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Understanding Rib Fracture Patterns: Incomplete and Buckle Fractures

ABSTRACT: Reconstructing traumatic thoracic events, especially when soft tissues are absent, requires an advanced understanding of ribcage fracture patterns. The morphology and orientation of ribs complicate the fracture pattern, as a single blow often causes multiple fractures at various locations. Furthermore, fracture types observed in ribs are not explained easily by current bone biomechanic literature. Using evidential skeletal material archived at the Regional Forensic Center, Memphis, the ribs of 43 blunt force trauma cases were analyzed. A total of 195 incomplete fractures and 63 buckle fractures were noted. Incomplete fractures, previously thought to be common in children but rare in adults, were found among individuals ranging in age from 21–76 years. A buckle fracture, failure resulting from compressive instability, has been undefined previously in bone trauma literature but was repeatedly observed in this sample. This study elucidates recognizable rib fracture patterns while emphasizing gross bone examination for force and mechanical factors.

KEYWORDS: forensic science, forensic anthropology, rib fractures, bone biomechanics, incomplete fractures, buckle fractures

An objective of forensic anthropology is to use bone fracture patterns as an interpretative tool to reconstruct a traumatic event. Rib fracture patterns are commonly complex, and adult rib fractures have received very little attention in the medical and anthropological literature. Many standard medical texts focusing on skeletal trauma fail to mention the ribs beyond their association with the thoracic vertebral column (1–4). The lack of attention paid to rib fractures appears to result from the fact that, although insult to the vital organs they protect is of immediate medical concern, the ribs themselves are not. While focusing on children, Blount summarizes the medical community's attitude towards rib fractures in his 1955 text, "The general condition of the child is then the first concern, the [rib] fractures may be disregarded" (5, p. 202). Although Galloway focuses briefly on the cause and morphology of rib fractures in her 1999 anthropological text (6), the anthropological literature appears to be as limited as the medical literature on thorax bone injury, despite the importance of ribs in breathing and protecting the heart and lungs.

Reasons for limited rib fracture research include 1) difficulties in studying the ribcage, which often requires removing and processing the entire torso (6), 2) difficulties in conceptualizing the ribs as part of a closed structural system and not as individual bones, and 3) extreme complexities of ribcage fracture patterns. A single blow to the chest often causes multiple fractures throughout the ribcage and generates adjacent fractures with alternating points of tension (6,7).

In an attempt to begin to fill the void, we developed a method to analyze systematically rib fracture patterns (7). We immediately became aware that ribs appeared to respond unexpectedly to force. First, ribs recurrently failed in compression prior to tension. Second, incomplete rib fractures were found in mature and even elderly adults. Each of these fracture types is contrary to current biomechanical principles of elastic bone (8–19) and illustrates a need to investigate rib structural composition and fracture biomechanics.

Bone is a strong yet lightweight material. These two basic, but crucial, properties are a result of material composition, hierarchical organization, and intrinsic factors of the tissue. First, the base unit of bone is organic collagen fibers impregnated with inorganic elongated crystals of calcium hydroxyapatite ($Ca_{10} (PO_4)_6 (OH)_2$) that produce both strength and elasticity of the tissue (6,9,10). Second, the impregnated fibers are organized into sheets of lamellae. Each sheet of lamellae is separated by a thin interlamellar cement band. Each sheet exhibits a predominate direction of fiber orientation that often varies between successive sheets (11). The lamellar bone is then oriented to support loads (10,17). This structural organization increases both bone density and strength. Density is correlated directly to tissue strength (12–16). Equally as important, and contributing to the lightness of the material, are the open spaces in the microstructure of bone. Depending on type and age of bone, only 1/10 to 1/3 of bone is solid material. The interfacial gaps between fibers strengthen the bone by inhibiting crack propagation (9,10). Third, viscoelasticity and elasticity contribute to tissue strength through force absorption. Most observable in trabecular bone, viscoelasticity increases bone stiffness under high loading rates by resistance of interstitial fluid to flow through the trabecular space (9,10,14,17). The organic component of bone tissue is elastic and capable of absorbing relatively large tensile and compressive forces. While under continual stress, bone absorbs forces first through elastic deformation (temporary bending of bonds between atoms) and then through plastic deformation (permanent bending of bonds between atoms) before ultimately failing (Fig. 1) (6,10,16–18).

