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Original article

Regional variation in bone mineral density of the distal radius

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ABSTRACT

Objectives: This study investigates the regional variation in areal bone mineral density (aBMD) at the distal radius, a critical site for osteoporosis-related fractures. Understanding aBMD distribution is essential for accurate diagnosis and management of osteoporosis.
Methods: The study involved 261 participants aged over 50. Using dual-energy X-ray absorptiometry (DXA) scans, aBMD was recorded across contiguous regions of the distal radius. Factors considered include age, sex, and hand dominance, providing a comprehensive view of aBMD distribution.
Results: The findings indicated a consistent pattern in aBMD distribution along the radius, with a plateau around the one-third distance from the wrist. Notably, significant differences in aBMD were observed between age groups, especially among post-menopausal women. The study also recorded minor variations in aBMD between dominant and non-dominant forearms.
Conclusions: The study's insights into aBMD variation at the distal radius have implications for osteoporosis research and clinical diagnosis. It highlights the importance of standardized region of interest placement in DXA scans for accurate assessment.

1. Introduction

Osteoporosis is a systemic skeletal disease leading to the progressive reduction in bone mineral density (BMD) and microarchitectural integrity, significantly increasing the likelihood of low impact fragility fractures [1]. Affecting over 3 million people in the UK [2], it is estimated that 1 in 2 adult women and 1 in 5 men will have 1 or more fragility fractures in their lifetime, associated with increased morbidity and mortality, as well as an increased healthcare burden [1]. Curtis et al. [3] report that between 1988 and 2012, the UK rate of fragility fractures in those 50 years and over is 38.4 and 98.6 per 10,000 person-years in men and women, respectively, with the most common fracture sites being the hip, spine, humerus and ulna/radius. Specifically, fracture rates reported for the ulna/radius were 8.9 and 39.7 fractures per 10, 000 person-years in men and women, respectively [3].

Dual Energy X-ray Absorptiometry (DXA) scans remain the mainstay of osteoporosis diagnosis. DXA scans of the forearm are commonly protocolled for use to assess osteoporosis when scans of the neck of femur and lumbar spine are unavailable, either due to hip replacements, vertebral fractures, or if the patient's weight exceeds the scanner table capacity [4]. In addition, the radius may be considered for specific clinical scenarios, such as for patients with hyperparathyroidism, where BMD changes at the radius are uniquely affected [5].

It is clinically important to consider the regional variation of areal BMD (aBMD) across the radius and its potential effects on DXA precision, particularly in situations of longitudinal monitoring. The International Society of Clinical Densitometry (ISCD) currently recommends the DXA assessment is the 33% radius or one-third radius region of interest (ROI) of the non-dominant forearm [6]. Rosen et al. [7] reported no significant change in aBMD for minor variations in ROI placement at the one-third radius, adding further support to the reliability of this measurement site. Conversely, despite ISCD guidance [6], there is variation in the ROI used for DXA scans between manufactures [8] and this may contribute to variability in results between different scanners.

Whilst not recommended as a routine primary clinical measurement site for DXA, the alternative ultra-distal ROI of the radius is often presented on DXA systems and may still also hold value in clinical and research settings. Evidence does exist around the importance of protocolled and consistent ROI placement for reliable measurement at this site. Rosen et al. [7] report that minor changes of 1 mm increments can significantly affect aBMD measurements of the ultra-distal radius. Ghasen-Zadah et al. [9] report on the importance of considering forearm

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length and cross-sectional area of the distal radius if considering comparison of data between participants.

Existing research focuses on reliability at the one-third and ultra-distal ROI sites alone, this study aims to expand on this by modeling the change in regional aBMD across the distal third of the radius. This study enables further insight into the physiology of the radius and will help inform future research into the radius as an anatomical site of interest for DXA. Trends based on biological sex, age, and hand dominance were also considered.

