ORIGINAL ARTICLE

Quantifying the ossification and fusion of the calcaneal apophysis using computed tomography

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Abstract

Knowledge of the anatomical development of the calcaneal apophysis is essential in clinical assessment and management of both paediatric and sub-adult patients presenting with heel pain. Despite this, the current understanding of calcaneal apophyseal development is constrained by the limitations of the imaging modalities used to examine the apophysis, with no current literature reporting the development of the medial and lateral processes. This study aimed to overcome these limitations by investigating the ossification and fusion of the calcaneal apophysis using three-dimensional computed tomography analysis, and statistically predicting the apophyseal developmental stage in contemporary Australian children. The development and fusion status of the apophysis was scored using a novel 11-stage scoring system on 568 multi-slice computed tomography scans (295 females; 274 males) and 266 lateral radiographic scans (119 females; 147 males) from the Queensland Children's Hospital. Multinomial logistic regression along with classification tables and predictive probabilities were then utilised to assess developmental stage likelihood from known age and sex. The apophysis commenced ossification at a mean age of 5.2 years for females and 7.2 years for males, and then elongated to form the apophyseal cap around 10 years for females and 12.4 years for males. Fusion of the apophysis commenced at a mean age of 11.18 years for females and 13.3 years for males, with the earliest age of complete fusion observed at 10 years for females and 14 years for males. The results demonstrate significant sexual dimorphism in ossification and fusion with females developing and fusing significantly earlier. Furthermore, the use of computed tomography in this study allowed for the first time evaluation of the ossification and fusion of the medial and lateral processes of the calcaneus. The medial process formed at a mean age of 9.5 years for females and 10.9 years for males while the lateral process formed at around 9.8 years for females and 11.7 years for males. The medial process demonstrated slower rates of fusion compared to the lateral process. The present study provides Queensland specific standards for assessing the calcaneal apophyseal developmental stage as well as novel predictive regression models for apophyseal stage estimation using known age and sex to aid in the diagnosis of heel pain conditions such as apophysitis or screen for developmental delays in children and subadults.

1 | INTRODUCTION

The calcaneal apophysis or traction epiphysis is a secondary ossification centre located posterior to the body of the calcaneus, that develops in early childhood. Knowledge of the anatomical spatial and temporal development of the apophysis and its relationship with the calcaneus is essential in the clinical assessment and management of both paediatric and sub-adult patients. Heel pain in children is extremely common and is typically diagnosed as calcaneal apophysitis in children aged 8–14 years, using either lateral radiographs or physical assessment (Kose, 2010; Kose et al., 2010; Volpon & de Carvalho Filho, 2002; Wiegerinck et al., 2014). Other common conditions that lead to heel pain in children include stress fractures, tendonitis or juvenile rheumatoid arthritis (Chiodo & Cook, 2010; Elengard & Silbernagel, 2010; Joseph, & Labib, 2013). Causes of paediatric heel pain differ from the causes of adult heel pain and therefore age is a significant predictor of differential diagnosis (Joseph & Labib, 2013). Current understanding of calcaneal apophyseal development that informs childhood heel pain assessment, relies on either lateral radiographic or magnetic resonance imaging studies, which have been shown to have limitations in the visualisation of complex ossification patterns or exhibit imaging artefacts during skeletal development, respectively (Rossi et al., 2016). Therefore, improved assessment of calcaneal apophyseal development is needed to aid clinicians in accurately diagnosing childhood heel pain and help identify delays in skeletal growth.

Development of the calcaneal apophysis has been investigated in several papers using lateral plain radiographs and magnetic resonance images (Cox, 1976; Ekizoglu et al., 2015; Harding, 1952; Li et al., 2019; Nicholson, 2015; Ogden et al., 2004; Ross & Caffey, 1957; Rossi et al., 2016; Saint-Martin, 2013; Volpon & de Carvalho Filho, 2002). Nicholson (2015) created a novel six-stage scoring system to assess apophyseal development using lateral plain radiographs, which was subsequently used by Li et al. (2019). In contrast, Saint-Martin (2013) and Ekizoglu et al. (2015) used three-stage scoring criteria using magnetic resonance imaging, focusing on the stages of fusion, with the stages being (1) no fusion and (2) partial fusion and (3) complete fusion. These studies demonstrated that the calcaneal apophysis develops in an orderly fashion from ossification to fusion.

Rossi et al. (2016) used sagittal MRI and lateral radiographic images to report that the calcaneal apophysis commences ossification as early as 5 years of age, with all individuals regardless of sex having one or multiple (2 or 3) secondary ossification centres by the age of 7 years. These secondary ossification centres first appear in the middle or inferior transverse region posterior to the calcaneal body, and then expand and unite superiorly/dorsally and inferiorly/plantarly until it forms a cap-like structure covering the posterior aspect

of the calcaneal metaphysis (Harding, 1952; Nicholson, 2015; Rossi et al., 2016). This cap-like appearance has been observed at around 8 years in girls and 10 years in boys (Hughes, 1948b). The superior transverse region is the last to ossify and can develop as an extension from the most superior aspect of the already present apophysis (middle region) or as a separate additional ossification centre (Harding, 1952; Nicholson, 2015).

MRI studies conducted by Saint-Martin (2013) and Ekizoglu et al. (2015) used the same scoring methodology (three stages) on individuals aged from 8 to 25 years. There was an approximate 1-year age difference between males and females in both studies for partial fusion/union, and a 1-year age difference between females for 'completely fused' between the two MRI studies as seen in Table 1. In addition to Table 1, plain radiographic studies reported in Cunningham et al. (2016) also report that complete fusion occurs at 15–16 years in females and 18–20 years in males. From a socioeconomic standpoint, based on the Human Development Index (HDI) ranking, the French citizens sampled in the Saint-Martin (2013) study have a higher ranking at '26' compared to the Turkish citizens in Ekizoglu et al. (2015) study with a ranking of '54'. Portugal has a ranking of 26 and the United States of America (USA; Ohio) has a ranking of 17. An HDI value closer to 1 suggests an overall improved life expectancy, increased years of schooling and national income. The Turkish citizens in the study performed by Ekizoglu et al. (2015) are ranked the highest at 54, and in their study, they demonstrated the oldest mean age for partially and completely fused apophyses, compared to citizens from the USA who are ranked 17 in the Nicholson (2015) and Li et al. (2019) studies and demonstrated significantly earlier mean age for partially and completely fused apophyses. These geographically distributed studies demonstrate that the timing of ossification is population-specific, and it is not surprising that the reported timing for ossification and fusion varies between studies justifying the need for additional population-specific studies to be performed.

Plain radiographs are currently used to assess apophyseal development due to their ease of access and already published scoring systems created using lateral plain radiographs in children (Nicholson, 2016). However, there are limitations to using plain radiographic scoring systems to assess age or development as seen in Lottering et al. (2017), who demonstrate that the superimposition of structures results in an inability to identify and separate complex ossification patterns. For this reason, current literature has limited documentation on the anatomical variation in ossification of the apophysis and fails to describe the ossification of the medial and lateral processes of the calcaneal tuberosity due to superimposition of these structures against the calcaneal body in lateral radiographs. Clinically, the medial and lateral processes distribute weight to the plantar surface and in an erect position, the calcaneus rests solely on these processes. The processes are also the attachment site for

TABLE 1 Comparison of mean ages for partial and complete fusion of the calcaneal apophysis between current studies

Study	Study population	Sex	Partially fused: mean age (years)	Completely fused: mean age (years)
Lateral radiographs				
Nicholson (2015)	USA	Females	12.03	13.44
		Males	13.85	15.24
Li et al. (2019)	USA	Historic females	12.03	14.70
		Historic males	13.85	16.60
		Modern white females	12.61	15.63
		Modern white males	14.05	16.46
Magnetic resonance imaging				
Saint-Martin (2013)	France	Females	10.9	18.8
		Males	15	21.3
Ekizoglu et al. (2015)	Turkey	Females	12.2	19.8
		Males	16.5	21.8
Dry bone observations				
Coqueugniot and Weaver (2007)	Portugal	Females	10	19
		Males	16	20

several tendons such as the abductor hallucis and abductor digiti minimi muscles (Cunningham et al., 2016). When unexpected variation is seen in radiographs it may be misinterpreted as either pathological findings such as fractures, fragmentations or inflammatory diseases including apophysitis (Volpon & de Carvalho Filho, 2002). Therefore, it is necessary to improve our understanding of the ossification pattern of the calcaneal apophysis through three-dimensional imaging studies to reduce misdiagnosis and improve patient management and clinical outcomes.

