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PAPER

ANTHROPOLOGY

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A Radiographic Assessment of Pediatric Fracture Healing and Time Since Injury*

ABSTRACT: Past studies and pediatric bone physiology indicate that younger individuals may heal at a faster rate. Additionally, in adults upper limb fractures heal faster than lower limb fractures; this trend is expected for pediatric fractures. This study aims to evaluate and compare rates of fracture repair in children based on age and skeletal element. Six stages are used to describe the bone repair process in 294 radiographs of tibial and radial fractures from 107 infants and young children. Healing rates are examined using ANOVA and Welch's *t*-test with a 95% confidence interval. Results indicate that younger individuals spend less time at stage 1, suggesting a delay in the start of healing. Furthermore, forearm fractures heal faster than leg fractures at stages 2 and 3, suggesting a role in the osseous reaction of bone healing. The healing schedule presented may allow the timing of injuries to be estimated from radiographs.

KEYWORDS: forensic science, forensic anthropology, radiographs, children, fracture, healing

One of the important considerations in the assessment of skeletal trauma in forensic cases is understanding the timing of skeletal injuries with respect to death. The ability to make an educated statement about how long an individual lived after the occurrence of a skeletal fracture may be a key contribution of a forensic anthropologist or medical examiner, particularly in pediatric cases, when antemortem trauma may signal physical abuse. While rates have been published for a normal bone healing process in adults, very little is known about healing rates in pediatric cases. Because children are still in the formative stage of bone growth, bone is expected to heal more quickly, perhaps in half the time of adults (1–3).

While the radiographic assessment of fracture healing is relatively absent in the forensic literature, one pertinent study was conducted by Hufnagl (4) in 2005. Examining 62 sets of radiographs from individuals ages 2–93, Hufnagl (4) gathered information on the sex of the individual, the ancestry of the individual, the type of fracture, and the date of the fracture. From this sample, Hufnagl (4) presented six stages of fracture healing that are demonstrated radiographically: fracture, granulation, mature callus, partial bridging, almost complete bridging, and complete bridging. The time that elapsed during each stage of healing was also determined for each of the sets of radiographs. These data allowed Hufnagl (4) to examine the role of age, sex, ancestry, and weight placed on the bone in the healing rates. Of these factors, it was found that only age was significantly correlated with the stages of fracture repair.

While there are many similarities in the clinical and radiographic healing process between children and adults, children have their own unique skeletal and physiological characteristics. Subadult bone is undergoing growth and as such may heal at a faster rate (2,3). The ossification and union patterns of the subadult skeleton create differences in the likelihood of fracture and in the healing time of certain regions of bone. Additionally, the increased vascularity and periosteal characteristics will cause subadult bone to heal at a faster rate (5). As an individual ages, the periosteum thins, decreasing in osteogenic activity and lengthening the healing time required after skeletal injury (6). Owing to the differences in bone structure and bone composition, subadult bone is less brittle, more porous, contains larger haversian canals, contains more water, and has a lower mineral content lending to an increased elasticity and plasticity in children's bone (7). Such qualities give rise to an increased tendency for tensile failure to be deficient, leading to incomplete fractures, such as plastic deformation and greenstick fractures (5,7). The porosity of bone and rough surface that results from pediatric bone structure contribute to the need for increased energy and time before bone will fail, aiding in the prevention of complete fracture (8).

In addition to age, fracture location has also been cited as a factor in fracture healing. This study focuses on the forearm, specifically the radius, and the leg, specifically the tibia. Forearm fractures are the most common location of skeletal trauma in childhood (6,7,9,10). The high frequency of skeletal trauma to the forearm and the extent of orthopedic participation in these injuries, especially in childhood, make the forearm an ideal location to examine in the present study. While precise healing times vary, the radiological union of fracture fragments in the forearms of adults may be indicated around 8 weeks, whereas in children, forearm fractures heal at a more rapid rate (11,12). Nonphyseal fractures of the leg are among the most common in the lower extremities of children (6,13). Spiral fractures in particular have often been cited as evidence of child abuse (14). Owing to the prevalence of tibial fractures in childhood and their potential association with child abuse, the tibia was selected as another location to examine in the

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present study. Tibial fractures are notorious for their long healing times. In adults, tibial shaft fractures heal in *c.* 16 weeks, but in children the healing occurs at a faster rate (15).