2. Methods

Data was sourced from a concurrently running study reviewed and approved by the UK Health Research Authority (21/LO/0772). This study was carried out at the University of Exeter. All participants gave their written informed consent prior to scans taking place. Forearm DXA scans were performed on 261 volunteer participants using a GE Lunar Prodigy DXA scanner (GE encore V 14.10.022 (Madison, WI, USA)). A daily calibration test with a phantom was performed by the operator and checked for no lateral drift of the scanner over the data collection period. Eligibility criteria was age over 50 without a history of wrist fracture. Patient demographics are reported in Table 1. No participants reported a known diagnosis of hyperparathyroidism.

Forearm scans were taken with the patient seated and their forearm resting horizontally in the AP position with their hand in a gentle clenched fist [10]. Usually, each participant had both forearms scanned although forearms with a history of fracture or radio-opaque implants were excluded meaning in some instances only one forearm was scanned. A field of view of 10.0 cm by 15.1 cm was used in line with local clinical protocols.

A data analysis template was used to ensure consistent ROI positioning. Within the scanner software, a template was created with regions of interest 1.5 cm long, extending from the end plate of the radius proximally with each region overlapping the previous one by 50%, up to 16 regions of interest were used depending on the length of the forearm scanned (see Fig. 1). The forearm length was measured using a tape measure from the tip of the ulnar styloid process to the proximal end of the ulna olecranon process.

The mean value of the areal bone mineral density (aBMD) within each ROI was derived by the DXA system and noted across participants. Each ROI was assigned a value representative of the distance from the center of the ROI and the distal starting point of measurements at the cortical endplate of the distal radius.

Descriptive and differential statistical analysis was conducted using R version 4.2.2. Means and standard deviation are presented having confirmed data is parametric.

3. Results

DXA scans of 503 forearms were included from 261 participants, comprising 220 male and 283 female forearms. 252 right forearms were scanned with 224 being dominant, and 251 left forearms were scanned with 26 being dominant. Missing data was due to only 1 wrist being scanned in cases of past fracture, or inadequate scan quality. Summary statistics on the participant characteristics are in Table 1, including T-scores from conventional ultra-distal and distal third radius ROIs based on a clinical DXA protocol. Fifty-nine participants were classified as having osteoporosis on the basis of their spine and/or hip T-scores. This resulted in 58 right and 57 left forearms in our study from participants with osteoporosis.

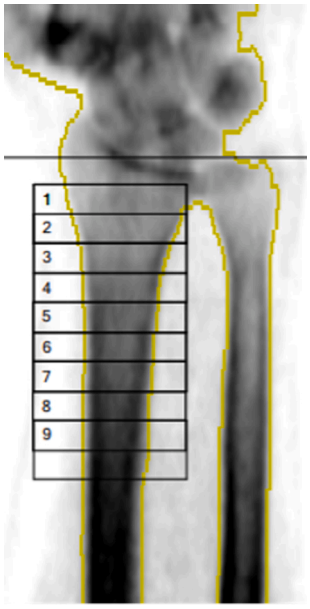

Fig. 1. Example DXA scan output showing placement of regions of interest (ROI). ROIs were 1.5 cm wide and placed at 1.5 cm overlapping intervals. ROIs were described by the center point relative to the distal cortex of the radius (ie, 0.75 cm, 1.5 cm, 2.25 cm etc.).

Minimum aBMD was recorded at the most distal ROI for all forearms, except for in 3 of 254 participants. Figures 2 and 3 and Tables 2 and 3 demonstrate the trend of aBMD values plotted as distance from the ultra-distal cortical end plate of the radius for males and females stratified by age deciles. Trends were also considered based on hand dominance as shown in Fig. 4 and Table 4.

The position of the one-third radius length was calculated for each participant and compared to the maximum aBMD value measured. The maximum aBMD values occurred within ± 1 cm of the 1/3 measurement position for 281 scans (56%) and within ± 2 cm for 438 scans (87%).