Age-related changes affect the strength of bone through decreased bone tissue and energy absorption capabilities and increased mineral density. Bone remodeling results in a net loss of tissue, narrower trabeculae, and increased intertrabecular space (21,22). Secondary osteons, with decreased fiber density, replace primary osteons, thereby increasing the percentage of cement lines

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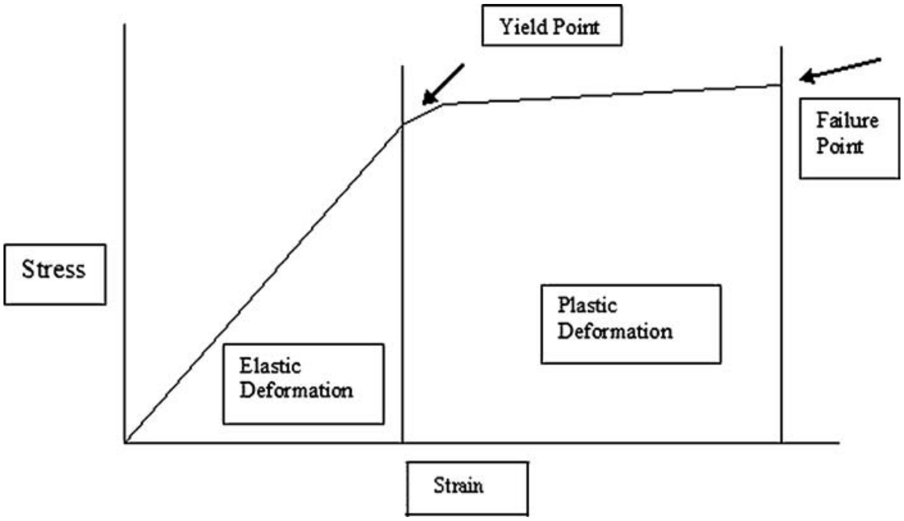

FIG. 1—*A stress-strain plot for bone showing the yield and failure points and elastic deformation and plastic deformation regions. The area under the curve is directly related to the "stiffness" or modulus of elasticity or Young's modulus of the bone (6,12,16–18,20).*

that are points of fracture proliferation (6,11,23). Researchers have shown that specimens of primary osteons demonstrate greater stiffness, yield strength, ultimate tensile strength, and fatigue resistance than do specimens of secondary osteons (11,15). With age, hematopoietic tissue is replaced by fat tissue that is less able to absorb energy (24). Osteocytes die, and their lacunae and canaliculi are filled with mineralized connective tissue, termed micropetrosis (19). Researchers hypothesize that micropetrosis increases the mineral density and brittleness of bone (19) and diminishes bone's ability to respond to fatigue microfractures (17,25). Aged, brittle bones typically fracture completely when they fail. In contrast, incomplete fractures are more common in young, elastic bones and are considered rare in adults (5,10,21,26,27). Adams states that incomplete fractures "are peculiar to children, whose bones . . . are springy and resilient like a freshly cut sapling" (27, p. 7). Harkess and colleagues state that incomplete fractures "so common in children, are rarely, if ever, found in adults, but occasionally an incomplete fracture or infraction may be seen" (10, p. 1).