The aims of the present study are to extrapolate data on fracture healing from radiographs, evaluate rates of fracture repair in young children and compare how these rates vary with the age of the individual and the skeletal element involved. Very few radiographic studies have focused on pediatric fractures; thus, through the present research, an outline for what can be expected in the fracture-healing process based on pediatric radiographs has been developed.

Methods and Materials

For this research, a collection of radiographs was obtained from a pediatric orthopedic specialist in Lansing, Michigan. Radiographs of fractured bones (radius and tibia) from infants and young children of ages 0–1, 2–3, and 4–5 were included, with ages recorded from the time of initial injury. The individuals in the sample represented male and female children of known age and time of injury from a mid-Michigan population. Information concerning any occurrence of child abuse within the sample was not available for research.

The radiographs examined consisted of images from each individual. If only one radiograph was available, the individual was not excluded, as there may have been healing evident with an associated time frame. Additionally, it was desired to include individuals with only one radiograph as a majority of these radiographs were taken after healing had already begun. The number of radiographs for each individual ranged from one to 11, with an average of three radiographs per patient. Table 1 provides an extensive overview of the sample indicating how many radiographs were used for each individual and when each was taken. Any individuals demonstrating comorbidity or any systemic disorder, which may affect the bone healing rate, were excluded from the study. The total sample examined consisted of 107 individuals and 294 radiographs. Table 2 summarizes the categorization of the sample based on age and skeletal element.

The radiographs were digitized by photographing the radiographic images on a light board. A tripod was set up and a Canon Rebel X digital SLR camera with a 50-mm macro lens (Canon U.S.A., Inc., Lake Success, NY) was directed perpendicular to the radiographs. Images were saved and labeled according to individual and radiograph date. The sample was then catalogued in an Excel 2003 worksheet. Data for each individual included the following: reference number, date of birth, date of fracture, date of subsequent radiographs, fracture location, fracture diagnosis, age at time of fracture, days of healing (calculated as the number of days between fracture occurrence and subsequent radiograph), and other comments.

Once digitized and catalogued, the radiographs were examined for evidence of fracture healing. The fracture healing was categorized into six stages, modified from Hufnagl (4). The characteristics of each of the stages were as follows:

Stage 1—No healing: sharp fracture lines, absence of bridging and callus formation.

Stage 2—Granulation: beginning of resorption along fracture line, "fluffy" callus formation, blurring of fracture line, absence of a complete mature callus.

Stage 3—Callus: mature callus formation around fracture site; callus bulging over site and demonstrating a radiopaque appearance, fracture line visible but may be blurred.

Stage 4—Bridging: fracture gap is connected across the fracture site in some, but not all areas (<50%), blurring of the fracture line, callus may still be present.