4. Discussion

The results from this cohort demonstrated a moderate positive correlation between BMD and distance from the ultra-distal radius proximally $r\,(7527) = 0.61$, $P < 0.001$ across all ages and age deciles. aBMD plateaus around one-third aBMD ROI measurement site, supporting its use as a versatile measurement site. The one-third distance is approximately 7.5–10.0 cm for the majority of forearms scanned (mean 9.3 cm (SD0.4) for males and 8.3 cm (SD0.7) for females). As expected, aBMD values are higher in males across the cohort, however, a similar trend in aBMD change across the distal radius is observed in both sexes.

Table 1
Summary of participant characteristics (SD, standard deviation; DXA, dual x-ray absorptiometry; aBMD, areal bone mineral density; TD distal-third; UD, ultra-distal).

	Mean (SD; N = 503)	Range	Female (N = 283)	Male (N = 220)	Dominant (N = 250)	Non-dominant (N = 253)
Age, yrs	71 (9.0)	50–94	70 (9.6)	73 (7.9)	71 (9.0)	71 (9.0)
Forearm length, cm	26.2 (2.0)	21.4–31.5	24.9 (1.4)	27.8 (1.3)	26.2 (2.0)	26.1 (2.0)
Distal-third radius length, cm	8.7 (0.8)	7.1–10.5	8.3 (0.7)	9.3 (0.4)	8.7 (0.9)	8.7 (0.7)
DXA T-score UD	−1.3 (1.9)	−6.1–3.3	−2.1 (1.8)	−0.3 (1.6)	−1.2 (1.9)	−1.4 (1.9)
DXA T-score TD	−1,2 (1.4)	−5.7–2.8	−1.7 (1.4)	−0.6 (1.0)	−1.2 (1.4)	−1.3 (1.4)

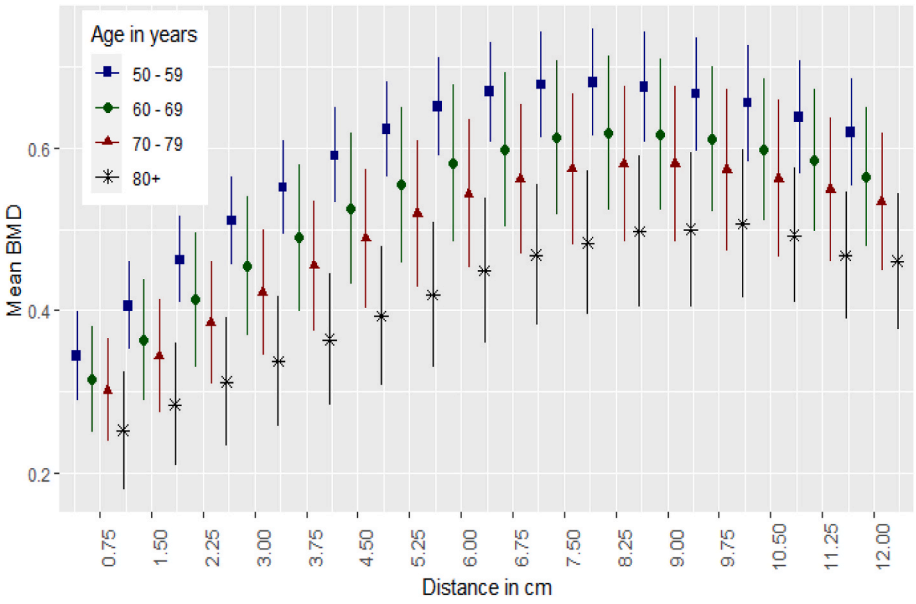

Fig. 2. Summary of mean ROI aBMD relative to anatomical distance to the cortical end plate of the distal radius for females, separated for age groups (ages 50–59 N = 53; 60–69 N = 73; 70–79 N = 123; over 80 N = 34). Error bars represent ± 1 standard deviation.