Whilst three-dimensional magnetic resonance imaging (MRI) studies have investigated calcaneal development in infants to adults, there are known limitations in using MRI to characterise the development of the apophysis (Rossi et al., 2016; Saint-Martin, 2013). For example, the cartilaginous precursors of the apophysis can have small foci of increased signal intensity which can mimic the appearance of secondary ossification centres, but likely reflect changes in vascularity or condensation of pre-ossification centres (Rossi et al., 2016). This can therefore result in inaccurate estimations of the timing and pattern of ossification of the apophysis in MRI studies.

This study aims to provide a detailed account of ossification of the calcaneal apophysis using computed tomography scans that overcome the limitations of plain radiography and MRI in skeletal development assessment to improve our understanding of apophyseal ossification and fusion. Reference standards for ossification and fusion timings are provided that can be applied to both lateral plain radiography and computed tomography imaging of a patient of known age. Scoring methods are compared between computed tomography and plain lateral radiographs to assess the impact of imaging modality selection on ossification interpretation. This not only improves our anatomical understanding of the development of the calcaneal tuberosity but will aid clinicians and health professionals in their clinical assessment of paediatric patients with heel pain.

2 | MATERIALS AND METHODS

2.1 | Sample

The study sample consisted of retrospective 568 multi-slice computed tomography (MSCT) scans (295 females; 274 males) and 266 lateral plain radiographs (119 females; 147 males) of the calcaneus from separate individuals aged birth to 20 years. In total, 834 individual scans were collected by a radiologist from the Queensland Health Enterprise PACS database, representing North-Eastern hospitals in Australia. Figure 1 depicts the distribution of each imaging modality for each year of age in this study, with a larger number of plain radiographs in the 0-to-6-year age range. As all samples were collected retrospectively, limited CT scans were available from young children. Therefore, all available CTs were collected and plain radiographs from different individuals were sourced only when insufficient CT scans were available within a particular age group ($n = 20$ per sex per year of age). All scans were conducted between 2010 and 2020 at a maximum slice thickness of 4 mm and slice interval of 0.5–2 mm, with a CT scanning parameter range from multiple CT scanners of 80–120 kV, 25–81 mA and 4–46 table feed per rotation. Scans were excluded from collection if the radiology report described the presence of any metabolic or skeletal disorders that may affect growth or trauma such as fractures to the calcaneus. It should be noted that scans were included if patients had fractures to surrounding bones but not to the calcaneus. At the Queensland Children's Hospital, DICOM files were imported into OsiriX™ (Version 4.1, 64 bit; Visage Imaging GmbH, San Diego, CA) for deidentification with remaining metadata including the patient's date of scan, age and sex. Ethical approval was granted by The Children's Health Queensland Hospital and Health Service Human Research Ethics Committee (LNR/19/QCHQ/51243), ratified by the Queensland University of Technology
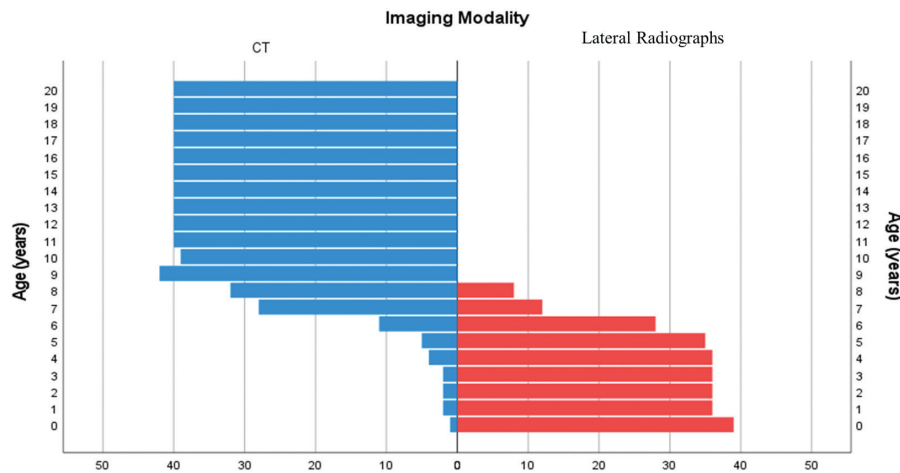
FIGURE 1 Distribution of computed tomography (CT) and lateral plain radiographs per year of age ($n = 2$- per sex per year of age)

Research Ethics Unit (Approval No. 1900000946) and approved by the Queensland Government under the Public Health Act (Section 284) 2020 (RD008018).

2.2 | Scoring

Horos was used to transform the DICOM data into three-dimensional (3D) volume-rendering reconstructions, complementary to two-dimensional multiplanar reconstructions (MPR) to assess the maturation and fusion of the calcaneal apophysis. Using the six-stage scoring criteria developed by Nicholson (2015) for lateral plain radiographs along with the morphological milestones presented by Cunningham et al. (2016), we constructed a novel 11-stage scoring criteria for application on computed tomography scans. The 11-stage scoring criteria was then subjected to inter- and intra-observer error testing to assess repeatability and reliability of the criteria, with the stages and descriptions provided in Table 2.

Ossification and fusion of the calcaneal apophysis were scored using an MPR view prior to verification of score using a 3D volume-rendered reconstruction of scans from right or left feet. Only 32 of the collected CT scans contained both left and right feet, with the remaining lateral radiographs and CTs containing imaging of 413 individual left feet and 389 individual right feet. An unpaired t-test was used to compare ossification scoring between the individual right and left feet and non-significant asymmetrical differences in maturation were observed in this preliminary analysis. Therefore, in individuals where scanning of both feet was available (32 CT scans), only the right foot was selected for analysis.

Through the comparison of lateral radiographs of younger individuals and pseudoradiographs generated from the available CT scans of older individuals to the available computed tomography scans, we identified that only 6 of the 11 stages for scoring using CT (0–3, 6 and 10) were applicable to lateral radiographs as seen in Figure 2. This led to the development of a truncated six stage classification system for lateral radiograph application (Table 3). However,

we determined that MSCT scans are required to visualise and score the ossification and fusion of the medial and lateral processes in stages 4, 5 and 7–9 due to superimposition limitations in lateral radiographs (Figure 3). Figure 3 demonstrates that lateral radiographs alone cannot visualise complex ossification and fusion patterns, where multi-slice computed tomography scans are needed.

2.2.1 | Observer error

To evaluate intra-observer error, the first author conducted a repeated assessment of 20 randomly selected MSCT tarsal/foot scans or ankle lateral radiographs on three different occasions with a minimum of 24 h between re-examinations using the novel 11-stage scoring criteria. To quantify inter-observer reliability and validate the application of the scoring criteria (Table 2) and associated diagrams, the same 20 MSCT scans and plain lateral radiographs were assessed by two observers over 1 day. Intra-observer repeatability was measured using the intraclass correlation coefficient (ICC), specifically a two-way mixed, single measures model, with an absolute agreement with a consistency-type 95% tolerance interval in SPSS, version 25 (2015; IBM Corporation, Armonk, NY). Inter-observer reliability was measured using a two-way random, average measures model, with an absolute agreement in SPSS. ICC estimates between 0.75 and 0.9 indicate good agreement and estimate greater than 0.9 indicate excellent measurement reliability and observer agreement (Koo & Li, 2016).

