A method for determining the origin of the trauma sequence at the pectoral girdle from an analysis of bone remains

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Rev. Esp. Antrop. Fís. (2008) **28**: 87-94
Aceptado : 10 noviembre 2008

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Keywords: fracture, post-traumatic, mechanism of injury, structural modification

This study analyzes a skeleton without data on origin, female, 55-60 years old, which is part of the bone collection of the Department of Anatomy of the Universidad Nacional Autónoma de México (UNAM), ID. No. 004-UNAM, and which shows fractures on both clavicles, left ulna, fifth right metatarsal, left side ribs C6 and C7, and right side ribs C5, C6 and C9. The results allowed to understand that the fracture analysis is a useful tool in order to know aspects previous to the subjects death which are relevant to clinical, anthropological and forensic issues. Because the major changes were seen on the displaced fracture of the right clavicle, the biomechanical consequences on the pectoral girdle were studied. A graphical force system model on a cross section of the pectoral girdle allowed to suggest the functional implications and post-traumatic structural modifications. The X-ray plates and the way the clavicle bones healed revealed that probably there was no medical treatment to reduce and/or align the fracture.

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Introduction

Fracture analysis can contribute to the knowledge of the mechanisms involving its formation, healing and consequences. From a morphological study of fractures it is possible to understand the repair processes at the bone level, as well as the structural and functional changes that occur in the bone and muscle when the structure does not recover its original shape (Neri and Lancelloti, 2004). This happens more often with displaced fractures, where the broken ends have moved away from each other some distance (Merbs, 1989), the post-traumatic consequences of which can limit the movement, structure and function of the segment involved.

The study of fractures in general provides relevant information which can be applied in several areas. From the clinical point of view, it can be useful for evaluating the rehabilitation techniques used and/or the more convenient surgical technique for a particular kind of fracture. On the forensic side, the analysis can help determine interpersonal conflicts, after effects of falls, and so on, as well as become a different way to apply methods of victim identification. Similarly to the way an individual can be identified on the basis of dental treatments, certain kinds of fractures, as well as the evidence of their treatment, can be useful for the same ends when the family or friends have radiographs available. Finally, from the anthropological perspective, their analysis and description can be useful for the interpretation of social, cultural or environmental issues which could be related to traumatic injuries, as well as of the relationship that can exist between them and biological variables such as sex and age (Lovell 1997; Galloway, 1999).

It is known that one of the major goals of physical anthropologists is trying to reconstruct the life history of an individual from his or her bone remains, which are usually the only source of information available, by finding, from the trauma or illness, the peculiarities which are present in the bone injuries, and trying to establish a diagnosis that reconstructs the life history of the individual. Fractures do not happen randomly. They are the result of a specific series of events which can be used to interpret how the fracture occurred. Traumas or blunt blows can happen under quite diverse circumstances. They are caused by low speed impacts on some body area; the bone breaks because of the type of impact experienced, which can be direct or indirect, by compression, twisting or bending of bone items. This definition includes fractures produced by vehicular accidents and falls. Fractures are a common cause of death in cases of homicide and/or physical violence (Galloway, 1999).

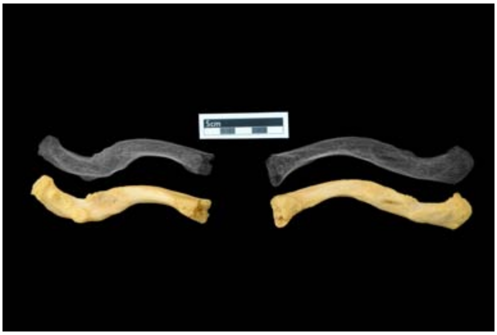

Figure 1. Inferior view photograph of both, the right and left clavicles with their corresponding X ray plates. The right side shows the fracture with shortening and displacement at the diaphysis and the changes on the ligamentous insertion points. Although, the left clavicle fracture had not structural changes.

