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Age Estimation of Adolescent and Young Adult Male and Female Skeletons II, Epiphyseal Union at the Upper Limb and Scapular Girdle in a Modern Portuguese Skeletal Sample

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KEY WORDS skeletal age; bone maturation; dry bone; Lisbon collection

ABSTRACT This study completes previously reported ages for timing of epiphyseal union in the postcranial skeleton in a recent sample, with data from the scapula, clavicle, humerus, radius, and ulna. A sample of 121 individuals between the ages of 9 and 29 (females = 65, males = 56) was derived from the Lisbon documented skeletal collection. Epiphyseal union was scored at 16 anatomical locations, using a three-stage scheme: 1) no union; 2) partial union; and 3) completed union, all traces of fusion having disappeared. In the upper limb, the epiphyses of the elbow are the first to fuse at around 11 to 15 years of age, followed by those of the shoulder and wrist. In the scapular girdle, the coracoid area is the first to fuse, followed by the glenoid surface and remaining epiphyses, with the medial clavicle fusing last, by the age of 25–27. There is a sex difference in maturation, with females showing an advance relative to males of about 2 years in the upper limb. Sex differences in maturation are less noticeable in the scapular girdle, but data suggest that females are also ahead of males. Results suggest overall similar age ranges for stages of union as previous dry bone observations, but some studies show significant divergences which seem to derive from methodological issues. Although some radiographic reference standards provide comparable age ranges, they should probably be avoided when aging skeletal remains. Am J Phys Anthropol 137:97–105, 2008. © 2008 Wiley-Liss, Inc.

Timing of epiphyseal union is an important means to estimate the age at death of adolescent and young adult skeletons in both bioarchaeological and forensic contexts. It is based on the known period of time and order in which the various epiphyses fuse, so that age at death of unidentified skeletal remains can be established by comparing the maturational state of the bone with a chronological age-based reference standard. Epiphyseal union standards obtained from radiographic studies have been compiled over the years, but data from direct dry bone observation are scarce, particularly for females and some anatomical locations. Dry bone data are essential because radiographic information may be unsuitable for the estimation of age at death in skeletal remains. This relates to methodological differences between radiographic and dry bone observation (Krogman and Işcan, 1986). For example, Meijerman et al. (2007) have shown recently that the predicted probability of being diagnosed with mature clavicles is greater when radiographs or computed tomography are used compared to when dry bone specimens are used.

In a previous study (Cardoso, 2008), the timing of epiphyseal union at the innominate and lower limb was documented from dry bone observations to aid the estimation of age at death of adolescent and young adult skeletal remains. These data were collected as part of a larger study, which used the Lisbon identified skeletal collection (Cardoso, 2006) and focused on the age-specific union of several epiphyses of the human postcranial skeleton in an effort to contribute to the understanding of its population variability. This collection is a series of Portuguese documented skeletons with a relatively large subadult segment, including several individuals in the adolescent and young adult age groups. Given the scarcity of these sorts of collections, it provides an exceptional opportunity to develop age-based bone maturity data. The study sample has been described as representing many populations experiencing lower levels of social and economic development (Cardoso, 2005, 2007), which means that its individuals may show, on average, the typical delay in bone maturation at adolescence due to malnutrition which has been documented in developing countries (Frisancho et al., 1970a,b; Pickett et al., 1995). Although the impact of socioeconomic status on bone maturation is relatively small, compared to the wide age intervals with which age can be established using epiphyseal union, it is not necessarily irrelevant (Cardoso, 2008). Therefore, for a correct use of the age-based reference standards for epiphyseal union, the forensic anthropologist and the bioarchaeologist should pay special attention to the different levels of social modernization

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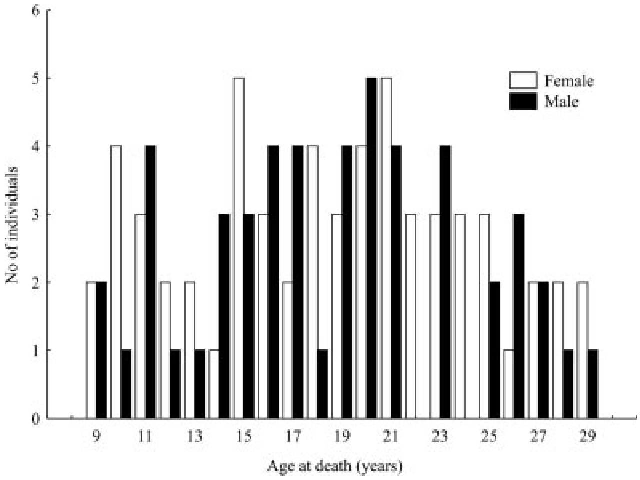

Fig. 1. Age and sex distribution of the study sample (females = 65, males = 56).

Fig. 2. Stages of union of the humeral head, 1, nonunion; 2, partial union; 3, completed union, all traces of fusion having disappeared.

and/or economic development of the population from which the standard was derived and from which the skeletal remains that are being aged originate.