2.3 | Statistical approach

Descriptive statistics including mean age, standard deviation and age range were calculated for each stage to compare the timing of ossification stages using SPSS, version 25 (2015; IBM Corporation, Armonk, NY). Using a general linear model, sex, age and sex*age interactions were tested. Sex was significantly different ($p < 0.001$)

TABLE 2 Eleven-stage morphological classification system for the maturation and fusion of the calcaneal the apophysis using 3D-MSCT volume-rendered reconstructions and multiplanar reformatting views

Stage	Name	Description
0	No ossification	No ossification of apophysis is visible
1	Clustered ossification	Several small radiopaque circles are present – centralised to middle or inferior transverse regions of apophysis
2	Early ossification	Apophysis (one or multiple centres) covers <50% of the posterior calcaneal metaphysis
3	Active ossification	Apophysis covers 50%–80% of posterior calcaneal metaphysis - plantar extension typically visible
4	Medial process formation	Medial process has started to ossify
5	Lateral process formation	Lateral process has started to ossify
6	Cap formation	Apophysis now covers the entire posterior calcaneal metaphysis and mimics a cap-like structure
7	Lateral process fusion/early fusion	The lateral process is partially or completely fused or fusion of apophysis commencing with metaphysis in the middle transverse region
8	Medial process fusion/active fusion	The medial process is fully fused, or the inferior transverse region of apophysis has started to fuse
9	Advanced fusion	Apophysis is fully fused except for the superior transverse region
10	Complete fusion	Fusion of the apophysis is complete – epiphyseal line/scar or sclerotic line may be present

and therefore male and female samples were split for all further analyses. Means for each neighbouring stage were compared to test for significant age differences by using a one-way ANOVA with unrelated groups using a post hoc Tukey test.

To predict the stage of apophyseal ossification and fusion of a child of known age, a multinomial logistic regression was needed. However due to statistical assumptions of the test in SPSS, the current 11-stage scoring system was condensed into fewer stages to remove high leverage values or highly influential points that were observed in stages with low sample numbers, to minimise the overall sample size bias. The 11-stage scoring criteria were collapsed into six stages for three reasons: (1) to increase sample size per stage to strengthen the regression analysis and reduce the 95% confidence intervals for odds; (2) as these stages were created to understand anatomical development, some of the stages have a wide distribution of age ranges and overlap with neighbouring stages, condensing these stages minimised this overlap; and (3) grouping of stages was based on a shared anatomical approach/pattern of morphological development between the neighbouring stages. For example, as seen in Table 4, stage 0 (no apophysis present) and stage 1 (small ossification centres present) were left unchanged because they are distinctly different developmental stages, however, stage 2 (early ossification) and stage 3 (active ossification) were pooled because they both involve ossification of the apophysis. Similarly, stages 4, 5 and 6 were pooled together as they pertain to the formation of the medial and lateral processes and the apophyseal cap formation. Stages 7–9 were pooled because they all involve some degree of fusion of the calcaneal apophysis. Therefore, the newly formed stages were grouped accordingly: stage 2 (pooled stages 2 and 3), stage 3

(pooled stages 4, 5 and 6), stage 4 (pooled stages 7–9) and stage 5 (stage 10), with stages 0 and 1 remaining unchanged. Alongside the multinomial logistic regression, we calculated Relative Risk Ratios (RRR), 95% confidence intervals, classification tables and predicted probability.

3 | RESULTS

Using the novel 11-stage scoring criteria (Table 2), we assessed the maturation and fusion of the calcaneal apophysis in individuals aged from 0 to 20 years using MSCT scans and lateral radiographs. Intra-observer repeatability demonstrated almost perfect agreement between the same observer over three separate days with an intraclass correlation coefficient of 0.997 (CI: 0.995, 0.999). Inter-observer reliability demonstrated almost perfect agreement between two observers with an intraclass correlation coefficient of 0.972 (CI: 0.880, 0.991), a raw agreement of 90% and a kappa coefficient of 0.936 (CI: 0.880, 0.991). Both observers have a high level of imaging experience, however, one of the two observers had an introductory level of experience in interpreting and applying this scoring classification system. The second observer exhibited a high level of experience and interpretation of the calcaneal apophyseal ossification and fusion using computed tomography and lateral plain radiographs.

Table 5 provides the frequency, percentage and mean age for each classification stage for females and males. Overall, there was a significant sex effect ($p < 0.001$) between males and females, so further statistical analysis was split by sex. Mean age for each stage can be seen in Table 5 and Figure 4. The p-values obtained from
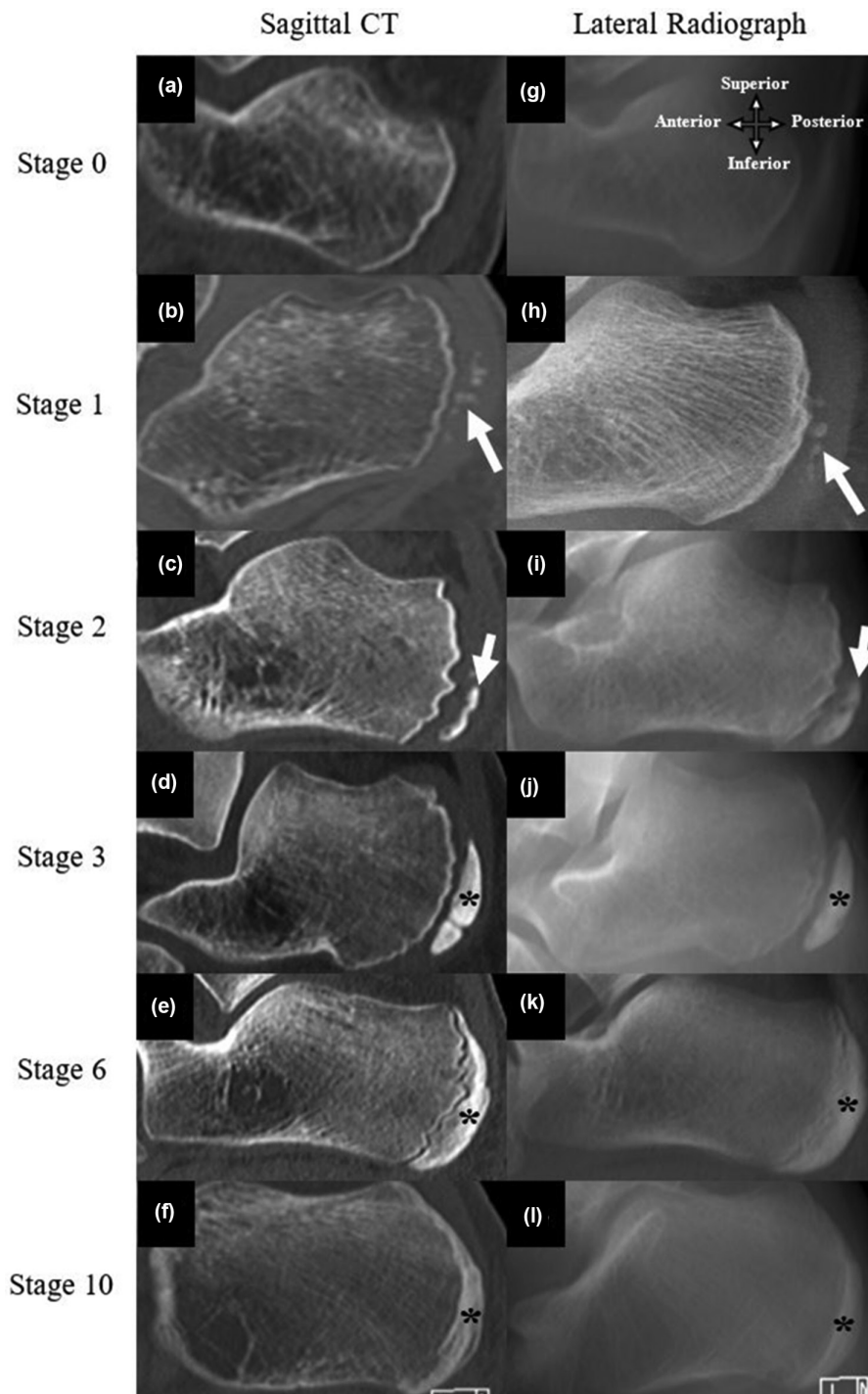
Sagittal CT | Lateral Radiograph

FIGURE 2 Sagittal MSCT scans (a–f) and matching lateral plain radiographs (g–l) depicting the stages of ossification and fusion visible in both imaging modalities and summarised in Table 3. Stage number reflective of CT-based stages. White arrow = secondary ossification centres/apophysis; * = apophysis

the one-way ANOVA with post hoc Tukey test comparing neighbouring stages are also presented in Table 5. Females demonstrated that there were significant differences in age between neighbouring stages; stage 0 vs stage 1, stage 2 vs stage 3, and stage 9 vs stage 10. Males only demonstrated significant differences between stage 0 and stage 1. Females demonstrated significantly earlier ossification and fusion times in all stages, except stage 8.