Bone biomechanical studies have shown that cortical and trabecular bones are stronger under compressive rather than tensile stress (6,10,12,17,20). The compressive strength of bone is directly proportional to its density (28). The porosity of trabecular bone significantly reduces tissue strength in both compression and tension, and experimentally trabecular bone yields at relatively low strain (12). Experimental observations have shown that when under stress (i.e., tension, angulation, torsion), bone will fail first at the point of greatest tension (6,10,14,15,17).

While current biomechanical research indicates that ribs are expected to fail in tension prior to compression and age-related changes decrease the elastic property of bone and increase the likelihood of a complete fracture upon failure, we noticed a different pattern. Failure initiated at the point of compression, and incomplete fractures were seen in ribs of mature and even elderly individuals during this study. In this research report we attempt to explain these unexpected observations.

Method

Evidentiary skeletal materials archived at the Regional Forensic Center, Memphis, were used in this study. The ribs of 43 blunt force trauma cases were analyzed totaling 492 ribs and 733 individual fractures (Table 1). The majority of the ribs were harvested during autopsy for bone trauma analysis during a 14-year period from 1990–2003. The ribs from three cases were skeletonized when recovered (cases 1,25,28). The causes of the rib fractures were motor vehicle accident, fall, beating, cardiopulmonary resuscitation (CPR), industrial accident, or unknown. In one case (case 15), CPR was reportedly administrated on a fall victim. The ages were recorded from police reports; the ages of two individuals were unknown (cases 4,21), and the age was estimated in two unidentified cases (cases 25,28). All ribs analyzed were developmentally mature. Ancestry was recorded from the autopsy reports and estimated in the two unidentified cases (cases 25,28).

Ribs were sided, ordered by morphology, and analyzed. At the time of harvesting, the rib numbers were noted, enabling us to determine the specific rib number when an incomplete set of ribs was studied. Fractures were examined under an operation microscope (Wild Heerbugg, Switzerland) with up to 40× magnification capability and assigned a descriptive code. Included in the code were the following: 1) individual's demographic profile (age, ancestry, and sex), 2) type of trauma, 3) side and rib number, 4) number of fractures on each rib, 5) whether the rib was completely or partially harvested, 6) location of the fracture, 7) type of fracture (i.e., transverse, oblique, butterfly, buckle), 8) fracture condition (reconstructed complete fracture, non-reconstructed complete fracture, incomplete fracture), 9) if the fracture was comminuted, 10) the point of tension, and 11) the localized direction of force. The majority of the ribs were reconstructed temporarily with adhesive tape to allow all fracture planes to be observed microscopically. The ribs of seven cases (cases 4,5,24,10,25,41,42) had been reconstructed previously by gluing the fracture planes.

The following definitions were applied consistently during the coding of the sample. *Incomplete fracture* was defined as any partial fracture, despite fracture location and morphology (Fig. 2). Longitudinal cracks following the bone grain and unassociated with more complex fractures were unclassified and regarded as possible processing artifacts. *Buckle fracture* was defined as a fracture wherein the bone failed at the point of compressive stress prior to failure at the point of tensile stress (Fig. 3) (see Discussion).

TABLE 1—*Demographic profile and numerical summary of the blunt force trauma cases studied.*