The purpose of this article is to complete previous bone maturation information with data from the scapular girdle and the upper limb. These two anatomical locations provide supplementary material which will contribute to anthropological assessments of age in adolescent and young adult skeletons. Differences in maturation are documented separately for males and females and results are compared to published standards. Comparisons are made with age determination standards obtained primarily from skeletal collections, where observations could be made on dry bone. A more comprehensive reference for this population provides further comparative data on the fusion of different epiphyses and important alternative tools for age estimation in bioarchaeological and forensic studies. A more diversified array of anatomical locations is also important in limiting the range of possible positive identifications in forensic investigations.

MATERIALS AND METHODS

The skeletal remains of 121 individuals of known sex and age at death were selected from the Lisbon identified skeletal collection (Cardoso, 2006) and comprise this study's sample. The skeletal remains represent middle to low social class individuals, who lived in the city of Lisbon at the time of their death. Years of birth in the current study sample range from 1887 to 1960, with a strong peak in the 1920s, and years of death range from 1903 to 1975, with most deaths occurring between 1930 and 1960. Individuals in this sample have also been utilized in the previous study (Cardoso, 2008), but samples do not overlap entirely. This is because the current study sample is slightly larger as it encompasses a wider age interval. Individuals' ages range from 9 to 29 years and both sexes are about equally represented, females being slightly more numerous (females = 65, males = 56). Observations of epiphyseal union during the data collection process established the upper and lower age limits. Exact calendar age was obtained from birth and death civil records and assessment of accuracy in reported ages at death has been described in greater detail in Cardoso (2008). The age and sex distribution of the sample is depicted in Figure 1.

A total of 16 anatomical locations in the humerus, radius, ulna, scapula, and clavicle were recorded for epiphyseal–diaphyseal union using a three stage scale (Johnston, 1961): 1) no union; 2) partial union; 3) completed union, all traces of fusion having disappeared (see Fig. 2). One seemingly important problem in recording stages of epiphyseal union is the epiphyseal line or scar. This gapless line, which can persist at the diaphyseo–epiphyseal junction sometime after complete union, must not be mistaken for partial union at the risk of overestimating age of fusion (Stevenson, 1924). In the author's experience, this epiphyseal scar can persist several years after complete union. This scheme was chosen because successive stages would be only marginally different, if more than three stages are considered, and this reduces the imprecision when scoring in repeated observations. In the scapula, eight locations were examined according to the detailed descriptions of Scheuer and Black (2000), for the parts of the scapula undergoing fusion during adolescence and early adulthood: 1) coracoid epiphysis, 2) subcoracoid epiphysis; 3) angle of coracoid; 4) apex of coracoid; 5) acromial epiphysis; 6) glenoid epiphysis; 7) inferior angle; 8) vertebral border. An illustration of these ossification centers is shown in Figure 3. The vertebral border is a fragile, long, and multipartite epiphysis and it was scored as partially united as long as only one element had begun union along its entire surface. It was only scored as completely fused when the whole epiphyseal strip showed no gaps with the scapular body. The fact that the inferior angle epiphysis extends into the vertebral border raised some concerns over the ability to distinguish the two epiphyses at their junction, if they were fusing at the same time. However, no scapula showed partial union at these locations simultaneously. The same concern was also raised over the union of the subcoracoid and glenoid epiphysis, which make up the glenoid articular surface. Yet, at this location it was always possible to distinguish the two epiphyses at the superior third of the glenoid surface. The glenoid epiphysis, which starts as small islands of ossification, was scored as partially fused if only one of those islets had commenced union.

In the clavicle the stage of epiphyseal union was assessed on the medial surface of the bone. This epiphysis changes its shape over the course of clavicular maturation but that was not taken into consideration. As long as the epiphysis showed partial union it was scored as

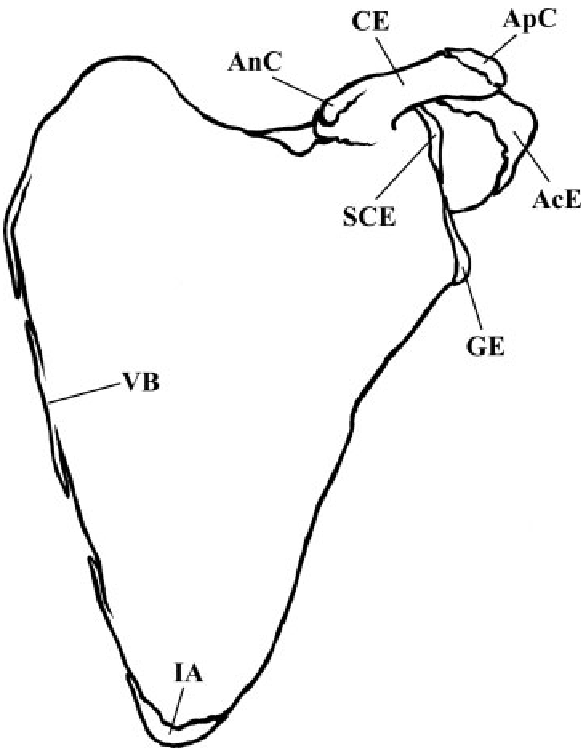

Fig. 3. Illustration of a scapula (anterior view) showing the location of the various centers of secondary ossification. The line drawing is a composite image of several specimens at various stages of union. CE, coracoid epiphysis; SCE, subcoracoid epiphysis; AnC, angle of coracoid; ApC, apex of coracoid; AcE, acromial epiphysis; GE, glenoid epiphysis; IA, inferior angle; VB, vertebral border.