3.1 | Ossification of the apophysis

The development of the apophysis follows an orderly path, starting with the appearance of several small secondary ossification centres located within the middle or inferior transverse region, posterior to the calcaneal metaphysis. These centres then coalesce and elongate to form a C-shaped structure with an anterior concavity in a sagittal

TABLE 3 Six stage scoring criteria for assessment of calcaneal apophysis ossification in lateral plain radiographs compared to CT stages, adjusted from Table 2

Plain Radiography Stage	CT stage/s	Name	Description
0	0	No ossification	No ossification of the apophysis is visible
1	1	Clustered ossification	Several small radiopaque circles are present
2	2 & 3	Elongation	Apophysis covers <80% of the metaphysis
3	6	Cap formation	Apophysis covers the entire posterior calcaneal metaphysis with a complete extension over the plantar and dorsal surface
4	7–9	Active fusion	Fusion of the apophysis is occurring but is not complete
5	10	Complete fusion	Fusion of the apophysis is complete

view. The superior and inferior aspects of the apophysis were the last to ossify. Eventually, elongation in both directions produces a cap-like structure that parallels the height of the posterior calcaneal metaphysis with a thin band of cartilage separating the two structures.

The secondary ossification centres first appear within the middle or inferior transverse region and are typically clustered together and span the entire width of the calcaneal metaphysis, but in some cases, the clusters are located more to the lateral aspect. The centres first appear at a mean age of 5.25 ± 1.1 years for females and 7.19 ± 1.1 years for males (stage 1) as seen in Table 5. The centres then coalesce and elongate through appositional growth until they span approximately two-thirds of the calcaneal metaphysis at a mean age of 8.15 ± 1.04 years for females and 10.28 ± 1.2 years for males (stage 3). At this point the appearance of the apophysis is not symmetrical; the lateral aspect of the apophysis tends to ossify towards the superior aspect at a faster rate and the medial aspect tends to ossify inferiorly towards the plantar surface, giving the appearance of a right-angled triangle. However, this shape tends to become more circular with age. The superior aspect of the apophysis is the last to ossify and develops via one of two mechanisms: (1) as an osseous extension from the already present apophysis; or (2) from a separate secondary ossification centre. Out of the 228 individuals that were scored between stages 3 and 9, 98 individuals (42.9%) demonstrated mechanism 1 while 35 individuals (15.35%) demonstrated mechanism 2. The remaining 95 individuals were classified in the earlier ossification stages (3 through to 5) and did not allow the mechanism to be assessed.

As the apophysis is elongating, the medial and lateral processes start to ossify (stages 4 and 5, respectively). The medial process appears on average at around 9.5 ± 1.34 years for females and 10.93 ± 1.64 years for males, while the lateral process appears at around 9.81 ± 1.16 for females and 11.68 ± 1.21 years for males. Even though the medial and lateral processes develop in sequential order, there was no significant difference in mean age of appearance. Females develop significantly earlier for medial process formation (stage 4) ($p < 0.01$) and lateral process formation (stage 5) ($p < 0.001$) forming approximately 1 year earlier than males. Development and ossification of these processes commenced via one of two main mechanisms: (1) as an osseous extension from the inferior aspect of the existing apophysis which then matures and fuses anteriorly with the posterior aspect of the calcaneus;

or (2) the medial and lateral processes develop as independent secondary ossification centres located in the cartilaginous zone lateral to the posterior metaphysis and then fuse posteriorly with the apophysis first and then with the body of the calcaneus as seen in Figure 5. Out of the 71 individuals that were scored stage 4 or 5, 43 individuals (61%) demonstrated mechanism 1 while the remaining 28 individuals (39%) demonstrated mechanism 2.

3.2 | Fusion of the apophysis

After the cap-like structure is formed, the lateral process is the first structure to fuse to the posterolateral aspect of the posterior calcaneal metaphysis (stage 7). The rate of fusion of the medial and lateral processes is significantly different between males and females. The mean age difference between the appearance and fusion of the medial process for females is 3.35 years (stage 4, 9.5 ± 1.3 years; stage 8, 12.85 ± 1.1 years) compared to males having a 2.74-year difference (stage 4, 10.93 ± 1.6 years; stage 8, 13.67 ± 0.6 years), with females having a significant mean difference between these two stages ($p < 0.001$) but not males ($p = 0.437$). Males demonstrate a slower fusion rate for the lateral process with a mean age difference between appearance and fusion of the lateral process of 1.70 years (stage 5, 11.68 ± 1.2 years; stage 7, 13.38 ± 1.4 years) compared to females at 1.37 years (stage 5, 9.81 ± 1.1 years; stage 7, 11.18 ± 1.3 years), however, this rate was not significant for either sex ($p > 0.25$). Complete fusion of the lateral process (stage 7) occurred significantly earlier for females compared to males, with approximately a 2-year difference. Complete fusion of the medial process (stage 8) occurred at 12.85 ± 1.1 years for females and 13.67 ± 0.6 years for males, with no significant difference present.

At this stage, the middle transverse region starts to fuse in a horizontal fashion in the axial plane, and then progresses inferiorly, with the superior transverse region being the last to fuse. Fusion of these transverse regions tends to start on the lateral aspect and fuses towards the medial aspect. By stage 9, all fusion is complete besides the superior aspect of the apophysis. Complete fusion occurs after the medial aspect of the transverse region has closed. Complete fusion of the apophysis to the posterior calcaneal metaphysis was as early as 10 years for females and 14 years for males, with
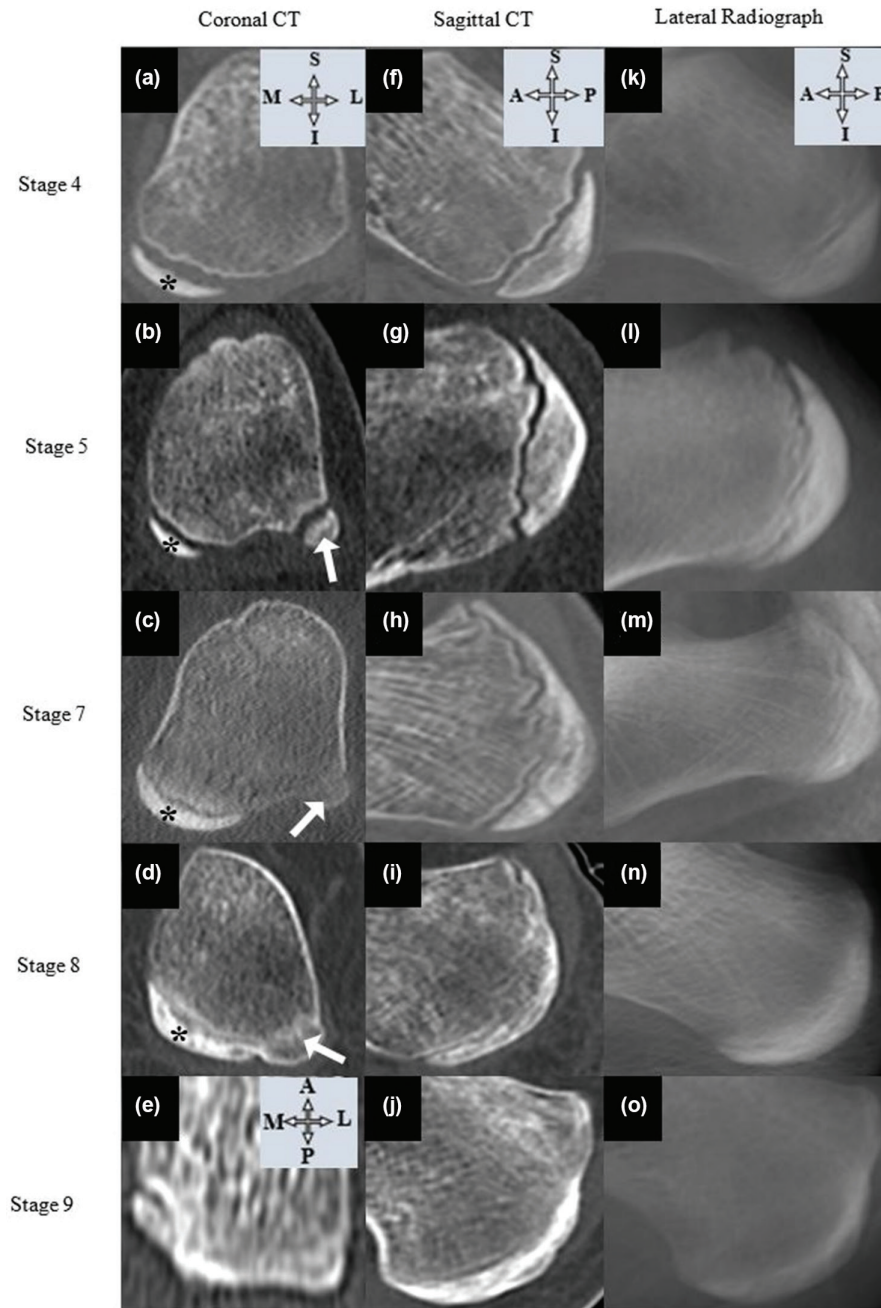
FIGURE 3 Coronal MSCT scans (a–d), axial MSCT scan (e), sagittal MSCT scans (f–j) and matching lateral plain radiographs (k–o) depicting that stages 4, 5, 7–9 require the use of computed tomography scans to visualise the ossification and fusion patterns of the medial and lateral processes, as it is not possible to identify these processes in lateral radiographs due to superimposition. Coronal MSCT scans are used to visualise the ossification and fusion of the medial and lateral processes. Axial scans are used to visualise the fusion of the superior transverse region. S = superior, I = inferior, M = medial, L = lateral, A = anterior, P = posterior. * = medial process; white arrow = lateral process