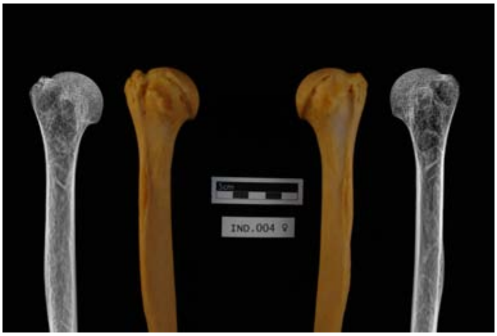

Figure 2. Anterior view photograph of both humerus with their corresponding X ray plates. These show the roughness on the greater tubercle of the right humerus caused by contact with the acromion on this area. See the difference with the other side.

Usually, clavicle fractures are due to an indirect force, and generally take place by two routes: (a) When falling on the extended wrist, the forces are transmitted by way of the arm towards the scapula and acromion and then to the clavicle; (b) when falling on the shoulder (Elstrom, 2000), in most cases the fracture mechanism is by longitudinal compression caused by forces transmitted through the acromion process of the scapula, towards the clavicle (Galloway, 1999). The double curvature of the clavicle contributes to an additional risk of fracture in the middle of the bone diaphysis, where fractures are more common, by bending or by the twisting movements on the axial load axis which take place (Mays et al., 1999). Clavicle fractures, medial to the insertion of coracoclavicular ligament, are more frequent in children and young adults. Following a clavicle fracture, the sternocleidomastoid muscle lifts the medial bone fragment. Since the trapezius muscle is incapable of lifting the lateral fragment, due to the weight of the upper limb, the lateral fragment is lowered. In addition to being sunk, the lateral fragment of the clavicle is medially tractioned by the muscles that adduct the arm, especially the *latissimus dorsi* and the *pectoralis major*. As a result of the displacement of the bone fragments, the clavicle is shortened when it heals (Drake et al., 2005) (García-Porrero y Hurlé, 2005; Moore, 2002).

Materials and methods

A morphological analysis of the skeleton without data on origin, female, 55-60 years old, which is part of the bone collection of the Department of Anatomy of UNAM was carried out, where the biological variables of sex, age (Lovejoy et al., 1985a; Lovejoy et al., 1985b; Iscan y Loth, 1989) and height (Genovés, 1967; del Angel y Cisneros, 2004) were defined, and the location, shape and type of fractures found were determined (Gustilo, 1992). The reconstruction of the events that generated the fractures were formulated from the observed fracture evidence in the right clavicle, which shows a remarkable displacement and shortening (Figure 1). The osteoarthrosis observed at the greater tubercle of the right humerus (Figure 2), the osteofphyte at the cervical

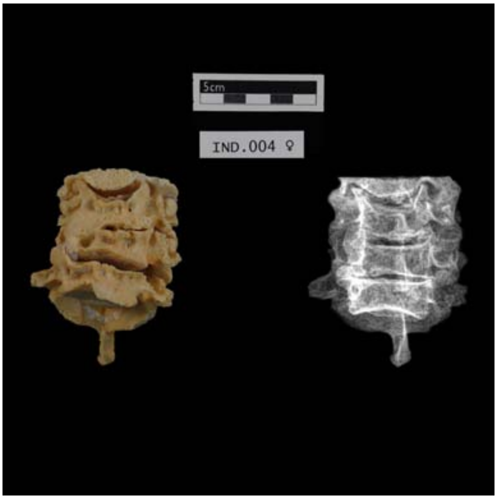

Figure 3. Anterior view photograph of the cervical vertebrae (C3, C4, C5 and C6) with their corresponding X ray plates. These show the pressure upon the vertebral bodies from the right side, due to the pressure exerted on the neck.

Figure 4. Anterior and lateral view photograph of the left ulna with their corresponding X ray plates showing two fractures. The first is one on the styloid apophysis and head of the ulna section, it is possible to see the compression on this area. The second one is an indirect type fracture. The first distal third shows formation of bone callus and the change on the axial axis caused by the fracture.

vertebrae C3, C4, C5 and C6 (Figure 3), and finally the osteoarthritis at the wrist bones (radio and ulna) (Figure 4), that as a whole could correspond to the post-traumatic consequences.