such, regardless of whether it had the shape of a small nodule or of a complete articular cap. The epiphyses examined in the humerus were: 1) proximal epiphysis or the humerus head; 2) distal epiphysis; 3) medial epicondyle. Two locations were observed in the radius and ulna: 1) proximal epiphysis; 2) distal epiphysis. Scoring of union stages was performed blind without prior knowledge of the sex and age of the individual. Maturation was scored on left bones only or on the right side if the left was unavailable. Some anatomical locations could not be observed due to differential preservation and thus sample sizes vary accordingly. Pathological skeletons were also excluded from the study. At this point, it is important to note that the skeletons of the Lisbon collection do not show glued epiphyses and, consequently, observations are not affected by restorative work as in, for example, the Coimbra collection (Coqueugniot and Weaver, 2007). Intraobserver agreement was estimated by re-assessing stages of union in a random sample of 10 individuals, several weeks after the initial assessment. Stage of union was agreed on for 100% of the anatomical locations.

RESULTS

Summary data for age of epiphyseal union at the scapula, clavicle, humerus, radius, and ulna are presented in Table 1. The sexes and anatomical locations are separated and ages are presented at one year intervals and represent the interval between the value of one age and the next (e.g. 14 years = 14.0–14.9 years). The last three columns of Table 1 are identified with the headings Stage 1, Stage 2, and Stage 3. The first column (Stage 1) indicates the age of the oldest individual at Stage 1 (no union), that is, the age after which the anatomical location is either partially or completely fused. The second column (Stage 2) shows the age range of individuals at Stage 2 (partial union), that is, the youngest and oldest ages at which the anatomical location is undergoing fusion. Finally, the third column (Stage 3) indicates the age of the youngest individual at Stage 3 (completed union), that is, the age before which the anatomical location is either unfused or only partially fused. These three columns provide fast and simple information for estimating the age of unidentified skeletal remains. If the remains under examination show a partially fused (Stage 2) epiphysis, an estimated age interval for the skeleton's true chronological age can be obtained from Table 1. For example, if the proximal humerus of the unidentified remains is examined and scored as Stage 2, the estimated age interval is 14–21 years (14–19 years for females and 16–21 years for males). If only an un-fused or completely fused epiphysis is scored, data in Table 1 will only provide a superior or inferior age limit for the estimated age interval, respectively. For instance, if the coracoid epiphysis is not fused, the remains are likely to be younger than 15 years of age. The appropriate male or female age ranges should be used whenever possible.

Tables 2 to 17 present ages of union in all 16 anatomical locations in more detailed form, by providing the distribution of individuals (%) in each stage. Age distributions for the eight scapular anatomical locations are presented in Tables 2–9. Table 10 shows the age distributions in the medial clavicle. Age distributions for the epiphyses of the humerus are shown in Tables 11–13, for the epiphyses of the radius in Tables 14 and 15, and for the epiphyses of the ulna in Tables 16 and 17. Most epiphyseal–diaphyseal locations provided a significant number of observations in all three stages, except for the apex of coracoid and distal humerus in both sexes, and for the angle of coracoid, the acromial epiphysis, and the vertebral border in males, where the sample provided no data for partial union. In other locations, age intervals for Stage 2 were established by very few observations, such as the inferior angle and vertebral border of the scapula or proximal radial and ulnar epiphyses. The age interval for partial union in some epiphyses has been established by several observations, namely the proximal humerus for females ($n = 9$) and males ($n = 10$) or the distal radius, also for females ($n = 10$) and males ($n = 10$). Given that data obtained in this study are cross-sectional, age variability in stages of union increases and the probability of observing the actual union of epiphyses tends to diminish, as the chance that the time of death coincides with the actual moment of union is small. The fact that some locations provided no or few data for partial union may be also related to their quicker rate of fusion and, consequently, decreased probability of being sampled.

The coracoid, subcoracoid, and glenoid epiphyses are the first to fuse in the scapula at around 11 to 16 years of age, with females showing a slight advance in the glenoid epiphysis. The apex and angle of the coracoid and acromial epiphyses follow, and by around 20 years of age the scapula attains its adult size and shape. Sex differences in maturation of the scapula are not very clear due to insufficient observations at Stage 2, but there

TABLE 1. Summary for the ages (in years) of epiphyseal union at the scapula, clavicle, humerus, radius and ulna. Stage 1 column indicates the age of the oldest individual at stage 1; stage 2 column indicates age interval between the youngest and oldest individuals at stage 2; and stage 3 column indicates the age of the youngest individuals at stage 3