all individuals over 16 years for females and 17 years for males being completely fused as seen in Table 6.

3.3 | Multinomial logistic regression

For multinomial logistic regression, the original 11 staged scoring criteria were collapsed into six stages as seen in Table 4. The multinomial

regression showed a strong relationship between age and calcaneal apophyseal stage for females ($p<0.001$, Nagelkerke = 0.925) and males ($p<0.001$, Nagelkerke = 0.929). It should be noted that both lateral plain radiographs and computed tomography scans were used to create the regression analysis and to calculate log odds, 95% confidence intervals, classification tables and predicted probability for both females and males.

Tables 7 and 8 report the predictive accuracy of the multinomial logistic model and from there Tables 9 and 10 were created,

TABLE 4 Comparison between CT stages and lateral plain radiography stages

Original computed tomography stages	Condensed stages for regression analysis	New description for lateral radiographs
Stage 0	Stage 0	No ossification of apophysis
Stage 1	Stage 1	Several small radiopaque circles are present
Stage 2 and 3	Stage 2	Apophysis covers <80% of the posterior calcaneal metaphysis
Stage 4–6	Stage 3	Apophyseal cap is formed[a]
Stage 7–9	Stage 4	Active fusion
Stage 10	Stage 5	Fusion of the apophysis is complete

[a]Lateral radiographs cannot be used to predict the formation of medial and lateral processes.

TABLE 5 Frequency, percentage, and mean age (years) for each stage of fusion of the calcaneal apophysis for females and males using the novel 11-stage scoring criteria

Stage	Female				Male				Sex difference
	n	Percent (%)	Mean age (years) + SD	*p*-value	*n*	Percent (%)	Mean age (years) + SD	*p*-value	*p*-value
0	91	22.0	2.02 ± 1.6		149	35.4	3.33 ± 2.3		<0.001
1	24	5.8	5.25 ± 1.1	0.001[a]	26	6.2	7.19 ± 1.1	0.001[a]	<0.001
2	31	7.5	6.13 ± 1.0	0.793	15[b]	3.6	8.73 ± 0.7	0.280	<0.001
3	27	6.5	8.15 ± 1.3	0.020[a]	32	7.6	10.28 ± 1.2	0.230	<0.001
4	14	3.4	9.50 ± 1.3	0.460	14	3.3	10.93 ± 1.6	0.990	0.010
5	21	5.1	9.81 ± 1.1	1.000	22	5.2	11.68 ± 1.2	0.450	<0.001
6	18[b]	4.3	10.44 ± 1.4	0.990	18	4.3	12.44 ± 1.5	0.580	<0.001
7	11[b]	2.7	11.18 ± 1.3	0.990	13[b]	3.1	13.38 ± 1.4	0.970	<0.001
8	13[b]	3.1	12.85 ± 1.1	0.480	3[b]	0.7	13.67 ± 0.6	1.000	0.250
9	13[b]	3.1	13.46 ± 1.3	0.990	9[b]	2.1	15.33 ± 1.4	0.960	<0.001
10	146	35.3	16.66 ± 2.4	0.001[a]	119	28.3	17.38 ± 1.9	0.060	<0.001

[a]Significant difference between the means of the current stage and previous stage (p < 0.05)
[b]Low sample size in current stage (<20). *n* = frequency count.

which contain the predicted probability of an individual aged 0–20 years being classified into an apophyseal developmental stage.

From our observed data, the models created were able to correctly predict the apophysis stages of 80.2% of the male and female patients in our sample based on an individual's known age, with higher accuracy in the earlier and later stages (Tables 7 and 8). Most misclassification occurred in neighbouring stages with the highest error in stages 1 and 4 where variation was the highest.

Using Tables 9 and 10, we can easily provide a prediction of the probability of an individual belonging to each stage. For example, a six-year-old female has a 30% probability of being classified as stage 1, a 65% probability of being classified as stage 2, and an extremely low probability of being classified into the remaining stages. A six-year-old male has an 81% probability of being classified into stage 0, and a 19% probability of being classified into stage 1. Therefore, the 6-year-old female would most likely be classified developmentally as stage 2 and the male would most likely be classified developmentally as stage 0.

4 | DISCUSSION

Overcoming the limitations of plain radiography and MRI in the assessment of ossification, this study used computed tomography for the first time to investigate morphological changes of the calcaneal apophysis with age and report calcaneal ossification in an Australian contemporary population. Our novel multinomial regressions can estimate the apophyseal developmental stage from the known sex and age of an individual which can be used as a clinical tool to assist clinicians in diagnosing or excluding apophyseal developmental conditions such as apophysitis.

