal); project administration (lead); validation (equal); visualization (equal); writing – original draft (lead); writing – review and editing (lead). **Meghan K. Shirley:** Conceptualization (equal); formal analysis (equal); investigation (equal); methodology (supporting); project administration (supporting); validation (equal); visualization (supporting); writing – review and editing (equal). **Jay T. Stock:** Conceptualization (equal); formal analysis (equal); investigation (supporting); methodology (supporting); project administration (supporting); supervision (lead); validation (equal); visualization (supporting); writing – review and editing (equal). **Jane E. Williams:** Conceptualization (supporting); writing – review and editing (supporting). **Mary S. Fewtrell:** Methodology (supporting); writing – review and editing (supporting). **Chris A. Clark:** Writing – review and editing (supporting). **Owen J. Arthurs:** Writing – review and editing (supporting). **Jonathan C. K. Wells:** Conceptualization (equal); formal analysis (supporting); investigation (supporting); methodology (supporting); supervision (lead); validation (equal); visualization (equal); writing – review and editing (equal).

CONFLICT OF INTEREST

None of the authors of this manuscript have any conflicts of interest to report.

DATA AVAILABILITY STATEMENT

Data available on request due to privacy/ethical restrictions.

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