Bone	Epiphysis	Sex	Stage 1	Stage 2	Stage 3
Scapula	Coracoid epiphysis	♀	≤14	12–13 (n = 2)	≥11
		♂	≤14	11–16 (n = 4)	≥15
	Subcoracoid epiphysis	♀	≤14	11–16 (n = 4)	≥14
		♂	≤14	11–16 (n = 3)	≥15
	Angle of coracoid	♀	≤15	15–16 (n = 5)	≥15
		♂	≤18	–	≥16
	Apex of coracoid	♀	≤16	–	≥15
		♂	≤17	–	≥17
	Acromial epiphysis	♀	≤16	15–19 (n = 6)	≥17
		♂	≤18	–	≥16
	Glenoid epiphysis	♀	≤13	13–16 (n = 5)	≥14
		♂	≤16	15–18 (n = 5)	≥16
	Inferior angle	♀	≤20	17 (n = 1)	≥18
		♂	≤18	16 (n = 1)	≥17
	Vertebral border	♀	≤19	19–20 (n = 2)	≥17
		♂	≤19	–	≥17
Clavicle	Sternal epiphysis	♀	≤21	17–27 (n = 12)	≥22
		♂	≤21	19–25 (n = 14)	≥26
Humerus	Proximal epiphysis	♀	≤16	14–19 (n = 9)	≥17
		♂	≤18	16–21 (n = 10)	≥17
	Distal epiphysis	♀	≤14	–	≥11
		♂	≤16	–	≥14
	Medial epicondyle	♀	≤16	15 (n = 2)	≥11
		♂	≤16	16–18 (n = 3)	≥16
Radius	Proximal epiphysis	♀	≤14	13–16 (n = 3)	≥11
		♂	≤16	15–18 (n = 4)	≥15
	Distal epiphysis	♀	≤16	14–19 (n = 10)	≥17
		♂	≤18	16–21 (n = 10)	≥17
Ulna	Proximal epiphysis	♀	≤14	11–13 (n = 2)	≥13
		♂	≤14	11–15 (n = 2)	≥15
	Distal epiphysis	♀	≤16	14–19 (n = 8)	≥17
		♂	≤18	16–20 (n = 5)	≥17

TABLE 2. Age distribution for the stages of union of the coracoid epiphysis of the scapula (%)

	Females				Males			
		Stage of union				Stage of union		
Age	N	1	2	3	N	1	2	3
9	2	100	–	–	2	100	–	–
10	3	100	–	–	–	–	–	–
11	4	75	–	25	5	80	20	–
12	1	–	100	–	1	100	–	–
13	3	–	33	66	1	100	–	–
14	2	50	–	50	1	50	50	–
15	5	–	–	100	3	–	33	66
16	3	–	–	100	4	–	25	75
17	3	–	–	100	4	–	–	100
18	5	–	–	100	2	–	–	100

TABLE 3. Age distribution for the stages of union of the subcoracoid epiphysis of the scapula (%)

	Females				Males			
		Stage of union				Stage of union		
Age	N	1	2	3	N	1	2	3
9	1	100	–	–	2	100	–	–
10	3	100	–	–	1	100	–	–
11	4	75	25	–	5	80	20	–
12	1	100	–	–	1	100	–	–
13	3	–	100	–	1	100	–	–
14	2	50	–	50	3	100	–	–
15	5	–	–	100	3	–	33	66
16	3	–	33	66	4	–	25	75
17	3	–	–	100	4	–	–	100
18	5	–	–	100	2	–	–	100

seems to be a 1- to 2-year delay in males, with some overlap at some locations. The fusion of the medial clavicle is more variable, as can be seen by the wide age intervals for partial union. Maturation of the clavicle does not seem to show any significant sex differences. The earliest epiphysis of the upper limb to fuse is the proximal ulna and, possibly, also the distal humerus, as suggested by youngest ages at Stage 3, although there were no observations for partial union. The following epiphysis to fuse is the proximal ulna, which fuses at around 11 to 13 years of age, slightly later in males. The proximal radius and the medial epicondyle of the humerus commence union after the proximal ulna has fused completely, with males showing a two-year delay compared to females. The proximal humerus, the distal radius and distal ulna are the last to fuse and at about the same time. This occurs in females between 14 and 19 years and in males between 16 and 21. Overall, in the upper limb, the epiphyses of the elbow fuse earlier than those of the shoulder and wrist, with females around 2 years ahead of males.

DISCUSSION

Data presented in this study complete previously reported ages for timing of epiphyseal union in the post-cranial skeleton in a Portuguese identified skeletal collection, by providing age intervals for the union of the

TABLE 4. Age distribution for the stages of union of the angle of coracoid of the scapula (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
13	3	100	–	–	1	100	–	–
14	1	100	–	–	3	100	–	–
15	5	20	60	20	3	100	–	–
16	3	–	66	33	4	50	–	50
17	3	–	–	100	4	25	–	75
18	5	–	–	100	2	50	–	50
19	4	–	–	100	3	–	–	100
20	4	–	–	100	5	–	–	100

TABLE 5. Age distribution for the stages of union of the apex of coracoid of the scapula (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
13	2	100	–	–	1	100	–	–
14	1	100	–	–	3	100	–	–
15	5	60	–	40	2	100	–	–
16	2	50	–	50	2	100	–	–
17	2	–	–	100	3	33	–	66
18	5	–	–	100	1	–	–	100
19	3	–	–	100	2	–	–	100