Case #	Age	Ancestry*	Sex	Trauma**	Ribs Analyzed	Fractures	Incomplete Fractures	Buckle Fractures
1	21	W	F	2	24	37	15	4
2	39	B	F	2	13	24	7	0
3	30	B	M	1	12	25	1	1
4		W	M	1	16	27	5	0
5	63	W	F	1	22	40	2	1
6	28	W	M	1	9	15	5	5
7	28	B	M	1	14	28	11	5
8	61	B	M	3	6	5	1	2
9	26	W	M	1	10	14	8	4
10	41	B	M	1	18	25	6	3
11	51	B	M	0	24	48	4	0
12	41	W	M	1	13	25	5	1
13	40	B	M	3	19	29	3	1
14	20	W	F	1	24	71	19	4
15	73	W	M	2,4	14	15	3	2
16	26	NA	M	4	11	9	7	2
17	51	A	F	1	6	17	5	3
18	81	B	M	3	12	10	0	0
19	33	W	M	3	3	3	0	0
20	80	W	F	3	3	5	0	0
21		W	F	3	8	6	4	4
22	53	B	F	2	9	5	2	0
23	18	W	M	1	10	10	9	0
24	18	W	M	1	12	12	1	0
25	15–20	W	M	1	12	15	4	1
26	42	W	F	1	5	8	0	0
27	46	W	M	5	6	6	4	1
28	30–50	B	F	1	24	22	7	1
29	18	B	M	1	10	19	7	2
30	61	W	M	4	11	10	4	1
31	33	W	F	3	7	6	3	2
32	69	W	M	3	13	11	4	4
33	36	B	F	2	24	50	9	1
34	38	W	M	4	7	7	7	6
35	49	W	F	2	3	4	2	0
36	20	W	M	1	8	5	4	0
37	41	W	F	0	4	6	4	0
38	56	W	M	1	8	9	2	0
39	58	B	M	0	2	2	0	0
40	76	W	F	0	18	22	3	1
41	61	B	M	3	6	5	2	0
42	39	B	F	3	3	3	0	0
43	43	B	F	3	9	18	6	1
Total					492	733	195	63

* W = White; B = Black; A = Asian; NA = Native American.

** 0 = Unknown; 1 = Motor vehicle accident; 2 = Fall; 3 = Beating; 4 = CPR; 5 = Industrial Accident.

The occurrence of incomplete and buckle fractures was calculated for the complete sample. The sample was then divided into several subsets for additional comparison, including age (excluding cases 4,21,25,28), sex, and ancestry (excluding cases 16,51). The sample was broken into six age groups. The subsets of the sample were compared using the Wilcoxon rank-sum test.

Results

The occurrence of incomplete and buckle fractures within the sample and subsets of the sample were tabulated. Table 2 lists the demography of the grouping, number of cases, total number of rib fractures, and percentage of incomplete and buckle fractures. The results of the Wilcoxon rank-sum test (Table 3) show no significant difference in the occurrence of incomplete or buckle fractures when comparing groups categorized by age, sex, and ancestry.

TABLE 2—*Occurrence of rib fractures in the sample and subsets of sample.*

Demography		# of Cases	Total # of Fractures	% Incomplete Fractures*	% Buckle Fractures*
	Complete sample	43	733	26	4
Age	15–24	6	154	35	6
	25–34	7	100	35	19
	35–44	10	195	24	7
	45–54	5	80	21	5
	55–64	6	71	15	10
	65+	5	63	16	11
Sex	Female	16	344	26	6
	Male	25	389	28	11
Ancestry	Black	24	318	21	5
	White	14	389	30	11

* % total number of rib fractures.