In order to analyze the structural changes of the displaced fracture of the right clavicle and the biomechanical modifications, a cross-sectional graphical model with the bones that make up the pectoral girdle (Sobbota, 2001) was used. The changes in the muscle insertions due to the shortening of the clavicle, the degree of displacement and torsion were analyzed, and the limitations to movement were suggested.

In order to support the hypothesis a model was used, of the kind known as "Free Body Diagrams" (FBD), a tool that is used in biomechanics, which allowed to carry out the analysis of the pectoral girdle. In biomechanics, the human body, a complex organism or structure, is often simplified. It is split into a system of rigid components connected by idealized joints; the effects of other parts and/or external loads are substituted by a set of defined forces and momentum of forces, known as FBD (Nordin and Frankel, 2001).

The FBD was analyzed by setting up a system of forces on a cross section at the level of the pectoral girdle; that is where the alterations to the musculoskeletal structure that determine the limits on movement were visible. The FBD includes a representation of all external forces and momentum that act on each rigid component. It comprises also a Cartesian coordinate system where the geometry of the force system is graphically displayed.

The system is simplified by selecting the major elements; in the current case, the main bones, specifically singlejointed ones, in order to be able to solve the system analytically. The system can be made more complex by adding new elements, for example, ligaments; this can make it indeterminate, and several compatible solutions (different efforts of the muscles) can coexist (Nordin and Frankel, 2001).

Initial position of the body: instant preceding production of the fracture	Impacts received when falling	Final position of the body after the fracture
Falling with extended left elbow and fractures on the left side of the body.		
Left arm with shoulder joint at flexion (angle between 70 and 80 degrees), elbow joint at extension, and wrist joint at hyperextension.	Direct impact on styloid apophysis; force applied along the axial axis of left ulna.	1.- Initial direct compression fracture at styloid apophysis. 2.- Indirect fracture at distal third of ulna. 3.- This impact may have been reflected on the left clavicle due to the force generated while falling.
Final position and fractures in the right side. On occurring the fracture at the left ulna (where most of the body weight was supported), an imbalance is created, together with a counterclockwise rotation of the upper limb on the longitudinal axis; the body weight falls upon the right humerus, and this could also have caused compression on the thoracic cage.		
Right arm at 0 degree position relative to the shoulder	Direct impact on the right humerus that is transmitted toward the pectoral girdle on the same side	Complete fracture at midpoint of the right-clavicle's diaphysis. In fractures of this kind the proximal fragment is displaced upwards, and the distal fragment is displaced downwards by the arm's weight. Commonly, this displaces the fracture (the bone is shortened).

Table 1. Interpretation of the sequence of events when the fracture was produced

Results

Sequence of events

The event of the fall proposed is explained according to the two possibilities, already mentioned, of fractures that can happen in the clavicle: (a) falling with extended elbow and hyper extended wrist, when the forces are transmitted from the arm towards the scapula and collarbone, or (b) falling on the shoulder.

The fall with hyper extended wrist and left-side fractures

The subject probably fell down with the left elbow extended (Table 1). When falling, the left arm receives the first impact against the floor; this produces first a direct compression fracture at the styloid apophysis (Figure 4), and then an indirect fracture at the first distal third of the left ulna. The force propagated toward the left clavicle and fractured it (Lovell, 1997; Galloway, 1999; Elstrom, 2000). If the subject lost the support she had from the left arm when the fracture occurred, and her body rotated counterclockwise on the longitudinal axis of the body, it is possible she fell down on her shoulder

Final position and right-side fractures

Due to the rotation, the body receives a lateral impact on the proximal third of the right humerus, thus fracturing the right clavicle. The right clavicle suffered a displaced fracture (Figure 1). On fractures of this kind, the proximal fragment moves upwards, and the distal fragment moves downwards because of the weight of the arm; therefore, the arm is commonly shortened (Elstrom, 2000).