TABLE 6. Age distribution for the stages of union of the acromial epiphysis of the scapula (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
13	3	100	–	–	1	100	–	–
14	2	100	–	–	2	100	–	–
15	5	60	40	–	3	100	–	–
16	2	50	50	–	4	75	–	25
17	2	–	50	50	4	25	–	75
18	4	–	–	100	1	50	–	50
19	4	–	50	50	4	–	–	100
20	3	–	–	100	5	–	–	100
21	5	–	–	100	5	–	–	100

TABLE 7. Age distribution for the stages of union of the glenoid epiphysis of the scapula (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
11	4	100	–	–	5	100	–	–
12	1	100	–	–	1	100	–	–
13	3	33	66	–	1	100	–	–
14	1	50	–	50	3	100	–	–
15	5	–	40	60	3	33	66	–
16	3	–	33	66	4	25	25	50
17	3	–	–	100	4	–	25	75
18	5	–	–	100	2	–	50	50
19	4	–	–	100	4	–	–	100
20	4	–	–	100	6	–	–	100

TABLE 8. Age distribution for the stages of union of the inferior angle epiphysis of the scapula (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
14	1	100	–	–	2	100	–	–
15	4	100	–	–	2	100	–	–
16	2	100	–	–	3	66	33	–
17	2	50	50	–	4	50	–	50
18	4	–	–	100	2	50	–	50
19	2	100	–	–	3	–	–	100
20	3	33	–	66	3	–	–	100
21	2	–	–	100	3	–	–	100
22	2	–	–	100	–	–	–	–

TABLE 9. Age distribution for the stages of union of the vertebral border epiphysis of the scapula (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
15	4	100	–	–	3	100	–	–
16	3	100	–	–	3	100	–	–
17	2	50	–	50	4	75	–	25
18	4	–	–	100	2	50	–	50
19	4	50	25	25	3	33	–	66
20	3	–	33	66	3	–	–	100
21	4	–	–	100	2	–	–	100
22	2	–	–	100	–	–	–	–

epiphyses of the scapula, clavicle, humerus, radius and ulna. Overall, the earliest union in the upper limb and scapular girdle occurs at the coracoid area in the scapula and at the proximal ulna. The remaining epiphyses at the elbow fuse next, as well as the epiphyses that make up the glenoid surface. The last epiphysis to fuse is the medial clavicle, which follows the complete union of the epiphyses of the shoulder and wrist in the upper limb and the remaining epiphyses of the scapula. In some locations, age ranges of partial union overlap completely between the sexes and do not seem to show significant differences. This is the case of the medial clavicle and, to a lesser extent, the subcoracoid and the inferior angle of the scapula and medial epicondyle of the humerus and the proximal ulnar epiphysis. These overlaps, however, may result from little variation being sampled. Except for the medial clavicle, variability in the ages of fusion is about the same in females and males.

When the upper limb is compared to the lower limb (Cardoso, 2008) in this sample, there seems to be a greater difference in timing between the elbow and the shoulder + wrist, compared to the difference between the knee and the hip + ankle. More time elapses between the union of the epiphyses of the elbow and the epiphyses of the shoulder and wrist, than the time between fusion of the epiphyses of the knee and fusion of the epiphyses of the hip and ankle. In addition, the upper limb tends to mature in advance of the lower limb, showing earlier ages of union in most epiphyses, namely those at the elbow. The upper and lower limbs also seem to differ in relative maturation between the sexes. Whereas in the upper limb there is a greater and more consistent sex difference of about 2 years in maturation, in the lower limb that difference is less consistent and slightly less than 2 years, on an average.

TABLE 10. Age distribution for the stages of union of the medial clavicle (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
15	5	100	–	–	2	100	–	–
16	3	100	–	–	4	100	–	–
17	3	66	33	–	4	100	–	–
18	5	60	40	–	2	100	–	–
19	4	100	–	–	4	50	50	–
20	4	50	50	–	5	40	60	–
21	5	40	60	–	5	40	60	–
22	3	–	33	66	–	–	–	–
23	3	–	–	100	4	–	100	–
24	3	–	66	33	–	–	–	–
25	3	–	–	100	2	–	100	–
26	1	–	–	100	1	–	–	100
27	2	–	50	50	2	–	–	100
28	2	–	–	100	1	–	–	100
29	2	–	–	100	–	–	–	–

TABLE 11. Age distribution for the stages of union of the proximal humerus (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
12	1	100	–	–	1	100	–	–
13	3	100	–	–	1	100	–	–
14	2	50	50	–	3	100	–	–
15	5	60	40	–	3	100	–	–
16	3	33	66	–	4	75	25	–
17	3	–	33	66	4	25	50	25
18	4	–	25	75	2	50	50	–
19	4	–	50	50	4	–	75	25
20	4	–	–	100	6	–	33	66
21	5	–	–	100	4	–	125	75
22	3	–	–	100	–	–	–	–
23	3	–	–	100	4	–	–	100