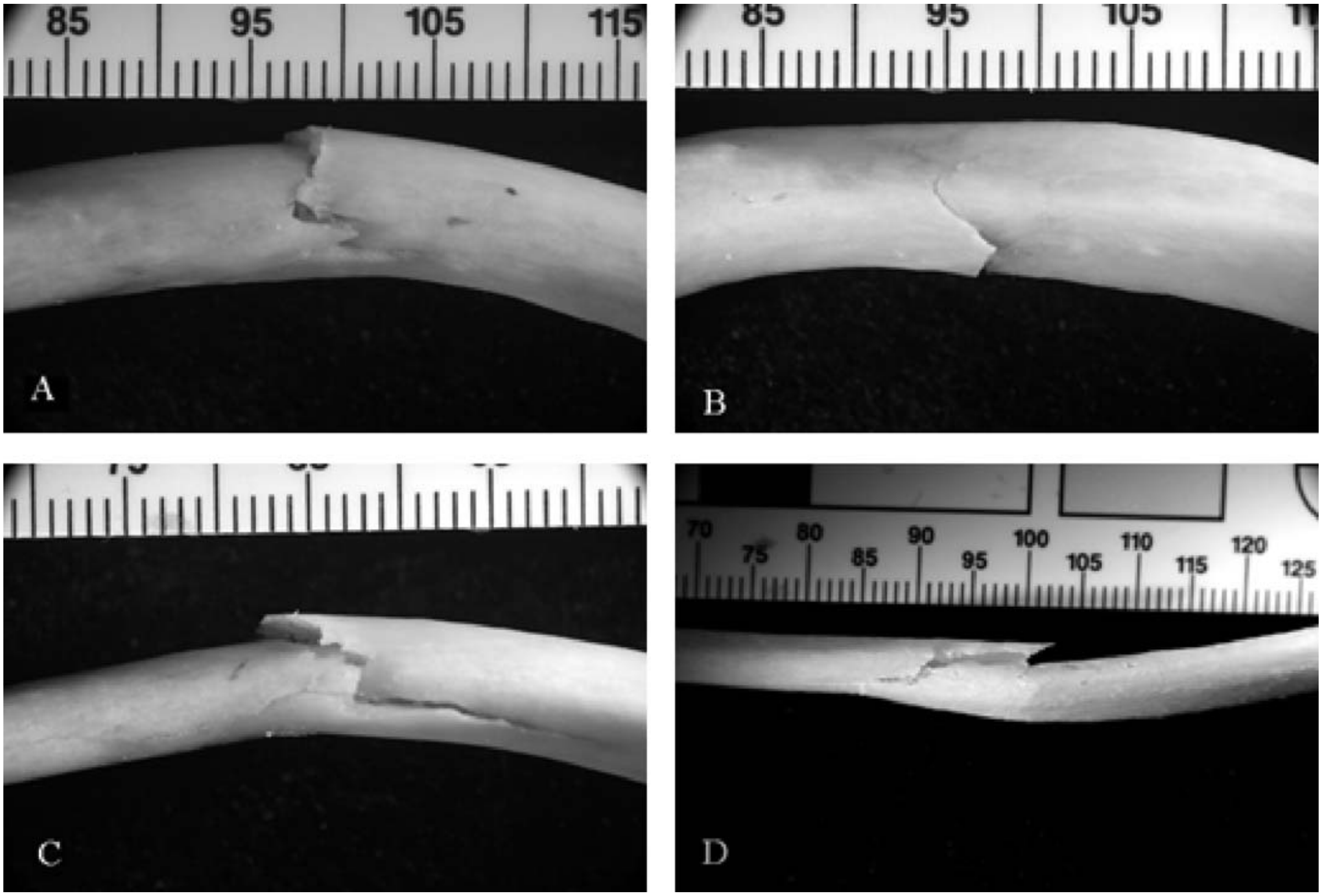

FIG. 2—*(a–d)—Four examples of incomplete fractures observed in the sample. The scale is in millimeters.*

TABLE 3—*Wilcoxon rank-sum test results.*

Groups Compared	Incomplete Fractures P-Value	Buckle Fractures P-Value
Age Groups	0.067	0.439
Sex Groups	0.907	0.689
Ancestral Groups	0.819	0.686

Figure 4 illustrates the approximate location and the number of buckle fractures at each location.

Discussion

Bone histological research has demonstrated that as bone becomes more brittle with age, its organic component decreases and inorganic component increases (6,11,15,26,29). As a result, we expected to see complete fractures at relatively low strain rates, especially among the elderly. However, we observed incomplete fractures in elderly individuals (Table 1), and although subset sample size was small, the Wilcoxon rank-sum test showed no significant difference in the occurrence of incomplete fractures between various age groups (Table 6). In light of our observations, chronological age may not be as influential in mechanical behavior of bone as originally described (5,10,21, 26,27).