Force diagrams

The use of a force diagram was proposed, showing the pectoral girdle on the transverse plane. The aim was to compare a "normal" pectoral girdle with one affected by clavicular shortening as a result of a displaced fracture. It was intended to see the subject's probable limitations regarding movement, due to the post-traumatic consequences. On diagram A (Figure 5A), showing a cross section of the pectoral girdle with the arms at 90 degrees at abduction, it is possible to see vector F_{ST} (incident force on the sternoclaclavicular joint) as the resultant force produced by contraction of the following muscles: deltoid, trapezius, subclavian, pectoralis major, and sternocleidomastoid, all of them with insertion on the clavicle. Vector F_{SC} (incident force on position and suspension of the scapula) is the result of contraction of the following muscles: deltoid, supraspinous, trapezius, rhomboid major, subclavian and levator scapulae. The vectors show that force F_{ST} is larger than F_{SC}. Vector R_A is the resultant force produced by contraction of the deltoid and supraspinous, which lift the arm to an horizontal position. Force R is the resultant from vectors F_{ST} and F_{SC}, is colinear with R_A, and incident on the anterior costovertebral joint (Sobbota, 2001).

On the parallelogram that is formed in the force system, the angles between vectors F_{ST} and F_{SC} and the resultant vector R are of nearly 30 degrees; there is some symmetry between the anterior and posterior parts. Diagram B (Figure 5B) shows the changes undergone by the pectoral girdle when the right clavicle is shortened as a result of disalignment and displacement of the clavicle's diaphysis caused by a fracture. The structure of the force system was modified. The right clavicle was shortened by about 10 mm. The figure shows that the acromioclavicular junction projected onto the transverse plane, where the shoulder's rotation axis is formed on this plane, moved to the anterior and medial parts of the body (Figure 6). Vectors F_{SC} and F_{ST} were decreased in magnitude, changed direction, and their angles with vector R increased. Forces R_A and R are no longer colinear, and force R is no longer incident on the costovertebral joint.

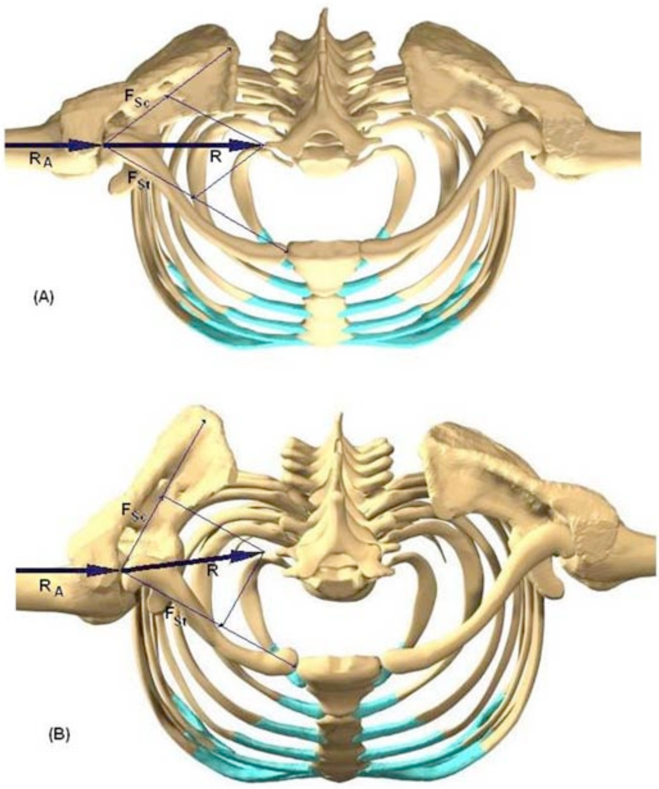

Figure 5. Force diagrams. (5A) Diagram showing a cross section of a fracture less pectoral girdle. (5B) Diagram showing the changes undergone by the pectoral girdle when the clavicle is shortened as a result of disalignment and displacement of the clavicle's diaphysis caused by a fracture. Changes in vectors are also shown. F_{ST} is the force incident on the sternoclavicular joint F_{SC} is the Force incident on position and suspension of the scapula R_A is the resultant or net force produced by contraction of the deltoid and supraspinous, which lift the arm to an horizontal position. R is the resultant force of vectors F_{ST} and F_{SC}..

