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A Case of Acute Plastic Deformation of the Forearm in a Medieval Hispano-Mudejar Skeleton (13–14th Centuries AD)

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Established Facts

- Acute plastic deformation is a rare traumatic injury, not described until the last century and only rarely described in palaeopathological contexts.

Novel Insights

- We contribute a new case, the first being sufficiently documented, to the few cases collected in paleopathology registries, contributing to the knowledge and diagnosis of this type of trauma in ancient skeletons, while deepening the knowledge of the living conditions of the medieval Mudejar population of Uceda.

Keywords
Plastic deformity · Traumatic bowing · Paleopathology · Bioarcheology · Islamic necropolis · Uceda

Abstract
Introduction: Acute plastic deformation refers to a traumatic bending or bowing without a detectable cortical defect. ***Case Presentation and Discussion:*** We describe a rare case from an individual that was exhumed from the Hispano-Mudejar necropolis in Uceda (Guadalajara, Spain) dated between the 13th and 14th centuries AD. The case corresponds to an adult woman, with a bowing involvement of the left ulna and radius. After making the differential diagnosis with various pathologies likely to present with this alteration, we reached the diagnosis of acute plastic deformation of the

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forearm through external and radiological examination and comparison with the healthy contralateral forearm. ***Conclusions:*** Acute plastic deformation is a rare traumatic injury, not described until the last century and only rarely described in palaeopathological contexts. We contribute a new case, the first being sufficiently documented, contributing to the knowledge and diagnosis of this type of trauma in the ancient bone, while deepening the knowledge of the living conditions of the medieval Mudejar population of Uceda.

Introduction

Acute plastic deformation (APD) refers to bending or bowing of traumatic origin in which no signs of fracture can be seen in external examination [1]. It is a rare lesion, although its true incidence remains unknown [2, 3]. In the scientific literature, it is also referred to as traumatic bowing deformities, plastic bowing deformities, plastic bowing fractures, acute bowing fractures, or acute plastic bowing deformities [4].

APD occurs in childhood, which mainly affects the bones of the forearm after falling to the ground with the hand outstretched, transmitting the force of the impact longitudinally. Bones, without fracturing, may thus be deformed with sufficient intensity to prevent them from recovering their original shape [5].

APD is a recently described traumatic injury. The first cases of APD of the forearm in children were presented by Borden [6]. This fact, together with the reports that these alterations are frequently not very obvious [1, 7, 8] and the low incidence of this pathology, make it likely to be underdiagnosed [9].

Radiological examination is essential for diagnosis, logically indispensable when the study is performed in a living individual and involves comparison with the contralateral bone to be able to assess slight or uncertain deviations [8, 10–12].

The analyzed medieval skeleton maintains a moderate state of preservation of both upper extremities, which has allowed its external and radiological study and the diagnosis of APD in both bones of the left forearm to be reached. It constitutes one of the few registered cases of this pathology in ancient bone, while contributing to the knowledge of health and disease in this medieval Hispano-Mudejar population.

Materials and Methods

The analyzed skeleton comes from stratigraphic unit 112 of the Hispano-Mudejar necropolis of Uceda, Guadalajara (Spain). In this necropolis, dated between the 13th and 14th centuries AD, 116 individuals have been excavated, all from individual burials. Very few historical and demographic data are available on the Hispano-Mudejar population of Uceda. This population constituted a minority that maintained a strong endogamy, carrying out various artisanal textile, carpentry, and masonry work [13].

The skeleton was not completely recovered because the grave was cut by adjacent burials, leading to the absence of the cranium, shoulder girdle, and both feet. The level of preservation was established according to the scale proposed by Connell and Rauxloh [14], corresponding to grade 2, which limits the amount of information available. Age was estimated based on changes in the auricular surface of the ilium [15], sex according to the morphological characteristics of the pelvis [16] and femur and radius measurements [17], and stature from femur length [18]. Radiological images obtained with digital Polyrad SE equipment were used for the bone examination.

To measure the degree of radius bowing and its precise location, we used the criteria set out by Firl and Wünsch [19]. In the anteroposterior radiological projection (Fig. 1a), y corresponds to the distance from the bicipital tuberosity to the distal radial epiphysis and r to the length of a line perpendicular to the anterior one, located at the level of greatest bowing of the bone. To measure the degree of ulna bowing, on the radiological image of the lateral projection (Fig. 1b), following Lincoln and Mubarak [20], a straight line, m, has been drawn along the dorsal border of the ulna from the level of the olecranon to the distal ulnar metaphysis.