A bone's response to stress depends on the force (amount, direction, area, and loading rate) and the mechanical properties of the bone (density, tissue composite, geometric shape, collagen orientation, and rigidity) (28,30–32). Using machine-cut human and bovine trabecular bone to study compressive behavior, Carter and Hayes (14) applied a wide range of strain rates and found that the apparent density (dry weight of the tissue divided by the volume of the tissue) was the most important factor when considering biomechanical behavior. They further concluded that the influence of strain rate was relatively small and approximately equal to the influence of bone tissue composition and trabeculae orientation. In contrast, Galloway and Zephro (33) hypothesized that when considering the whole bone in anatomical context, the type of the fracture (incomplete or complete) may be highly correlated to strain rate; suggesting incomplete fractures may be a result of a slow loading, low energy force. The extreme differences in Carter and Hayes' (14) analysis of machine-cut miniscule trabecular bone specimens and Galloway and Zephro's (33) analysis of complete bones emphasizes the difficulty of applying experimental research to gross bone observations.

In contrast to the debate on the effects of strain rate, nearly all the experimental and observational bone biomechanic literature agree that bone is strongest under compressive stress and weaker under tensile stress (6,10,12,14,15,17,20,21,25,34). However, we repeatedly observed failure at the point of compression prior to the point of tension. The majority of the rib is a thin-walled tube, and, based on morphology, we hypothesized it was buckling. Figure 4 shows that the majority of buckle fractures occurred in areas where the cortical bone is thin. Buckling is a collapse due to compressive instability. Engineers have defined this type of failure and reported