In this study, we observed that there are several (~5+) small secondary ossification centres that first appear clustered within the middle transverse region of the calcaneal apophysis. The number of centres we observed is higher than reported by Ross and Caffey (1957), Volpon and de Carvalho Filho (2002), Ogden et al. (2004) and Rossi et al. (2016), who describe only two or three centres. The number of secondary ossification centres described in the literature may be under-reported due to superimposition in
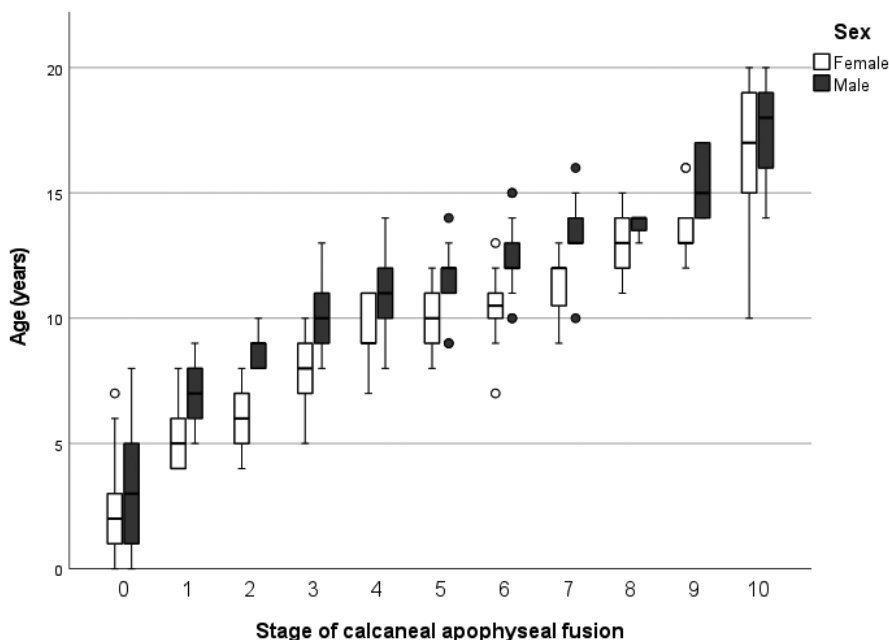
FIGURE 4 Stages of ossification and fusion of the calcaneal apophysis in individuals from birth to 20 years of age ($n = 834$) separated by sex (female: white; male: black). All stages are significantly different ($p < 0.05$) between females and males except stage 8 ($p = 0.25$) with earlier ossification and fusion observed in females
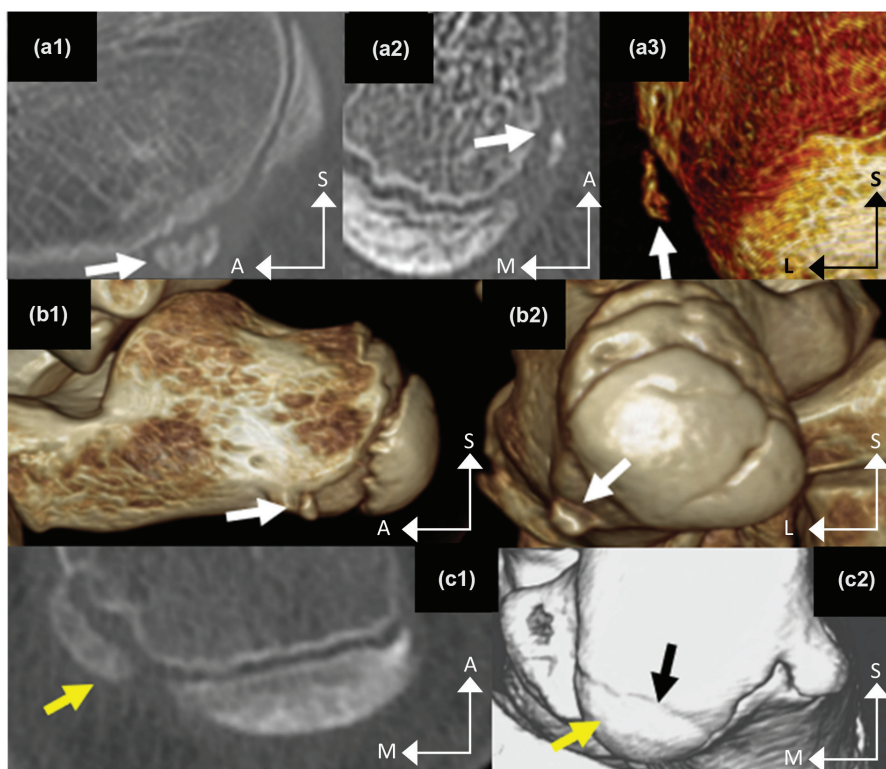

FIGURE 5 Three different individuals demonstrating separate/independent secondary ossification centres for the medial and lateral processes (a–c) using multiplanar reconstruction (MPR) MSCT scans and corresponding 3D-MSCT volume-rendered reconstructions. (a) Separate lateral secondary ossification centre: 13-year-old male (a1 = parasagittal view, a2 = axial view in inferior transverse region, a3 = 3D reconstruction in a posterolateral view). (b) Irregular separate lateral ossification centre: 9-year-old female (b1 = 3D reconstruction in a lateral view, b2 = 3D reconstruction in a posterior view). (c) Separate medial ossification centre: 14-year-old male (c1 = axial slice, c2 = 3D reconstruction in a posterior view). Lateral process (white arrows), medial process (yellow arrows), with a clear cartilage plate separating the centre from the apophysis (black arrow). S = superior, A = anterior, M = medial, L = lateral

TABLE 6 Minimum and maximum age ranges (years) for stage of fusion of the calcaneal apophysis for females and males

Sex	Classification stage of calcaneal apophyseal fusion										
	0	1	2	3	4	5	6	7	8	9	10
Female	≤ 7	4–8	4–8	5–10	7–11	8–12	7–13	9–13	11–15	12–16	≥ 10
Male	≤ 8	5–9	8–10	8–12	8–14	9–13	10–15	10–16	13–14	14–17	≥ 14

TABLE 7 Classification table demonstrates the percentage of correct stages of calcaneal apophysis ossification and fusion predicted using the multinomial logistic model with known child age for females

Observed stage	Predicted stage of apophyseal ossification and fusion						Percent correct
	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	
Stage 0	86	3	2	0	0	0	94.5%
Stage 1	7	8	9	0	0	0	33.3%
Stage 2	1	9	40	8	0	0	69.0%
Stage 3	0	0	7	41	4	1	77.4%
Stage 4	0	0	0	6	13	18	35.1%
Stage 5	0	0	0	3	3	140	95.9%
Overall percentage	23.0%	4.9%	14.2%	14.2%	4.9%	38.9%	80.2%

TABLE 8 Classification table demonstrates the percentage of correct stages of calcaneal apophysis ossification and fusion predicted using the multinomial logistic model with known child age for males

Observed stage	Predicted stage of apophyseal ossification and fusion						Percent correct
	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	
Stage 0	145	4	0	0	0	0	97.3%
Stage 1	15	8	3	0	0	0	30.8%
Stage 2	0	7	28	12	0	0	59.6%
Stage 3	0	1	8	39	4	2	72.2%
Stage 4	0	0	1	9	7	8	28.0%
Stage 5	0	0	0	0	9	110	92.4%
Overall percentage	38.1%	4.8%	9.5%	14.3%	4.8%	28.6%	80.2%

lateral plain radiography studies (Ross & Caffey, 1957; Volpon & de Carvalho Filho, 2002), small sample sizes in the infant category (Rossi et al., 2016) or studies reporting more mature stages of development when multiple centres have already started to coalesce into a smaller number of large centres (stage 2 in our study).

Many factors (internal and external) are believed to influence the development of secondary ossification centres, with the most common theory being that mechanical stress initiates and accelerates the formation of secondary ossification centres (Xie et al., 2020). Acceleration in ossification of secondary centres has been observed in similar pressure epiphyses such as the proximal epiphysis of the femur due to stresses placed upon the cartilage mass by muscle involvement (Xie et al., 2020). The calcaneal tendon, which is composed of tendinous fibres from the

gastrocnemius and soleus muscles, inserts into the most inferior part of the apophysis or cartilaginous apophyseal region (Chao et al., 1997), with the percentage of tendinous fibres inserting on the medial aspect of the calcaneus larger compared to the lateral aspect (Doral, 2010; Lohrer, 2008). This uneven mechanical stress from the tendon may explain why the medial process of the calcaneus ossifies first and is generally larger than the lateral process. To the best of our knowledge, there have been no papers published that have investigated the ossification and fusion of the medial and lateral processes of the calcaneal tuberosity. The ossification of the medial process commenced at a mean age of 9.5 years for females and 10.93 years for males (stage 4). The lateral process is smaller in size and typically ossified around the same time as the medial process, with a mean age of appearance