TABLE 12. Age distribution for the stages of union of the distal humerus (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
9	2	100	–	–	2	100	–	–
10	3	100	–	–	2	100	–	–
11	4	75	–	25	2	100	–	–
12	–	–	–	–	2	100	–	–
13	3	–	–	100	1	100	–	–
14	2	50	–	50	3	66	–	33
15	5	–	–	100	2	–	–	100
16	3	–	–	100	4	25	–	75
17	3	–	–	100	4	–	–	100
18	5	–	–	100	2	–	–	100

TABLE 13. Age distribution for the stages of union of the medial epicondyle of the humerus (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
10	3	100	–	–	2	100	–	–
11	4	75	–	25	2	100	–	–
12	–	–	–	–	2	100	–	–
13	2	50	–	50	1	100	–	–
14	2	50	–	50	2	100	–	–
15	5	–	40	60	2	100	–	–
16	1	100	–	–	3	33	33	33
17	2	–	–	100	3	–	33	66
18	5	–	–	100	2	–	50	50
19	4	–	–	100	2	–	–	100
20	3	–	–	100	5	–	–	100

TABLE 14. Age distribution for the stages of union of the proximal radius (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
9	2	100	–	–	1	100	–	–
10	3	100	–	–	2	100	–	–
11	4	75	–	25	4	100	–	–
12	–	–	–	–	2	100	–	–
13	3	33	33	33	1	100	–	–
14	2	50	–	50	3	100	–	–
15	5	–	20	80	3	33	33	33
16	2	–	50	50	4	25	50	25
17	3	–	–	100	4	–	–	100
18	5	–	–	100	2	–	50	50
19	4	–	–	100	4	–	–	100
20	4	–	–	100	6	–	–	100

TABLE 15. Age distribution for the stages of union of the distal radius (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
12	2	100	–	–	1	100	–	–
13	3	100	–	–	1	100	–	–
14	2	50	50	–	2	100	–	–
15	5	60	40	–	3	100	–	–
16	3	66	33	–	4	25	75	–
17	3	–	66	33	4	25	50	25
18	5	–	20	80	1	100	–	–
19	3	–	100	–	4	–	50	50
20	4	–	–	100	5	–	40	60
21	5	–	–	100	4	–	25	75
22	3	–	–	100	–	–	–	–
23	3	–	–	100	4	–	–	100

Age-based maturity data presented here can provide important and alternative information that can be used in a variety of situations for age estimation, when, for example, only the upper limb or scapular girdle are recovered from a certain context, or to reduce the probable age range of the individual if the skeleton is retrieved in a relatively complete state. However, skeletal maturity is not synonymous with calendar age. Skeletal maturity is a complex process which shows significant individual variability, and thus only an age range can be established for the union of a certain epiphysis. These age ranges can be used to the determine age directly, making use of the appropriate age interval of each epiphysis, or indirectly, by modifying previous incomplete or imprecise data. Establishing a probable age within a certain range requires information at Stage 2, because only those epiphyses which are undergoing union can provide a lower and an upper age limit. In

TABLE 16. Age distribution for the stages of union of the proximal ulna (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
9	2	100	–	–	1	100	–	–
10	3	100	–	–	1	100	–	–
11	4	75	25	–	3	66	33	–
12	1	100	–	–	2	100	–	–
13	3	–	33	66	1	100	–	–
14	2	50	–	50	3	100	–	–
15	5	–	–	100	2	–	50	50
16	1	–	–	100	3	–	–	100
17	3	–	–	100	4	–	–	100

TABLE 17. Age distribution for the stages of union of the distal ulna (%)

	Females				Males			
		Stage of union				Stage of union		
Age	*N*	1	2	3	*N*	1	2	3
12	2	100	–	–	1	100	–	–
13	3	100	–	–	1	100	–	–
14	1	–	100	–	2	100	–	–
15	5	60	40	–	3	100	–	–
16	3	66	33	–	4	75	25	–
17	3	–	33	66	4	25	25	50
18	5	–	–	100	2	50	–	50
19	3	–	100	–	4	–	50	50
20	2	–	–	100	6	–	17	83
21	5	–	–	100	4	–	–	100
22	3	–	–	100	–	–	–	–

contrast, if the epiphysis is un-fused (Stage 1) or shows complete fusion (Stage 3), only an upper or a lower age limit can be established, respectively. The age intervals for maximum error in estimating age can be obtained for each individual anatomical location by subtracting the youngest from the oldest age of partial union minus one. For partially fused epiphyses, when only one location can be assessed and the sex can be determined, age can be estimated within a maximum range of 5 years for the epiphyses of the scapula and of the upper limb. The medial clavicle shows greater variation in maturation and provides an age interval for a maximum error of 9 years. If sex cannot be determined, the maximum error will increase as it will incorporate the age ranges of both sexes. For this reason, sex should be determined whenever possible. Alternatively, the age range should be expanded to include the possibility of either sex, whenever sex cannot be determined. If several epiphyseal locations are available it is possible to calculate a modal age. By overlapping the age ranges (Stage 2) of all available epiphyses, one can determine the most likely (modal) age.