TABLE 1—*Categorization of sample with number of radiographs and when taken.*

Individual	Fracture Location	Age at Time of Fracture (years)	Number of Radiographs	Days Healing
1	Forearm	0–1	3	2, 16, 29
2	Forearm	0–1	2	8, 42
3	Forearm	2–3	4	0, 8, 28, 31
4	Forearm	4–5	7	0, 8, 14, 21, 28, 45, 112
5	Forearm	4–5	4	0, 4, 18, 45
6	Forearm	0–1	5	4, 11, 18, 25, 49
7	Forearm	0–1	3	0, 1, 35
8	Forearm	4–5	4	4, 13, 33, 46
9	Forearm	4–5	6	0, 3, 17, 30, 46, 750
10	Forearm	2–3	3	0, 6, 39
11	Forearm	2–3	6	2, 8, 16, 22, 30, 51
12	Forearm	2–3	2	6, 42
13	Forearm	4–5	3	6, 27, 43
14	Forearm	4–5	2	0, 27
15	Forearm	4–5	3	6, 22, 24
16	Forearm	4–5	3	5, 17, 35
17	Forearm	0–1	2	8, 42
18	Forearm	4–5	1	13
19	Forearm	4–5	5	5, 7, 14, 26, 51
20	Forearm	0–1	2	0, 27
21	Leg	2–3	3	3, 22, 43
22	Leg	0–1	4	0, 8, 22, 36
23	Leg	4–5	1	2
24	Leg	4–5	3	2, 32, 63
25	Leg	0–1	1	0
26	Leg	2–3	2	3, 16
27	Leg	0–1	2	37, 38
28	Leg	0–1	1	5
29	Leg	2–3	1	24
30	Forearm	0–1	1	20
31	Forearm	2–3	1	28
32	Leg	4–5	2	10, 45
33	Forearm	4–5	3	5, 19, 40
34	Forearm	2–3	4	6, 13, 20, 41
35	Forearm	4–5	1	24
36	Forearm	4–5	2	16, 30
37	Forearm	4–5	2	0, 33
38	Forearm	4–5	6	12, 20, 27, 49, 200, 418
39	Forearm	4–5	1	18
40	Forearm	4–5	1	31
41	Forearm	4–5	11	0, 1, 3, 12, 17, 24, 28, 48, 60, 67, 82
42	Forearm	4–5	2	0, 24
43	Forearm	4–5	4	5, 14, 23, 44
44	Forearm	4–5	4	4, 11, 25, 45
45	Forearm	4–5	3	8, 15, 50
46	Forearm	2–3	4	5, 25, 46, 111
47	Leg	4–5	3	4, 25, 46
48	Leg	0–1	2	18, 32
49	Forearm	4–5	3	4, 16, 45
50	Leg	2–3	2	1, 42
51	Forearm	4–5	3	4, 18, 38
52	Forearm	4–5	3	5, 17, 47
53	Forearm	4–5	4	0, 2, 16, 50
54	Forearm	4–5	4	1, 12, 22, 44
55	Leg	2–3	4	1, 6, 23, 44
56	Forearm	4–5	3	5, 22, 43
57	Forearm	4–5	3	5, 19, 40
58	Forearm	2–3	1	24
59	Leg	0–1	2	9, 32
60	Forearm	2–3	1	17
61	Forearm	4–5	4	0, 1, 6, 35
62	Leg	4–5	2	6, 20
63	Leg	2–3	4	0, 28, 54, 64
64	Leg	0–1	2	13, 34
65	Forearm	2–3	2	4, 33
66	Leg	2–3	3	1, 18, 28

Continued.

TABLE 1—*Continued.*

Individual	Fracture Location	Age at Time of Fracture (years)	Number of Radiographs	Days Healing
67	Leg	0–1	3	1, 11, 26
68	Leg	0–1	1	1
69	Forearm	0–1	3	0, 7, 35
70	Leg	4–5	3	8, 22, 39
71	Forearm	2–3	1	8
72	Leg	4–5	2	3, 4
73	Forearm	2–3	3	6, 20, 41
74	Forearm	0–1	2	0, 21
75	Leg	2–3	1	45
76	Forearm	2–3	4	0, 8, 15, 33
77	Forearm	0–1	2	1, 4
78	Leg	2–3	2	14, 37
79	Forearm	0–1	6	0, 8, 47, 61, 75, 177
80	Leg	0–1	2	2, 32
81	Leg	4–5	2	33, 47
82	Forearm	0–1	2	3, 30
83	Forearm	2–3	2	0, 27
84	Leg	0–1	1	1
85	Leg	0–1	3	1, 5, 53
86	Forearm	0–1	2	0, 24
87	Leg	2–3	2	1, 26
88	Leg	2–3	1	36
89	Leg	2–3	2	32, 156
90	Leg	2–3	4	0, 15, 42, 69
91	Leg	2–3	1	32
92	Leg	4–5	2	7, 40
93	Leg	4–5	2	7, 49
94	Leg	4–5	2	29, 418
95	Leg	2–3	1	35
96	Leg	0–1	4	0, 5, 19, 35
97	Leg	0–1	2	0, 37
98	Leg	4–5	4	6, 11, 28, 49
99	Forearm	2–3	4	0, 3, 24, 46
100	Leg	4–5	4	0, 6, 22, 47
101	Leg	0–1	2	0, 33
102	Leg	4–5	2	6, 50
103	Forearm	0–1	1	13
104	Forearm	0–1	4	0, 8, 35, 93
105	Leg	4–5	3	1, 24, 46
106	Leg	2–3	4	0, 28, 48, 188
107	Leg	0–1	1	28