TABLE 9   The predicted probability of a child of known age being classified into each apophyseal stage for females using the multinomial logistic model, with the bolded values indicating the highest predictied probability per age category

| Age (years) | Predicted Probability | | | | | | Predicted stage |
	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	
0	**1.00**	0.00	0.00	0.00	0.00	0.00	Stage 0
1	**1.00**	0.00	0.00	0.00	0.00	0.00	Stage 0
2	**0.99**	0.01	0.00	0.00	0.00	0.00	Stage 0
3	**0.93**	0.07	0.01	0.00	0.00	0.00	Stage 0
4	**0.67**	0.25	0.08	0.00	0.00	0.00	Stage 0
5	0.23	**0.42**	0.35	0.00	0.00	0.00	Stage 1
6	0.03	0.30	**0.65**	0.02	0.00	0.00	Stage 2
7	0.00	0.14	**0.76**	0.10	0.00	0.00	Stage 2
8	0.00	0.05	**0.65**	0.30	0.00	0.00	Stage 2
9	0.00	0.01	0.35	**0.61**	0.03	0.00	Stage 3
10	0.00	0.00	0.12	**0.75**	0.12	0.01	Stage 3
11	0.00	0.00	0.03	**0.59**	0.32	0.07	Stage 3
12	0.00	0.00	0.00	0.27	**0.49**	0.24	Stage 4
13	0.00	0.00	0.00	0.07	0.43	**0.51**	Stage 5
14	0.00	0.00	0.00	0.01	0.25	**0.73**	Stage 5
15	0.00	0.00	0.00	0.00	0.12	**0.87**	Stage 5
16	0.00	0.00	0.00	0.00	0.06	**0.95**	Stage 5
17	0.00	0.00	0.00	0.00	0.02	**0.98**	Stage 5
18	0.00	0.00	0.00	0.00	0.01	**0.99**	Stage 5
19	0.00	0.00	0.00	0.00	0.00	**1.00**	Stage 5
20	0.00	0.00	0.00	0.00	0.00	**1.00**	Stage 5

at 9.81 years for females and 11.68 years for males (stage 5). The mean age for lateral fusion was 11.18 years for females and 13.36 years for males with the maximum age of fusion occurring at 13 and 16 years, respectively. The mean fusion time for the medial process was 12.92 years for females and 14 years for males. Females demonstrated significantly earlier ossification timing for both the medial and lateral processes ($p < 0.01$) and demonstrated significantly earlier fusion time for the lateral process ($p < 0.01$). There was no significant difference in the fusion of the medial process between males and females.

It was previously understood that the calcaneal tendon was inserted into the superior and middle aspects of the apophysis (Milz et al., 2002). However, most studies that investigate the insertion of the calcaneal tendon use cadaveric studies of older individuals. Kim (2011) used magnetic resonance imaging in individuals aged 12–40 years of age and demonstrated that the tendon moves dorsally/superiorly with age, which may explain why the inferior/middle transverse region ossifies and fuses first (mean age for stage 2: females = 6.13, males = 8.73 years; stage 7: females = 11.18, males = 13.38 years) and the superior transverse region of the apophysis ossifies and fuses last (mean age for stage 6: females = 10.44, males = 12.44 years; stage 10: females = 16.66, males = 17.38 years).

4.1 | Comparison of imaging modalities

In agreement with Li et al. (2019) and Nicholson (2015), who both used lateral plain radiographs, our computed tomography and lateral plain radiography study observed females demonstrating significantly earlier ossification of the calcaneal tuberosity ($p < 0.001$), with apophyseal cap formation reported at a mean age of 10.44 years for females and 12.44 years for males, compared to Li et al. (2019) and Nicholson (2015) who report similar mean age ranges from 10 to 13 years. Apophyseal cap formation can therefore be seen in both modalities demonstrating that imaging modality should not affect the visualisation of this stage. Saint-Martin (2013) reported a much later mean age of apophyseal cap formation for males at 15 years. Saint-Martin (2013) did not specifically separate cap formation from early fusion in their methodology so the later reported age range will also reflect patients undergoing early fusion.

Commencing fusion of the apophysis in this study was as early as 9 years for females and 10 years for males with a mean age of 11.18 years for females and 13.38 years for males, with females commencing fusion significantly earlier ($p < 0.001$). Although we cannot directly compare our results to other studies due to methodological differences, we noted that our reported ages for commencing fusion are earlier compared to those using lateral radiographs (mean

TABLE 10 The predicted probability of a child of known age being classified into each apophyseal stage for males using the multinomial logistic model, with the bolded values indicating the highest predictied probability per age category

Age (years)	Predicted Probability						Predicted stage
	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	
0	**1.00**	0.00	0.00	0.00	0.00	0.00	Stage 0
1	**1.00**	0.00	0.00	0.00	0.00	0.00	Stage 0
2	**1.00**	0.00	0.00	0.00	0.00	0.00	Stage 0
3	**0.99**	0.01	0.00	0.00	0.00	0.00	Stage 0
4	**0.98**	0.02	0.00	0.00	0.00	0.00	Stage 0
5	**0.93**	0.07	0.00	0.00	0.00	0.00	Stage 0
6	**0.81**	0.19	0.00	0.00	0.00	0.00	Stage 0
7	**0.55**	0.43	0.02	0.00	0.00	0.00	Stage 0
8	0.19	**0.47**	0.31	0.03	0.00	0.00	Stage 1
9	0.01	0.09	**0.73**	0.17	0.00	0.00	Stage 2
10	0.00	0.01	**0.62**	0.37	0.01	0.00	Stage 2
11	0.00	0.00	0.39	**0.58**	0.03	0.00	Stage 3
12	0.00	0.00	0.19	**0.70**	0.10	0.01	Stage 3
13	0.00	0.00	0.06	**0.57**	0.28	0.09	Stage 3
14	0.00	0.00	0.01	0.24	**0.40**	0.35	Stage 4
15	0.00	0.00	0.00	0.05	0.26	**0.69**	Stage 5
16	0.00	0.00	0.00	0.01	0.12	**0.88**	Stage 5
17	0.00	0.00	0.00	0.00	0.04	**0.96**	Stage 5
18	0.00	0.00	0.00	0.00	0.01	**0.99**	Stage 5
19	0.00	0.00	0.00	0.00	0.00	**1.00**	Stage 5
20	0.00	0.00	0.00	0.00	0.00	**1.00**	Stage 5

age of 12–15 years: Nicholson, 2015; Li et al., 2019). Similar to other studies, we have demonstrated that CT can detect fusion earlier using MPR formatting (Lottering et al., 2017), as fusion commences within the centre of the middle transverse region, which cannot be visualised in lateral radiographs. Our reported ages for commencing fusion are also much earlier than MRI studies conducted by Saint-Martin (2013), Ekizoglu et al. (2015), and Rossi et al. (2016), who reported apophyseal fusion between 12 and 17 years of age for both females and males. The later age ranges reported by the MRI studies could be due to the use of only one classification stage called fusion, therefore, any stage of fusion including, commencing, partial and advanced fusion would increase the age range reported. In addition, there are imaging pitfalls of MRI such as the presence of curvilinear low signal lines which parallel the appearance of the growth plate in fused adult calcanei, which may confuse fusion timing (Rossi et al., 2016).

Saint-Martin (2013) and Ekizoglu et al. (2015) both reported the earliest age of complete fusion at 17 and 16 years for males, respectively, and 12 years for females. Similarly, Rossi et al. (2016) reported their earliest age of complete fusion at 14 years. Our study observed the earliest complete fusion 2 years earlier for females at 10 years and 2–3 years earlier for males at 14 years. All individuals in our sample demonstrated complete fusion by 16 years for females and

17 years for males. In contrast, our observed complete fusion times are later than lateral plain radiograph studies such as Volpon and de Carvalho Filho (2002), who observed that the apophysis was completely fused by 15 years of age for all individuals in a Brazilian population and Nicholson (2016) who demonstrated complete fusion at 13 years for females and 15 years for males in a North American population. Lottering et al. (2017) demonstrated that there are discrepancies between reported ages when 3D-MSCT scans and lateral radiographs are compared, mainly due to obstruction of the field of view and superimposition. Because the apophysis wraps around the posterior aspect of the calcaneus and the superior and inferior aspects of the apophysis are the last to fuse, superimposition obscures the field of view resulting in lateral radiographs being scored as fused earlier, therefore, underestimating the age of complete fusion compared to computed tomography studies.