Case Presentation

The analyzed skeleton belonged to a female individual, aged between 25 and 29 years old and with a height of around 153 cm (standard deviation of 6.26 cm). Skeletal lesions are only located on the left forearm (Fig. 2a, b). The radius shows a break of taphonomic character in the middle and distal third and a marked bowing of external and posterior concavity.

In relation to the depth of bowing, r, the difference between the two radii is evident. While r measures 16.81 mm in the left radius, it measures only 10.22 mm in the right. When these values are considered in relation to the length of the radius, y, they represent 9.46% of the length in the left radius and 5.80% in the right.

Regarding the location of the greatest degree of bowing of the bone, it is similar in both radii. With the value of y being 177.64 mm in the left radius and 176.18 mm in the right, the greatest bowing occurs at 46.59% of this value in the left radius and 49.59% in the right.

The left ulna presents a poorer general degree of preservation, also presenting a postmortem break between the middle and distal thirds. Analogous to the left radius, it shows a marked deformity of external and posterior convexity. The practical absence of bowing of the right ulna can be seen, in contrast to the depth m of 4.95 mm in the left ulna. In the right forearm, only postmortem alterations are observed, without pathological bowing, with loss of the head and styloid process in the radius and the distal epiphysis and part of the olecranon in the ulna. The left humerus is missing the

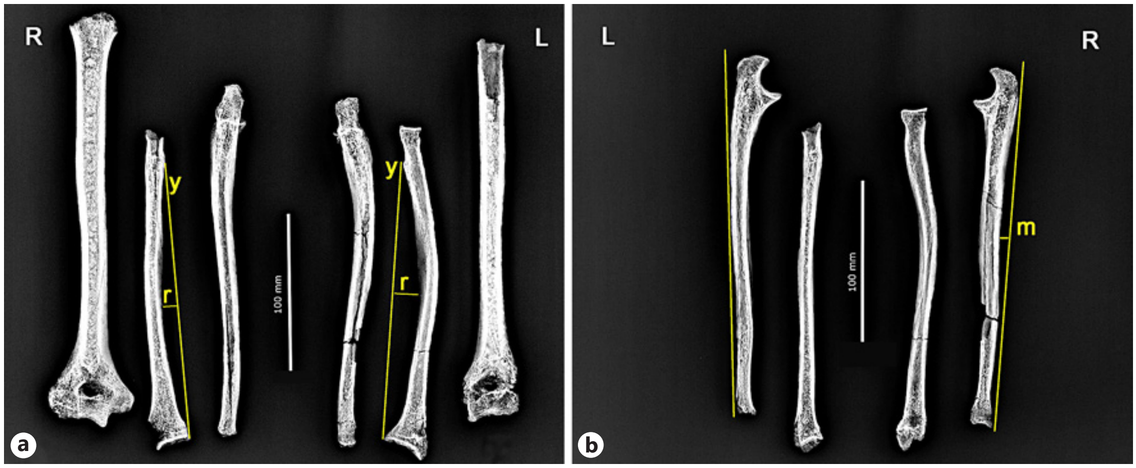

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Fig. 1. Radiograph of the upper limb long bones. **a** A-P projection. *y*, distance from de bicipital tuberosity to the distal radial epiphysis; *r*, line at maximum bow. **b** Lateral projection. *m*, bowing of the ulna.

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Fig. 2. Long bones of the upper limbs. **a** Anterior view. **b** Posterior view.

proximal epiphysis and the distal epiphysis is only partially preserved, while the right humerus is missing the head and part of the capitulum and lateral epicondyle.

Discussion

In the examined skeleton, the left ulna and radius appear curved in a characteristic image of APD, which is a typical lesion of children when falling on the outstretched hand [7, 21]. The external morphology of both bones, their radiological images, the exclusive involvement of one forearm without other similar alterations in the rest of the long bones, as well as their origin in childhood, as discussed below, support this diagnosis.