TABLE 2—*Summary of individuals (and radiographs) in the sample by age and fracture location.*

	Age 0–1 Years	Age 2–3 Years	Age 4–5 Years	Total
Forearm	15 (40)	15 (42)	30 (105)	60 (187)
Leg	16 (33)	16 (37)	15 (37)	47 (107)
TOTAL	31 (73)	31 (79)	45 (142)	107 (294)

Stage 5—Clinical Union: fracture line is significantly blurred; fracture line is connected in most areas (more than 50%), callus presence minimal.

Stage 6—Completion: No evidence of fracture line, callus presence minimal or not observable.

Each radiograph was assigned a stage, and this information was added to the Excel worksheet.

A database including the days of healing, the stage scored for each radiograph, the patient age, and the fracture location was created for statistical analysis. One-way analysis of variance (ANOVA), a parametric test for the assessment of differences in mean in independent samples, was performed to determine whether there was a significant difference, with a 95% confidence interval, in the healing time among each of the first five stages. In addition to ANOVA, the Bonferroni correction, a *post hoc* test of multiple comparisons, was added to determine where inequalities were present in the samples. ANOVA with Bonferroni correction was also used to determine whether there was a significant difference in the time of healing among the three age groups at each of the stages and at what point in the healing process, earlier versus later, they occurred. Welch's *t*-test, a parametric test used to determine whether the mean differs for two independent samples, was performed for the two fracture locations to establish whether there was a significant difference, with a 95% confidence interval, in the time of healing between fractures of the forearm and leg at each of the stages.

FIG. 1—*Stage 1—No healing. Individual no. 16, forearm fracture, 5 days of healing.*

Results

A main objective of this research was to develop a set of images that demonstrate the radiographic features evident in pediatric fracture healing. Figures 1–12 depict each of the radiographic stages of healing for forearm and leg fractures. Stage 1 (Figs 1 and 2) shows no presence of bone healing and all fracture margins are sharp. At stage 2 (Figs 3 and 4), bone formation has begun and initial callus formation is present. Stage 3 (Figs 5 and 6) is identified by the presence of a mature callus bulging over the fracture site. The original fracture line is still observable. By stage 4 (Figs 7 and 8), this fracture line has blurred, but some callus is still present. Notice at stage 5 (Figs 9 and 10) callus is markedly reduced and only a faint trace of the fracture line is present. At stage 6 (Figs 11 and 12), the fracture is no longer observable. Figures 13–15 show an example of healing in one individual over time.

While such radiographic images depict an atlas of radiographic healing, a statistical aim of this research was to determine the usefulness of categorizing radiographs by the stages of healing

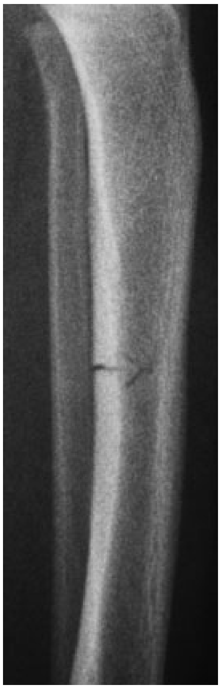

FIG. 2—*Stage 1—No Healing. Individual no. 87, leg fracture, 1 day of healing.*

FIG. 4—*Stage 2—Granulation. Individual no. 70, leg fracture, 39 days of healing.*

FIG. 3—*Stage 2—Granulation. Individual no. 13, forearm fracture, 27 days of healing.*

FIG. 5—*Stage 3—Callus. Individual no. 45, forearm fracture, 50 days of healing.*

presented. Mean healing times were expected to increase across the stages. This expectation was confirmed; all differences demonstrate increased healing time with later stages, with 3.3 days at stage 1 to 313.3 mean days healing at stage 6, as shown in Table 3. While mean healing times and ranges are given for stage 6, no further statistical analysis could be performed because of limited sample size and inclusion criteria.