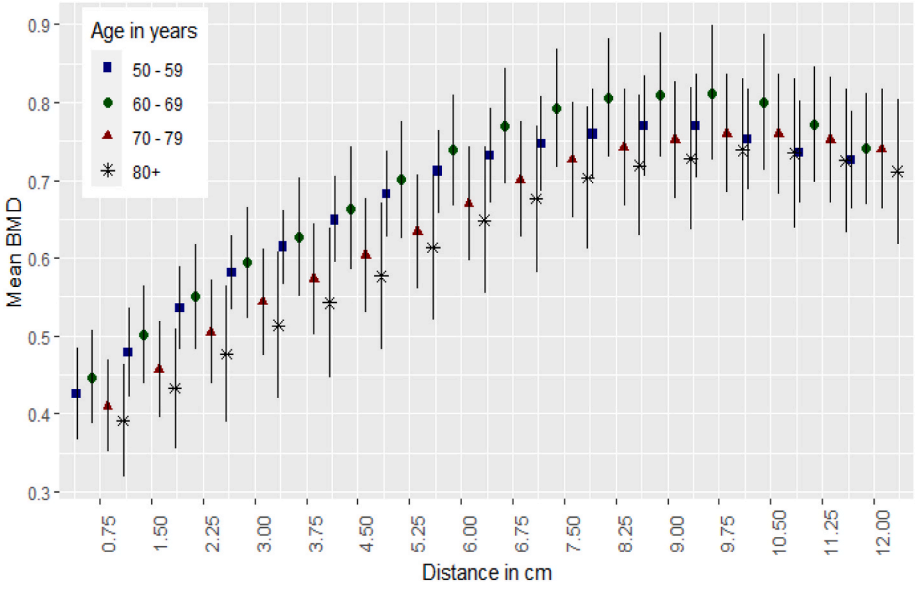

Fig. 3. Summary of mean ROI aBMD relative to anatomical distance to the cortical end plate of the distal radius for males, separated for age groups (ages 50–59 N = 19; 60–69 N = 49; 70–79 N = 111; over 80 N = 41). Error bars represent ± 1 standard deviation.

4.1. aBMD changes with age

Figures 3 and 4 demonstrate a general trend for decreasing aBMD with age although the changes between 50–59 and 60–69 age deciles are more marked in females, as is expected with menopause. There is a notable decrease in aBMD for those aged over 80 with a larger decrease more proximally (at 6–8 cm) than distally (1–2 cm). In general, as expected the female measurements appear to show a larger decrease in aBMD with age than that seen in males [3].

4.2. Dominant vs non dominant aBMD

The ISCD guidelines recommend DXA scans are carried out on the non-dominant forearm [6] implying that there is a difference between dominant and non-dominant aBMD. A paired T-test was performed for the 242 participants where both forearms were scanned and the results compared for each ROI. As demonstrated in Table 4, whilst there is a statistically significant difference between the non-dominant and dominant forearms (P-value < 0.01; paired T-test; N = 242), with the dominant having a higher aBMD, the difference in measurements is small and unlikely to have clinical significance. As such the data supports the ISCD guidance but reassures that in instances where only 1 wrist DXA scan is available, results are still likely justified for research or clinical use.

4.3. Ultra-distal aBMD compared to one-third aBMD

The aBMD at the ultra-distal radius is approximately half of the aBMD of one-third radius in the population studied (see Table 2). This is comparable with the Framingham Osteoporosis Study [11] which

Table 2
Summary of areal bone mineral density results for female participants bracketed for age, as illustrated in Fig. 2.