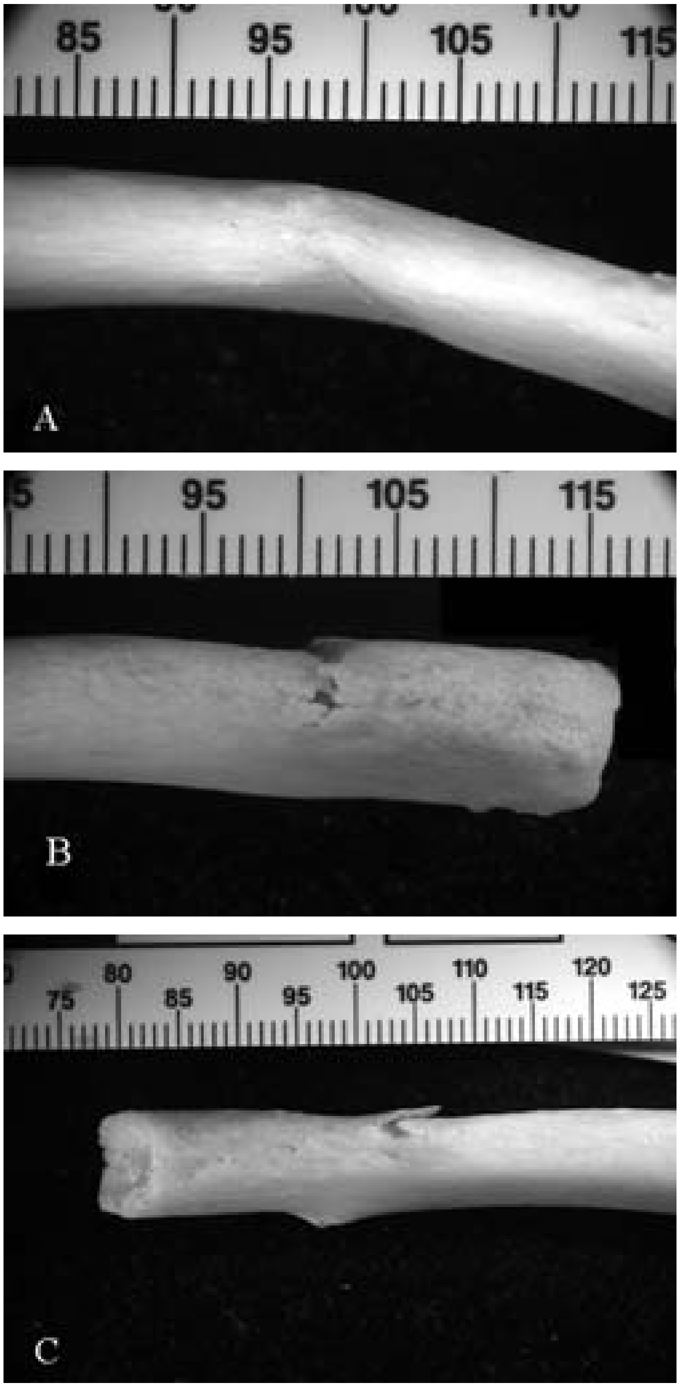

FIG. 3—*(a–c)—Three examples of buckle fractures observed in the sample. The scale is in millimeters.*

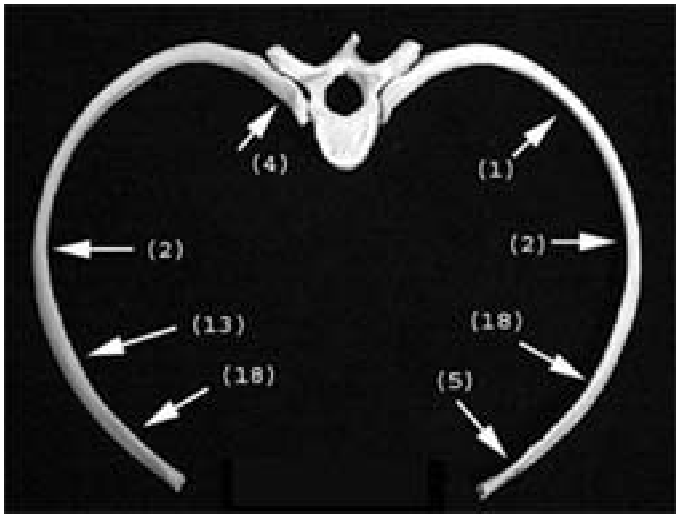

FIG. 4—*Right and left ribs and thoracic vertebra placed in anatomic position. The arrows are pointing to the approximate location of the buckle fractures; the numbers indicate the number of buckle fractures observed in the immediate area.*

it occurring on the "compressive (concave) side of a member under a bending load, such as a thin-wall type or a flange of a channel or I-beam section" (31, p. 16). Wulpi (31) further states that the load under which the component fails does not depend on the strength of the material but the dimensions of the part and the modulus of elasticity of the material, ". . . [B]uckling is a geometric problem, not a material problem" (31, p. 17).

Unfortunately, the term buckle fracture has been used previously as an alternative term for torus fracture, to describe an incomplete fracture in which, under compressive forces, the cortical bone is ballooned outward (6,35). Despite possible future confusion, we are introducing this engineering term into the anthropological literature without alteration because it most accurately describes the morphology of a fracture resulting from compressive instability.

In summary, our observations of the recurrence of incomplete and buckle rib fractures highlight the inadequate understanding of bone biomechanics and the importance of considering all factors when analyzing the mechanical behavior of bone at the gross level. Experimental research has been invaluable in defining the basic biomechanical principles of bone tissue, but applying experimental findings to gross observations is problematic. The true value of this study is not the calculated frequencies of incomplete fractures in the sample or defining buckle fractures, but the realization that to understand the biomechanics of bone, the mechanical behavior must be studied experimentally at the gross level, as well as at the tissue level.

Conclusion

Incomplete and buckle rib fractures were observed recurrently in a sample of 43 blunt force trauma victims. Incomplete fractures showed no significant difference in frequency between age groups. Buckle fractures, failure due to compressive instability, also was observed among the subset samples without significant difference in frequency. The observation of both incomplete and buckle fractures reinforces the need to study bone biomechanics at the gross level.

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