The ANOVA analysis of the stages indicates that the differences in the healing time among the stages are significant. At the same time, the results of ANOVA with Bonferroni correction indicate some limitations in the statistical differences in mean healing time. While most stages demonstrate significant differences from one another, stages 3 and 4 are not statistically different.

FIG. 6—*Stage 3—Callus. Individual no. 90, leg fracture, 42 days of healing.*

FIG. 7—*Stage 4—Bridging. Individual no. 33, forearm fracture, 40 days of healing.*

A goal of this research was to determine the influence of the patient's age on the rate of the healing process. Results of ANOVA with Bonferroni correction indicate that at stage 1 the healing time of individuals 0–1 years old is significant from the healing time of individuals 4–5 years old, with the younger individuals having a shorter healing time. At stages 2, 3, 4, and 5, no statistically significant results are obtained. These results indicate age influenced the healing time at stage 1.

FIG. 8—*Stage 4—Bridging. Individual no. 24, leg fracture, 63 days of healing.*

FIG. 9—*Stage 5—Clinical Union. Individual no. 6, forearm fracture, 49 days of healing.*

A final statistical goal of the research was to determine the influence of the fracture location on the rate of the healing process. Welch's *t*-test indicates that at stages 1, 4, and 5 the mean healing times are not statistically significant between the fracture locations. At stages 2 and 3, the mean healing time of forearm fractures is shorter than the mean healing time for leg fractures. These results indicate fracture location influenced the mean healing time at stages 2 and 3.

FIG. 10—*Stage 5—Clinical Union. Individual no. 46, forearm fracture, 111 days of healing.*

FIG. 12—*Stage 6—Completion. Individual no. 106, leg fracture, 188 days of healing.*

FIG. 11—*Stage 6—Completion. Individual no. 38, forearm fracture, 418 days of healing.*

FIG. 13—*Individual no. 10, 0 days of healing, stage 1.*

Discussion

This study presents a timeline of six stages of bone fracture healing in children. Images of each of these stages present radiographic examples of the appearance of fracture lines, fracture bridging, and fracture callus formation throughout the healing process. Future radiographs may be compared to these images and the stage descriptions to obtain an estimate of healing time in young children and infants from birth to 5 years old.

Each of the six stages demonstrated an increased healing time when compared to the previous stages. When individually comparing stages, mean healing times were significantly different for most stages. The reasons some individual stages lacked significance could include natural variation in the fracture healing once repair

FIG. 14—*Individual no. 10, 17 days of healing, stage 2.*

FIG. 15—*Individual no. 10, 46 days of healing, stage 3.*

TABLE 3—*Stages and healing times.*

Stage	Mean Healing Time (days)	Range in Healing Time (days)	SD
Stage 1	3.3	0–14	3.4
Stage 2	21	4–50	10.5
Stage 3	38.4	15–75	13.4
Stage 4	43.9	24–93	15.2
Stage 5	65.2	24–156	48.2
Stage 6	313.3	42–750	235.7

has begun, thus indicating the importance of the initial fracture response. Alternately, the limited sample size, especially in later stages, may have prevented differences from being accurately depicted. A third reason for the lack of significance is that healing in the latter aspect of one stage would be difficult to differentiate from healing in the earlier part of the subsequent stages. Finally, the lack of significance may be because of other contributing factors influencing the healing process, such as abuse or other conditions resulting in poor health. Nonetheless, radiographic features present in the six stages should be considered when analyzing radiographic images, but an examiner should be cautious when employing a healing time estimate.

The individual's age did influence the fracture-healing process at one stage, and significant differences demonstrated increased mean healing time with increased age. The difference indicated between the age groups suggests that there may be a certain point in the development process where fracture healing may slow. To further examine this result, age groups should be expanded and older children and adolescents included. While age differences were shown at the beginning of the healing process, the middle stages are where the majority of healing is occurring. Age may not play an active role at this point in the healing process, or some factors, unrelated to age, may be delaying or speeding up the osseous reaction that occurs in these stages. Additionally, as stage 1 was the only instance where age influenced healing time, the results indicate not an influence on mean healing time, as healing is not demonstrated in stage 1, but rather a delay in the start of the healing process is suggested.