It should be noted that Li et al. (2019), Nicholson (2015), Saint-Martin (2013), Ekizoglu et al. (2015), and Rossi et al. (2016) all reported mean ages for complete fusion. The reported mean age for complete fusion can be affected by the age range used in the study sample, therefore age bias occurs and the mean age can be inflated. This is a major limitation in these studies as it is not an accurate representation of fusion times, and therefore even though comparisons were made, we cannot accurately compare our results to theirs. To

avoid age bias and inflation we report minimum and maximum age ranges for each developmental stage in our study.

Our condensed six-stage classification system which can be used with either computed tomography or lateral radiographs is the same number of stages reported by Nicholson (2015). It should be noted that the description for each developmental stage has minor but important differences from Nicholson (2015), and the application of both methods applied to the same person may result in a different developmental stage classification. Application of the multinomial regression models reported in this study, should therefore only be used in combination with the classification system described in this paper.

4.2 | Secular Changes and Socioeconomic Differences

Currently, the most in-depth calcaneal apophyseal classification system that has published was created by Nicholson (2015) using a historic population. However, Li et al. (2019) has demonstrated the need for contemporary reference standards with modern females having a significant delay in reported bone age from the calcaneus compared to historic females. In addition to needing contemporary studies, there is also a need for population-specific studies with reported ages for apophyseal development varying significantly depending on the population used (Coqueugniot & Weaver, 2007; Ekizoglu et al., 2015; Li et al., 2019; Nicholson, 2015; Rossi et al., 2016; Saint-Martin, 2013; Volpon & de Carvalho Filho, 2002). This is supported by Mora et al. (2001) and Russell et al. (2001) who report that modern black females are skeletally advanced compared to modern white females when assessing the hand and wrist. Therefore, it is our recommendation that the methods reported in this paper be applied to a Queensland-specific population, and if these methods are applied to other populations, caution should be taken due to known population differences in skeletal development.

4.3 | Clinical application

Our in-depth review of calcaneal apophyseal development using computed tomography and lateral radiographic images has resulted in a regression model that can be used clinically to accurately predict (in 80% of female and male cases) the stage of apophyseal development of a child of known age and sex using the multinomial logistic regression models presented in this paper (Tables 9 and 10). These predictive tables should be used to determine the apophyseal developmental stage and therefore the likelihood the child has apophyseal developmental related conditions such as calcaneal apophysitis. If a child's developmental stage is active fusion then the diagnosis is likely apophysitis however if the developmental stage is early ossification, then heel pain is more likely to be related to stress fractures or juvenile rheumatoid arthritis. The use of these predictive models can eliminate the need for radiographs to diagnose apophysitis and

supports Kose (2010) who believes that there is no real justification for radiographic evaluation as an initial step for diagnosis.

Painful heels in children and adolescents are typically due to apophysitis or the presence of sclerotic and fragmented parts of the apophysis, typically seen in individuals aged 9–11 years (Volpon & de Carvalho Filho, 2002). Lateral radiographs are most often used to assess the heel for pathology, stress fracture or disease which may cause pain in that region, generally coined apophysitis, which usually goes untreated and will resolve itself with time (Kose, 2010). The aetiology of apophysitis is still debated with Volpon and de Carvalho Filho (2002) reporting that it is due to increased fragmentation of the apophysis due to mechanical stress during the stages of development where the apophysis is present but not fused. In contrast, Ogden et al. (2004) have stated that apophysitis may be due to metaphyseal trabecular stress fractures and is not related to the apophysis at all. Either way, the time frame in which apophysitis related heel pain is typically observed is after the apophysis appears and before it completely fuses, due to increased mechanical stresses such as growth spurts or participation in competitive sports affecting skeletal development (Nery et al., 1996; Ogden et al., 2004; Shopfner & Coin, 1966; Volpon & de Carvalho Filho, 2002).

Diagnosis of apophysitis using radiographs is ambiguous as the diagnostic criteria is an increased number of apophyseal fragments. Volpon and de Carvalho Filho (2002) reported that children with apophysitis had 'more fragmentations' compared to healthy children, however, they did not describe or determine what 'more' meant for diagnostic evaluation. In addition, studies have demonstrated that the typical number of apophyseal fragments or centres in healthy children range from one to three (Ogden et al., 2004; Ross & Caffey, 1957; Rossi et al., 2016; Volpon & de Carvalho Filho, 2002). However, it is our suggestion that the reports of increased fragmentations in children with apophysitis compared to healthy children are natural stages of ossification and that limited visualisation due to lateral radiography or sagittal MRIs may have led to this assumption. Our computed tomography study which has improved 3D visualisation capabilities has demonstrated a high number of ossification centres or fragments in early development (typically 5 or more observed) which will eventually coalesce together. It is our recommendation that computed tomography studies of patients with diagnosed apophysitis are needed to improve the visualisation of the secondary centres during ossification in these patients, which will improve our understanding of apophysitis development and presentation.

Depending on the age of an individual and presenting symptoms, a clinician may use our sex-specific probability tables to predict the apophyseal stage to aid diagnosis and patient management. Our models suggest that there is a high probability (>60%) that a girl ≤4 years of age and a high probability (<80%) that a boy ≤7 years will be in stage 0 (no ossification centres present), and therefore the pain of the heel is unlikely to be caused by metaphyseal trabecular stress fractures or apophysitis.

Furthermore, a girl between the ages of 5 and 13 years of age will be classified as stage 1 (several small radiopaque circles are present) to stage 4 (active fusion), and a boy between 8 and 13 years will be

undergoing apophyseal development and elongation. These stages typically align with apophysitis related pain and therefore, a radiograph or computed tomography scan may not be needed. However, females older than 13 years have a high probability (>50%) of being classified as stage 5 (complete fusion) and boys older than 15 years will also be classified as stage 5. If these individuals have heel pain, then a clinician should request medical imaging to identify pathologies such as bursitis, osteoarthritis, osteomyelitis or neuroma, as apophysitis or metaphyseal trabecular fractures are less likely. In stages 1 and 4, our regression model's predictive probability of classifying the apophyseal stage is less than 50%. For stage 1 (commencement of ossification) females at 5 years of age and males at 8 years have a 42% and 47% chance of being classified as stage 1, respectively. For stage 4 (active fusion) females at 12 years of age and males at 14 years of age have a 49% and 40% chance of being classified as stage 4, respectively. Caution should therefore be applied when using the multinomial prediction tables to assess patients at these ages, and medical imaging of the patient may therefore be warranted. Whilst stage 1 represents the commencement of early ossification and stage 4 indicates active fusion, it is stage 3 the formation of the apophyseal cap that is an important developmental period when apophysitis can present, with stage 3 having an accuracy of 77.4% and 72.2% in females and males, respectively. Overall, the regression models created in this study can be used to aid diagnosis, reduce the number of radiographs needed, and therefore minimise exposure to radiation in paediatric patients.

In conclusion, this first computed tomography study of calcaneal ossification provides a comprehensive 3D analysis which overcomes the limitations of superimposition and magnification present in lateral radiographs and artefacts present in MRIs. This comprehensive analysis provides an in-depth examination of the development of the calcaneal apophysis in neonates to young adults and provides the first sex-specific predictive modelling of the timing of ossification and fusion of the apophysis using a reliable morphological classification system. For our Queensland Australian representative population, we observed complete fusion of the apophysis between the ages of 10 and 16 years in females and between 14 and 17 years for males; with the highest probability of fusion at 13–16 years for females and 15–16 years for males. Furthermore, the condensed lateral plain radiograph scoring system can be applied to our logistic regression analysis and can be accurately used to score an individual's apophyseal development based on known age and sex.

AUTHOR CONTRIBUTIONS

Connor S. Blythe designed the study, conducted all data collection and quantitative analysis, conveyed the authorship team, and had final editorial decision over content of the submission. C.B., M.R., L.G. actively participated in the development of ideas in the paper and contributed critical revision of the manuscript in addition to adding text, providing resources and feedback throughout the writing of this manuscript.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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