Distance of ROI center from cortical endplate of radius (cm)	Female age brackets (N = 283)			
	Age 50–59 (N = 53)	Age 60–69 (N = 73)	Age 70–79 (N = 123)	Age 80+ (N = 34)
0.75	0.343 (0.054)	0.315 (0.065)	0.301 (0.063)	0.252 (0.072)
1.50	0.405 (0.054)	0.363 (0.074)	0.343 (0.069)	0.284 (0.075)
2.25	0.462 (0.053)	0.413 (0.082)	0.385 (0.074)	0.312 (0.078)
3.00	0.510 (0.054)	0.454 (0.086)	0.422 (0.076)	0.337 (0.079)
3.75	0.551 (0.058)	0.489 (0.089)	0.455 (0.079)	0.364 (0.080)
4.50	0.590 (0.058)	0.524 (0.093)	0.488 (0.085)	0.393 (0.085)
5.25	0.623 (0.059)	0.554 (0.095)	0.518 (0.089)	0.419 (0.088)
6.00	0.651 (0.060)	0.580 (0.096)	0.544 (0.091)	0.449 (0.088)
6.75	0.669 (0.061)	0.598 (0.094)	0.561 (0.091)	0.468 (0.086)
7.50	0.677 (0.064)	0.613 (0.094)	0.574 (0.093)	0.483 (0.088)
8.25	0.680 (0.065)	0.618 (0.094)	0.580 (0.095)	0.497 (0.092)
9.00	0.675 (0.067)	0.616 (0.092)	0.580 (0.096)	0.500 (0.094)
9.75	0.666 (0.069)	0.610 (0.089)	0.572 (0.098)	0.507 (0.090)
10.50	0.655 (0.071)	0.598 (0.086)	0.562 (0.096)	0.492 (0.083)
11.25	0.638 (0.070)	0.585 (0.086)	0.548 (0.088)	0.467 (0.077)
12.00	0.619 (0.066)	0.565 (0.085)	0.534 (0.084)	0.460 (0.083)

Values are described as mean (1 standard deviation).

showed that the ultra-distal aBMD in older males and females was approximately 50% of the radial shaft aBMD. The difference was found to be approximately 33% in a Japanese cohort [12].

4.4. Implications and limitations

The ISCD Guidelines [6] recommend that the forearm aBMD reading is taken at one-third distal radius, and our results show that positioning is important. If the reading is taken too distally the value is likely to be significantly less than that at one-third distal position and this could have implications for diagnosis and treatment. Positioning the measurement distally by more than 2 cm is likely to lead to a lower reading due to the regional decrease in strength towards the wrist, rather than a lower actual aBMD relative to population databases.

The regional changes in aBMD are perhaps intuitive when the anatomy of the distal radius is considered. Composition of the radius varies along its length, with the ultra-distal end containing predominantly trabecular bone, transitioning through the mid-distal and one-third zones where the bone structure contains predominantly cortical bone with fatty marrow [13]. Ghasem-Zadeh et al. [9] report that the total bone mass can be expected to remain approximately constant along the distal third of the radius while the cross sectional area increases towards the ultra-distal end, resulting in decreased density of trabecular bone at the ultra-distal radius.

The variation of regional changes in aBMD within the distal radius is a topic of interest for further research. Observable changes in the aging and/or progression of osteoporosis in the distal radius may give valuable insight into the fragility fracture risk of the radius, and optimize the measurement of the radius. Cortical bone generally reduces in thickness with age and increases in porosity [14]. Gautam [13] also reports that trabecular bone loss starts earlier than cortical bone loss. It may therefore be expected that aBMD in the ultra-distal radius is particularly susceptible as an early fracture site due to inherently reduced cortical thickness and higher proportion of trabecular bone. This could be a contributor to the increased incidence of ultra-distal forearm fractures in early post-menopausal women. Further research would benefit here incorporating high-resolution peripheral computed tomography to give insight into changes in cortical thickness and trabecular integrity with age and/or osteoporosis integrity, and subsequent changes in the radial aBMD measures observed. This might include the pattern of aBMD changes along the length of the distal radius, as well as absolute changes in BMD. Research such as this may also have an application to surgical decision making of radius fractures, where consideration of regional aBMD is pivotal in estimating the likely success of open reduction internal fixation of radial fractures [15].