Dry bone observations reported in this study are important for a few reasons. First, this type of data is relatively scarce, especially for females and some anatomical locations. For example, some of the most utilized reference standards for epiphyseal union provide information only for males (McKern and Stewart, 1957, reproduced in White, 2000; Buikstra and Ubelaker, 1994; Krogman and Iscan, 1986); do not discriminate between the sexes in most or some anatomical locations (Brothwell, 1981; Ferembach et al., 1980; Stevenson, 1924), or collapse information from adjacent epiphyses (Brothwell, 1981; Ferembach et al., 1980). Second, while some standards provide incomplete data by using truncated samples at either the lower (Stevenson, 1924; McKern and Stewart, 1957; Veschi and Facchini, 2002) and upper age limits (Veschi and Facchini, 2002), in this study there is an ample age range, well beyond the ranges of fusion. Third, differences between radiological and gross inspection of epiphyseal union (Krogman and Işcan, 1986; Meijerman et al., 2007), such as the earlier detection of epiphyseal–diaphyseal union in radiographs, will probably establish dry bone reference standards as the most suitable for the estimation of age in skeletal remains. In addition, radiographic atlases are also usually designed to provide normative data instead of the full range of variation in epiphyseal union. And fourth, the importance of the data in this study also resides in the fact that it derives from nonreconstructed material, unlike some other samples, such as that of the Coimbra collection, where the epiphyses have sometimes been glued to the diaphyses (Coqueugniot and Weaver, 2007), raising some concerns as to the reliability of the established age ranges.

Comparing this study's results with other published data is useful to assess population variation in bone maturity, by identifying differences or similarities in the timings of fusion. Because of the above mentioned differences between radiological and gross inspections, data in this study should be compared to similar osteological studies. For this comparison, the choice of age determination standards was mainly restricted to those which have been supported on dry bone observations (Stevenson, 1924; Todd and D'Errico, 1928; McKern and Stewart, 1957; Webb and Suchey, 1985; Veschi and Facchini, 2002; Schaefer and Black, 2005; Coqueugniot and Weaver, 2007). The exceptions are widely used or accessible compilations of radiographic data, such as the one provided by Scheuer and Black (2000), by the Workshop of European Anthropologists (Ferembach et al., 1980), and by a series of recent radiographic and CT scan studies using the clavicle (Kreitner et al., 1998; Schmeling et al., 2004; Schultz et al., 2005; Schultze et al., 2006). Comparisons provided here are not exhaustive because they are only meant to examine major divergences.

The ages of union of the medial clavicle in this study are similar to those documented in Stevenson (1924), Todd and D'Errico (1928), Webb and Suchey (1985) and Black and Scheuer (1996). The major differences are related to the fact that Stevenson (1924) and Black and Scheuer (1996) do not discriminate between the sexes, and have a slightly wider age interval, including both younger and older ages of union for females and males, reported by Webb and Suchey (1985). This may result from Webb and Suchey's (1985) study having sampled more variation. Schmeling et al. (2004) have collected radiographic union times for the clavicular epiphysis and obtained earlier ages (by 1 $\sim$ 3 years) of union compared to the gross inspections of this study. Comparatively, the timing of epiphyseal union at the medial clavicle overlaps almost entirely with that of thoracic CT scan studies (Kreitner et al., 1998; Schultz et al., 2005; Schultze et al., 2006), albeit these seem to show a slight advance. Kreitner et al. (1998) and Schultze et al. (2006), however, do not discriminate between the sexes. Comparisons with these radiographic and CT scan results were done with respect to the stages defined as partial union

(Kreitner et al., 1998), epiphyseal cartilage partly ossified (Schmeling et al., 2004; Schultz et al., 2005) or epiphyseal ossification with bridging (Schultze et al., 2006).

Three studies (McKern and Stewart, 1957; Veschi and Facchini, 2002; Schaefer and Black, 2005) provide age ranges for most epiphyses of the scapular girdle and upper limb, but are all truncated at the lower end of the age range (at ~16–17 years). Although there is a high degree of overlap in ages at Stage 2 of union, between this study and those reported by Veschi and Facchini (2002), the absence of individuals under 16 years of age complicates any attempts for comparison, because at this age most epiphyses have already commenced fusion, with the exception of the medial clavicle. On the other hand, in Veschi and Facchini's (2002) study, the end point of epiphyseal union tends to extend towards the older ages, showing a delay of about 2 to 4 years in upper ages of union. The medial clavicle shows truncated data at the upper age limit (Veschi and Facchini, 2002), but the lower age limit is similar to this study. As suggested in the previous study (Cardoso, 2008), differences in timing with Veschi and Facchini's (2002) study are likely to derive from the epiphyseal scar being mistaken for the gaps in the diaphyseo–epiphyseal junction of a partially fused epiphysis.