There are numerous diseases that can occur with bowing of the long bones of the extremities, but with very different characteristics to those observed here. We are going to establish the differential diagnoses with the most relevant. Fibrous dysplasia, in its monostotic form, rarely affects the bones of the forearm; the incurvation is characteristic of load-bearing bones, and the radiological image is a well-defined radiolucent lesion. In rickets and osteomalacia, the involvement is bilateral and multiple, with manifest incurvations in load-bearing bones, metaphyseal involvement in rickets, and typical pseudofractures in osteomalacia. Paget's disease occurs at ages above the estimate for this skeleton and its morphology is very characteristic, with the bowing being characteristic of load-bearing bones secondary to pathological fractures. Osteogenesis imperfecta is bilateral and generalized in the skeleton, with osteopenia, cortical thinning, bone fragility, and, in some forms, shortening of the extremities and bowing due to multiple fractures, essentially in the lower extremities and pelvis. Poland's syndrome usually presents alterations in the upper limbs such as shortening of the middle phalanges and hypoplasia of the upper limb. In greenstick fractures, the affected bone surface is on the convex aspect. In postmortem deformation, the dry bone, hard and at the same time fragile, has lost its elasticity, not allowing this type of fracture [22–25].

In relation to the pathophysiological mechanism of this lesion, Chamay's studies on dog ulnae are fundamental [5, 26]. He verified how the bone deformed, up to a degree of longitudinal compression, recovering its shape when the force was withdrawn, which corresponded to the elastic phase. With increased pressure, the next phase of plastic deformation was reached, in which the bone, after the removal of the force, remained incurved, in a plastic bowing deformity. A higher force had already caused the bone fracture, making this the precursor phase of the greenstick fracture [2, 27]. The time for which the force exerting pressure is maintained plays an important role in this mechanism, because the load-deformation proportionality is no longer constant when the limit values between the elastic and plastic deformation phases are reached [28].

During the plastic deformation phase, microfractures occur in the concave zone of the bone, where the compression is the greatest. They are oriented between 28° and 35° with respect to the longitudinal axis of the bone and frequently cross the cortex completely [7, 29–31]. These microfractures are ultimately responsible for the bone not being able to recover its previous shape [32].

APD is a lesion typical of childhood because it is precisely in an immature bone that the plastic deformation phase is greater. In addition, the greater elasticity of the epiphyseal plates, the natural curvature of long bones, a more active periosteum, greater flexibility, and less bone mineralization, as well as the greater size of the Haversian canals, contributes to these ages [2, 9, 29, 33].

This phase of plastic deformation is longer in the ulna and radius than in the femur [30], which favors the greater frequency of these injuries in the forearm, in addition to the higher incidence of trauma at this level [6, 34]. Globally, in addition to the radius and the ulna, the bones that are most frequently involved in APD in childhood are the clavicle and fibula [29].

Crowe and Swischuk [35] have classified these forearm lesions as the fracture of one bone and bowing of the other; the dislocation of one bone and bowing of the other; and the bowing of one or both bones without fracture or dislocation. In the analyzed skeleton, the bowing affects both bones, although it cannot be ruled out that a dislocation of the head of the radius or the distal radioulnar joint coexists.

In childhood, the most common mechanism by which this forearm injury occurs is a fall to the ground onto an outstretched hand [30, 36, 37]. If the forearm is in pronation, the force is transmitted along the radius, while if it is in supination, the greatest force will fall on the ulna [6]. Currently, these falls are described in the most diverse circumstances, such as riding a bicycle [9, 30, 33, 38], swinging [2], practicing gymnastics [39], running and jumping [40], or falling from a tree or ladder [32, 39]. Logically, in ancient cases, such as the medieval skeleton analyzed here, they cannot be considered part of these options, nor can their precise origin be known. In a different way, injury of the lower limbs is caused by direct trauma exerting transverse rather than longitudinal forces [4].

In the medieval skeleton from Uceda, which was of adult age, the lesion occurred during childhood, as evidenced by the radiological findings discussed below. After the plastic deformation of the bone, the mechanisms responsible for its spontaneous correction are initiated, by virtue of Wolff's Law, where the bone is deposited in places of intermittent loading, and Hueter-Volkmann Law, by which the physis grows asymmetrically to counteract any angulation of the bone [33, 41]. This remodeling begins months after the trauma to the concavity of the bone [6, 28, 32, 40], becoming complete in children under 4 years of age, partial up to 10 years of age, and minimal in adolescents [2, 10, 40].

In the analyzed skeleton, periosteal and cortical thickening is evident in the ulna and radius, mainly in the concavity of the latter, showing signs of remodeling and consolidation after the fracture (Fig. 3). However, a significant degree of deformity remained in the bone, which places the probable origin of the trauma in childhood, at an age between 4 and 10 years.