Our results should be observed in context with some inherent limitations. The participant cohort is predominately Caucasian and different physiological distribution of aBMD across the ultra-distal radius may be expected in other ethnicities. The cohort size is modest but representative of the population of interest for DXA scanning. The participants for

Table 3
Summary of areal bone mineral density results for male participants bracketed for age, as illustrated in Fig. 3.

Distance of ROI center from cortical endplate of radius (cm)	Male age brackets (N = 220)			
	Age 50–59 (N = 19)	Age 60–69 (N = 49)	Age 70–79 (N = 111)	Age 80+ (N = 41)
0.75	0.425 (0.059)	0.446 (0.060)	0.410 (0.059)	0.391 (0.071)
1.50	0.478 (0.056)	0.500 (0.063)	0.456 (0.062)	0.432 (0.076)
2.25	0.535 (0.053)	0.550 (0.067)	0.505 (0.066)	0.476 (0.086)
3.00	0.581 (0.046)	0.593 (0.070)	0.543 (0.068)	0.513 (0.094)
3.75	0.614 (0.047)	0.627 (0.076)	0.573 (0.070)	0.542 (0.096)
4.50	0.648 (0.055)	0.663 (0.078)	0.602 (0.072)	0.576 (0.093)
5.25	0.682 (0.054)	0.700 (0.075)	0.633 (0.073)	0.613 (0.093)
6.00	0.711 (0.053)	0.738 (0.071)	0.669 (0.073)	0.648 (0.094)
6.75	0.731 (0.061)	0.769 (0.073)	0.701 (0.073)	0.676 (0.094)
7.50	0.747 (0.061)	0.792 (0.076)	0.726 (0.073)	0.702 (0.091)
8.25	0.759 (0.058)	0.805 (0.076)	0.741 (0.075)	0.718 (0.090)
9.00	0.769 (0.064)	0.809 (0.080)	0.751 (0.074)	0.727 (0.090)
9.75	0.769 (0.066)	0.811 (0.086)	0.759 (0.075)	0.738 (0.091)
10.50	0.752 (0.064)	0.800 (0.087)	0.759 (0.077)	0.734 (0.096)
11.25	0.735 (0.065)	0.771 (0.074)	0.751 (0.081)	0.725 (0.092)
12.00	0.726 (0.062)	0.740 (0.070)	0.739 (0.076)	0.710 (0.093)

Values are described as mean (1 standard deviation).

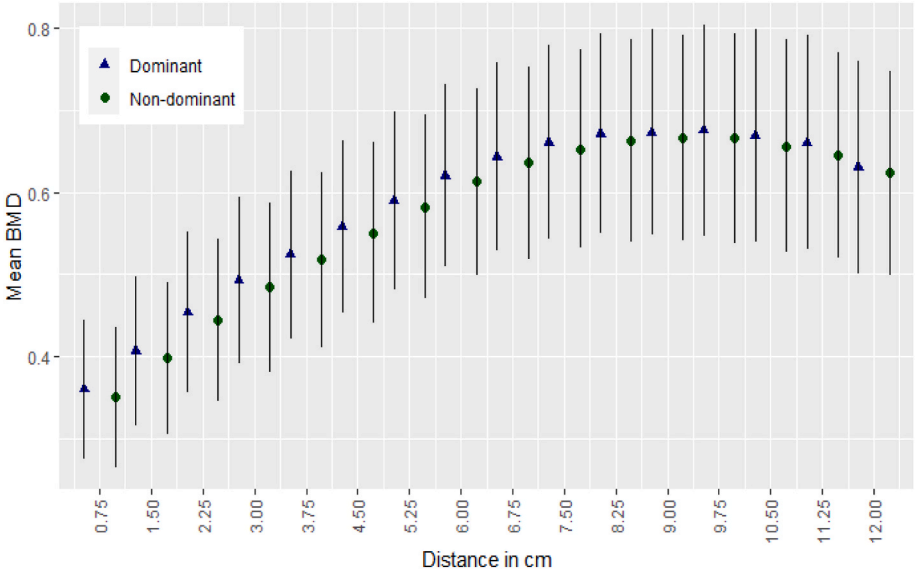

Fig. 4. Summary of mean aBMD for each ROI relative to anatomical distance to the cortical end plate of the distal radius for dominant (N = 242) and non-dominant (N = 242) forearms. Error bars represent ± 1 standard deviation.