On the parallelogram formed in the force system on the transverse projection, the angles between vectors F_{ST} and F_{SC} and the resultant vector R are different; they are smaller toward the anterior part (approximately 37 degrees), while in the posterior part they are around 48 degrees. The scapular structure is now asymmetrical on the transverse plane. The decreased magnitude of F_{SC} and F_{ST} means that the muscular force has decreased; the direction of the resultant of these two forces, R, is no longer incident on the backbone. All this produces instability and possibly an incapability of rising the arm by lateral abduction.

Discussion

The study has established the possible events causing both clavicles and left ulna fractures, and the biomechanical changes developed as a result of them. The model proposed by the F_{DB} allowed to reconstruct the pectoral girdle with the affected bone items, and to observe the structural and movement modifications. Although the individual presented fractures in other bones no related to the pectoral girdle (the left ulna, the fifth right metatarsal and the left side ribs: 6 and 7, and of the right side ribs: 5, 6 and 9) the analysis focused in the fractures consequences that the individual suffered on the pectoral girdle including the humerus (without fracture but with osteoarthrosis on the greater tubercle), and the cervical vertebrae (that presented osteophyte).

This opens up the possibility of integrating reconstructions of affected bone items in biomechanical studies, and is undoubtedly a new perpective that can be used in both forensic and physical anthropology

From this representation, it can be seen that the first lateral third of the clavicle distorted the shoulder joint and modified the structure of the three bones that make it up. It is likely that, before the fracture, rotation of the scapula and clavicle formed an angle of approximately 60 degrees (Nordin and Frankel, 2001). After the fracture, the angle increase to about 70 degrees. The displacement of the clavicle probably caused the arm to hang loose and move 30 degrees forward..

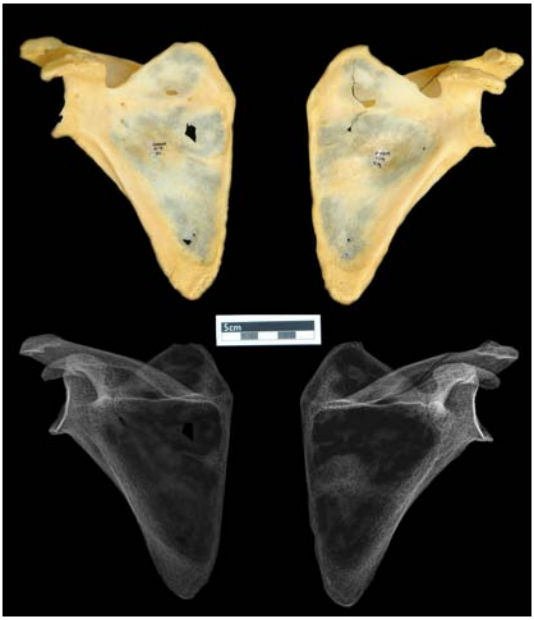

Figure 6. Anterior view photograph of both scapulas with their corresponding X ray plates. It is possible to see osteoarthrosis at the joint surface of the right acromion.

Osteological evidence supports the new adjustment of the humerus-clavicle joint. Miles (1999) points out that, in people more than 50 years old, the mechanism of the humerus' proximal joint degenerates. This author states that, when the arm is at abduction, there is wear between the lateral edge of the greater tubercle and the lower surface of the acromion, due to the wear on the walls of the subacromial bursa.

In the present case, due to the presence of a shortened clavicle and scapula rotation, no wear is seen on the lateral edge, but instead on the greater tubercle (Figure 2). It is likely that the changes on the resultant R caused the force to be directed toward the posterior part of the spines of the vertebrae, and the muscles counterbalanced this force. This is reflected at the bone level in the right anterior parts of the cervical bodies of the subject, where pressures on the vertebral bodies are visible (Figure 3). It may be that the medial portion of the fractured and healed clavicle created tensions in the trapezius and sternocleidomastoid muscles; the former may have elongated, while on the anterior part, the pectoral muscle may have shortened. Perhaps the subclavian muscle, which is inserted on the internal surface of the clavicle, suffered an anteroposterior bifurcation due to the unevenness of the bone in the fractured and healed clavicle.

The humerus undergoes medial traction caused by the pectoralis major; this can be explained on the basis of displacement of the broken ends of the clavicle.