In the adult, the bone is more mineralized, less elastic, and has a very limited plastic phase, so these lesions are very rare and respond to a different production mechanism [1, 3]. The cases described in the literature mostly correspond to those under 24 years of age and are related to arm entrapment in moving machinery, during work

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Fig. 3. Radiograph of both radii. A-P projection. Bone remodeling (arrow).

with rotating machines [3, 21, 36, 37, 42, 43]. Rarer still are those resulting from direct trauma in traffic accidents [30, 44], and only exceptionally are they collected by falling onto the hand [1, 45, 46].

The signs and symptoms of APD in the forearm typically include pain, diffuse swelling, gross deformity, tenderness, and the limitation of supination pronation movements [2, 3]. Permanent bowing can limit the movement of pronation supination, especially when it affects both forearm bones [32]. In the analyzed skeleton, the evident permanent bowing of both bones would remain throughout life; in addition to an aesthetic deformity, there is a possibly painful limitation to pronation and supination [39].

In general, a trauma in children has been rarely discussed in paleopathology. Among other causes, this is because their healing will make them undetectable in the adult skeleton and because of the greater bone fragility in the face of taphonomic processes such as temperature and humidity [4, 47]. The most frequent fractures in childhood are greenstick fractures, torus o buckle fractures, metaphyseal fractures, and plastic deformation [47, 48].

Cases of APD are only rarely presented in paleopathology studies, meaning that it is very important to have the contralateral side for adequate analysis [46]. The investigator's unfamiliarity with this type of lesion may have contributed to such low scores in paleopathological studies [35].

Rohnbogner [49], in her study of infant skeletons from Roman Britain (1st to 5th centuries), described bowing of the proximal third of the left ulnar shaft in a child aged between 10.6 and 14.5 years. However, the alteration occurs in the context of a Monteggia fracture, which occurs with a fracture of the ulna and dislocation of the radial head. The author proposes working with animals or heavy farming equipment, and the associated accidents, as a possible origin of the trauma.

In a skeleton that was dated later, belonging to an individual between 14 and 17 years old from the Glen Williams Ossuary (13th–16th centuries), Stuart-Macadam et al. [4] described a deformity in the distal third of an ulna, of internal convexity and with moderate periosteal reaction along the concave surface. The same authors reported a diaphyseal deformity in the ulna, with posteromedial convexity and without radiographic evidence of periosteal involvement or thickening of the cortical region in another skeleton from the Milton Ossuary (17th century). Walker [50] describes this lesion in the fibula of a child from the cemetery of the Catholic Mission of St Mary and St Michael, Whitechapel, London, where burials took place between 1843 and 1854.

In conclusion, the case of the medieval skeleton presented here, from the locality of Uceda, therefore contributes a new case of APD to the paleopathological record, contributing to the knowledge and diagnosis of this type of trauma in ancient bone, while deepening the knowledge of the living conditions of this medieval Mudejar population.

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Statement Ethics

This study does not require an ethical statement or informed consent since the material used is ancient bone remains. The study has the authorization of the archaeologist responsible for the excavation. The study was performed in accordance with the Code of Ethics outlined by the British Association for Biological Anthropology and Osteoarchaeology [51].

Conflict of Interest Statement

The authors declare no conflicts of interest, financial, or otherwise.

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Author Contributions

Enrique Dorado-Fernández, David Cáceres-Monllor, and Jorge Murillo-González contributed to the conception of the study. Enrique Dorado-Fernández, José Aso-Escario, Manuel F. Carrillo-Rodríguez, David Cáceres-Monllor, and Jorge Murillo-González contributed to the study design. Enrique Dorado-Fernández, José Aso-Escario, Alberto Aso-Vizán, Ildefonso Ramírez-González, Manuel F. Carrillo-Rodríguez, David Cáceres-Monllor, and Jorge Murillo-González contributed to the laboratory investigations. Enrique Dorado-Fernández, José Aso-Escario, Alberto Aso-Vizán, Manuel F. Carrillo-Rodríguez, David Cáceres-Monllor, and Jorge Murillo-González contributed to the data analysis and interpretation. Enrique Dorado-Fernández, José Aso-Escario, Alberto Aso-Vizán, Manuel F. Carrillo-Rodríguez, and Jorge Murillo-González contributed to the manuscript preparation. Enrique Dorado-Fernández, Ildefonso Ramírez-González, David Cáceres-Monllor, and Jorge Murillo-González contributed to the revision and editing of the manuscript.

Data Availability Statement

All data used to support the findings of this study are included within the article.

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