Table 4
Summary mean (standard deviation) results of areal bone mineral density (aBMD; g/cm^2) between dominant (N = 242) and non-dominant (N = 242) hands for each of the most distal 12 ROI. A statistically significant reduction in the non-dominant wrist was observed between all ROI placements in paired data (N = 242; P-value < 0.01; paired T-test).

Distance of ROI center from cortical endplate of radius (cm)	aBMD of all forearms (N = 503)	aBMD of dominant forearms (N = 242)	aBMD of non-dominant forearms (N = 242)	Difference in aBMD	Paired T-test P-value
0.75	0.354 (0.085)	0.359 (0.084)	0.350 (0.086)	0.009	< 0.001
1.50	0.401 (0.091)	0.405 (0.089)	0.397 (0.093)	0.008	< 0.001
2.25	0.448 (0.098)	0.452 (0.097)	0.443 (0.099)	0.009	< 0.001
3.00	0.487 (0.102)	0.491 (0.100)	0.483 (0.103)	0.008	< 0.001
3.75	0.520 (0.104)	0.523 (0.101)	0.517 (0.107)	0.006	< 0.001
4.50	0.553 (0.107)	0.556 (0.104)	0.550 (0.110)	0.006	< 0.001
5.25	0.585 (0.110)	0.588 (0.107)	0.581 (0.112)	0.007	< 0.001
6.00	0.615 (0.112)	0.619 (0.110)	0.612 (0.115)	0.007	< 0.001
6.75	0.638 (0.116)	0.642 (0.114)	0.635 (0.117)	0.007	< 0.001
7.50	0.656 (0.119)	0.660 (0.118)	0.652 (0.121)	0.008	< 0.01
8.25	0.666 (0.121)	0.670 (0.121)	0.662 (0.122)	0.008	< 0.001
9.00	0.669 (0.124)	0.672 (0.124)	0.666 (0.125)	0.006	< 0.001
9.75	0.670 (0.128)	0.674 (0.128)	0.665 (0.127)	0.009	< 0.001
10.50	0.662 (0.129)	0.667 (0.129)	0.656 (0.130)	0.011	< 0.001
11.25	0.652 (0.127)	0.659 (0.130)	0.645 (0.124)	0.014	< 0.001
12.00	0.626 (0.125)	0.629 (0.128)	0.623 (0.123)	0.006	< 0.01

Values are described as mean (1 standard deviation).

this study had no history of radial fracture. It is possible and of interest that there is a more significant decrease in ultra-distal regional aBMD in those people with history of radial fragility fracture.

With an aging population, it is becoming ever more important to have accurate ways to identify people who are at risk of a fragility fracture. DXA scans or alternative assessment methods of the radius are an obvious site to try and help identify patients at risk [16]. However, regional variation of aBMD and anatomical changes along the distal radius are important considerations.

5. Conclusions

This study has given insight into regional aBMD distribution of the distal radius as measured by DXA. The trends observed highlight the importance of reliability assessment and standardization in ROI placement when undertaking DXA assessment of the ultra-distal radius in the context of both longitudinal assessment and comparison between participants in a research setting.

CRediT author statement

Helen Morgan: Data curation, Formal analysis, Writing – original draft. **Katy Knight:** Data curation, Validation. **Robert Meertens:** Conceptualization, Writing – original draft, Writing – review & editing.

Conflicts of interest

The authors declare no competing interests.

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contributed their time towards data collection. **ORCID** Helen Morgan: 0009-0006-8099-0930. Katy Knight: 0009-0001-8934-1199. Robert Meertens: 0000-0002-2120-8877.

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