Reconstruction of the joint between the bones that make up the acromioclavicular junction on the right side allows to perceive the changes caused by the fracture. It is likely that the scapula rotated forwards in an attempt to maintain acromioclavicular ligamentous contact, and the bone was shortened; this supports the distortion of joints by a change in structure. The displaced clavicle limited the four different movements of the head because the right sternocleidomastoid muscle varied in length when it was shortened (García-Porrero y Hurlé, 2005). The post-traumatic consequences are related to the marks that are seen on the right clavicle, which on shortening rotated the scapula forwards and created an osteoarthrosis on the greater tubercle; the cervical vertebrae C3, C4, C5 and C6 show osteophytes caused by tension from the sternocleidomastoid muscle when the structure of the clavicle changed. The bones that make up the wrist (radius and ulna) show posttraumatic arthritis. The subject assumed possibly a position with the head bent to the right, for two reasons: first, to balance the head on both sides, right and left, as regards contraction and length for the sternocleidomastoid muscle; second, to avoid the probable pain produced by contraction of the right sternocleido mastoid, that pulled upwards the medial end of the clavicle. The effect of gravity is limited by the concentric or excentric contraction of several muscles, including the sternocleidomastoid on each side. Bending and rotation movements of the head and neck are affected unilaterally.

In the flexion movements of the head and neck there is no bilateral contraction of the sternocleidomastoids. Due to shortening of the right muscle, total flexion is not feasible. As regards extension movements of the head and neck, it is likely that they could not have been completed due to pain on the right side, which may have caused the head to hang backwards, pulling the medial part of the clavicle upwards. Hyperextension of the head is also not bilateral. It would appear that bending and rotation movements of the head and neck were totally free; however, toward the left side they may have been limited because the right sternocleidomastoid muscle was pulling up the medial part of the clavicle and probably causing pain. Bone evidence is rarely conclusive. In this case, however, assessment and interpretation allowed to realize that fracture analysis can be helpful to find out issues preceding the death of the subject. The compression fracture at the styloid apophysis of the ulna points toward a fall (Walker, 1997).

The wrong way the right clavicle healed made suppose that there was was absence of any medical care in order to align the fracture, and also, that during the fracture consolidation phase there was movement about the joint. The result of a careful diagnosis with only bone evidence available, provides useful tools that can be applied to clinical, anthropological and forensic issues. These injuries were not fatal, but were a key influence on the life of the subject because she did not receive any medical care and there were post-traumatic squeals. In contrast, the left clavicle, though fractured, was not shortened and there were no post-traumatic consequences.

Acknowledgements

This work was supported by grant IN404906 from Dirección General de Asuntos del Personal Académico, Universidad Nacional Autónoma de México (UNAM). And CT Scanner for the facilities for the X ray plates.

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Resumen

Este estudio analiza un esqueleto sin datos de procedencia, de sexo femenino, entre 55 y 60 años de edad que forma parte de la colección ósea del Departamento de Anatomía de la UNAM, el cual muestra fracturas en ambas clavículas, ulna izquierda, quinto metatarsiano derecho y costillas del lado izquierdo la C6 y C7 y del lado derecho C5, C6 y C9. Los resultados permitieron entender que el análisis de las fracturas es un apoyo para conocer aspectos anteriores a la muerte del sujeto, que pueden aplicarse en contextos clínicos, antropológicos y forenses. Debido a que los mayores cambios estructurales se observaron en la fractura desplazada de la clavícula derecha, se estudiaron las consecuencias biomecánicas en la cintura escapular. Un modelo gráfico de un sistema de fuerzas sobre un corte trasversal de la cintura escapular, permitió sugerir las implicaciones funcionales y las modificaciones estructurales postraumáticas. Las placas de los RX y la forma en cómo los huesos de la clavícula sanaron, revelaron la posibilidad de que no existió tratamiento medico que redujera y/o alineara la fractura. .

Palabras clave: fractura, postrauma, mecanismo de lesión, modificación estructural

Método para determinar el origen de la secuencia de traumatismos en la cintura escapular a partir del análisis de restos óseos