To completely understand the influence of age in the fracture-healing process, it is also necessary to examine the rates evident in adult fracture healing. Using comparable stages, Hufnagl (4) obtained mean healing times as follows—stage 1: 0.22 days; stage 2: 22.37 days; stage 3: 79.42 days; stage 4: 116.96 days; stage 5: 124.20 days; and stage 6: 260.86. Hufnagl's (4) sample of 62 individuals included three equal age groups (2–10, 11–45, and 45 and older) with results indicating statistically significant differences among the age groups. The mean healing times given would have been skewed toward individuals over the age of 5. Comparing such healing times to the present study demonstrates some differences. Stages 1 and 2 demonstrated healing times within a couple of days of each other. Stages 3, 4, and 5 were shortened by approximately one-half in the present study of young children, whereas stage 6 demonstrated a longer mean healing time. Stages 3, 4, and 5 may be demonstrating the stages in fracture repair where age is most influential when comparing adults to children. When looking more precisely at children in the present study, differences were found earlier in the healing process. Additionally, while stage 6 would demonstrate a deviation from expectation, in both studies stage 6 was the most limited in number of individuals and warrants further examination.

Fracture location also influenced the healing time in the sample examined. When location did affect the healing time, forearm fractures healed faster then leg fractures. While it was expected, such a finding would be consistent across the stages, only stages 2 and 3 were affected. This result may be a reflection of stages 2 and 3 being the first stages where osseous reaction is occurring. Fracture location may be a particularly important factor for the initiation of fracture healing, with diminished impact after healing has begun. Additionally, the other stages may be more likely to encounter other contributing factors. For instance, mobility may affect healing time. During the beginning stages of fracture repair, mobility may be limited because of discomfort or stabilization.

Several aspects of the present study warrant further examination. First, the limited sample size of radiographs in later stages of healing was problematic. Radiographs are most commonly used at the beginning of the fracture-healing process. The need for radiographs is determined on a clinical basis that may not be conducive to research interests; thus, the original intent of the radiographs should be acknowledged as a limitation of the study. Second, stage 6 was problematic. There is no limit to the end of stage 6, so these data would be more likely to indicate significant differences if radiographs were taken after an individual had previously reached stage 6. Because of this limitation, stage 6 was not suitable for statistical analysis. Third, radiograph quality and the presence of external stabilization (casts), especially around the beginning of the healing process limited the ability to accurately categorize some of the images into stages. The presence of external stabilization in radiographs should be acknowledged as a limitation of this research. Finally, the possibility of other contributing direct or indirect factors may have influenced the rate of the fracture-healing process. While not a goal of this research, the type of fracture should be considered when assessing healing time in future research.

Conclusion

The goal of the present study is twofold. First, the research aims to identify a set of radiographic stages of healing for infants and young children. The stages are useful in categorizing the sample and demonstrated the utility of assessing radiographic features in the fracture-healing process. The limited significance of certain stages from one another later in the healing process suggests caution should be used when estimating healing times. Second, the present study identifies patient age and fracture location as factors influencing the healing rate of fractures in children. The differences identified in the mean healing time among the age groups suggest that fracture healing may be delayed in older individuals. The middle of the fracture-healing process, a time when a large amount of osseous repair is occurring, may not be influenced by age in young children, but most likely will be affected by age when comparing adults with children. The variations in mean healing time between forearm and leg fractures indicate that forearm fractures heal at an accelerated rate. This finding, identified at stages 2 and 3 of the healing process, may indicate an increased role of fracture location in the initiation and osseous reaction of callus formation in fracture healing. Contributing factors, such as fracture site mobility, may influence the effects of fracture location on the rate of the healing process. This paper supports the use of radiographic stages of fracture healing in young children and infants. While more research is needed to confirm and reassess the implications of age and fracture location, anthropologists and others dealing with dried bones might benefit from radiographing remains and comparing the images obtained to the examples presented in this text. This research also suggests the need for incorporation of clinical literature from pediatric biology and radiology into the field of forensic anthropology.

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