Although the samples of McKern and Stewart (1957) and Schaefer and Black (2005) are also truncated at the lower end of the age range, if the appropriate adjustments are made with respect to the different scoring methods, age ranges for epiphyseal union of the proximal humerus, distal radius and ulna are similar between both samples and those of this study. In the clavicle, timing is also similar to that reported by Schaefer and Black (2005), but slightly delayed to that observed by McKern and Stewart (1957). Stevenson's (1924) data are also truncated, since they only start at age 17 and the sexes are pooled. However, the upper age limit of ranges of union are comparable, the humerus, radius, and ulna all showing about the same end point as that found here. When the scapula is considered in Stevenson's (1924) study, only the acromial epiphysis and the inferior angle seem to show a slight delay.

Compared to the Coimbra sample (Coqueugniot and Weaver, 2007), this study's age ranges appear similar in both sexes, but there are some noticeable differences. For example, in the scapula, the coracoid epiphyses show a considerably delay in Coimbra males of 4–7 years; and in the upper limb, the Lisbon and Coimbra samples differ in the union of the proximal epiphysis of the humerus, which is delayed in Coimbra by around 3 years in both sexes. A similar delay is found in union of the distal epiphysis of the radius and ulna, where the Coimbra males show a delay of about 5 years. Overall, the Coimbra sample does not show any evidence of advanced union relative to the Lisbon sample. A similar maturation delay in the Coimbra sample had already been documented in the lower limb and innominate (Cardoso, 2008). This again, may derive from methodological differences, namely the persistence of the epiphyseal scar and possibly by the presence of glued epiphyses (scored as unfused by Coqueugniot and Weaver, 2007), which had commenced union and were glued due to postmortem breakage.

The last two reference standards compared are compilations of mostly radiographic data (Ferembach et al., 1980; Scheuer and Black, 2000), and in these it is assumed that established age ranges of union represent the interval between the youngest and oldest ages of partial union. In Ferembach et al. (1980), age ranges for clavicular union overlap with those of this study, but are considerably narrower. Age ranges for the various epiphyses of the scapula show later ages, particularly the glenoid epiphysis (5 ~ 6 years) (Ferembach et al., 1980). In the upper limb, some locations have similar ages of fusion, but in others there is a delay in ranges of fusion reported by Ferembach et al. (1980), such as in the proximal humerus, which shows union about 4–5 years later. Some difficulties arise with the remaining locations, because Ferembach et al. (1980) do not distinguish between the four different epiphyses at the elbow. Scheuer and Black (2000) also do not distinguish between the sexes in so far as the scapula is concerned, where most epiphyses show a considerable delay relative to this study, of as much as 4–5 years. In contrast, the epiphyses of the upper limb in Scheuer and Black (2000) compilation show similar or slightly advanced (1 ~ 2 years) ages of union. The exception is the ulna, where both epiphyses fuse later (1 ~ 2 years) compared to this study, particularly the proximal one. This may result from the fact that Scheuer and Black's (2000) atlas results from several different sources being compiled.

There seems to be an overall pattern of similarity between the results of this study and the various studies compared. The greatest discrepancies are found in the study carried out by Veschi and Facchini (2002) and in the compilation of Ferembach et al. (1980). Other standards show less recurrent divergences, such as in Coqueugniot and Weaver (2007), but differences are still noticeable. Several methodological aspects may explain these differences, namely the method of epiphyseal union examination (dry bone or radiograph), the late persistence of an epiphyseal scar that can mislead to the classification of a partially fused epiphysis, and the amount of variation which has been sampled in each study. These methodological differences are likely, however, to conceal important socioeconomic variation in timing. Because of this, the impact of socioeconomic circumstances on the timing of epiphyseal fusion documented in each reference standard cannot be properly evaluated. Nonetheless, Meijerman et al. (2007) have shown that socioeconomic status has a negative impact on epiphyseal union of the medial clavicle, by decreasing the predicted probability of individuals having mature clavicles at each age. The decrease in probability suggests a delay of about one year in low socioeconomic status individuals. One year is approximately the amount of delay that one would expect from the studies carried out by Frisancho et al. (1970a,b), who report a 5–9% delay in skeletal maturation at adolescence due to poor nutrition. Therefore, proper recognition of the potential impact of socioeconomic status in skeletal maturation will probably improve the accuracy with which age ranges can be established (Schmeling et al., 2006). Although age intervals for maximum error in estimating age are about 5 years in the scapula and upper limb, errors of assessment due to socioeconomic status should not be considered irrelevant, as they are likely to shift the starting and ending points of the probable age ranges, during which epiphyses are fusing.

CONCLUSION

By completing the reporting of timings of epiphyseal union described in a previous article, both sources provide a more comprehensive compilation for age ranges that can be used in human skeletal remains in both bioarchaeology and forensic situations. Data for age range at epiphyseal closure is particularly useful for the estimation of age at death of adolescent and young adult skeletons, as these are the most common age groups in forensic investigations. The age of unidentified skeletal remains can be established to within 5 years using timing of epiphyseal union of the upper limb and scapula, and to within 9 years when the timing of clavicular union is used. Since females are almost always in advance of males in skeletal maturation, it is desirable to determine the sex of the remains prior to the estimation of age. Because there are differences between radiological and gross inspection of epiphyseal union, only published data collected on osteological collections should be used to estimate the age of dry bone remains. However, such collections are rare and this is where data presented here may prove to be most useful.

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