THE TORSION OF THE HUMERUS: ITS SITE, CAUSE AND DURATION IN MAN

By

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CHAPTER I

INTRODUCTION

Torsion or twisting of long bones about their long axes has been recognized and described by anatomists for many years. Martins (1874) gave a long list of prominent early anatomists who made reference to the torsion of the humerus, including such names as Bertin, Lecat, Sabatier, Soemmering, Boyer, Barclay, Meckel, Jules and Hippolyte Cloquet, Louth, Blandin, Cruveilhier, Jamin, Sappey, Henle, Humphrey and Maclise. Winslow (1763), Bell (1802) and Bichat (1822) also noted the twisted appearance of the bone and reported it in their works.

It is not intended here to give a complete review of the literature on humeral torsion. A considerable portion of the work has been cited by Evans and Krahl (1945) and Krahl and Evans (1945) and additional references may be found in Martin's "Lehrbuch der Anthropologie" (1928). However, there should be mentioned a few of the more important contributors to our knowledge of humeral torsion.

Meyer (1856) appears to have been the first to make a quantitative study of torsion in the humerus and he gave an illustration showing the ends of the bone superimposed so that the angle formed by the crossing of the epiphyseal axes was clearly evident.

However, credit for the formulation of the first real theory to explain humeral torsion must be given to Charles Martins (1857 a, b and c). The French botanist noted the similarity of torsion as it occurred in plant stems to the torsion that had apparently taken place in the humerus. He used his theory to explain the homology of the extremity skeletons. However, he apparently made no accurate measurements, but judged the degree of torsion merely by eye measure. He estimated that the human humerus had been twisted approximately 180 degrees on its long axis.

Interest in the problem of humeral torsion began to be exhibited by many workers and Lucae (1865, 1866) and Welcker (cited by Broca, 1881) devised graphic methods for measuring torsion with some degree of accuracy.

Employing Welcker's technique, Gegenbaur (1868) measured the degree of torsion in the humeri of certain lower animals and man. He found the average torsion to be 168 degrees (or, in terms of the supplementary angle, 12 degrees) for adult man and was the first to show that humeral torsion (based upon the complementary angle) increased during the development and growth of the individual.

In his earlier work Martins had only considered torsion to be a <u>virtual</u> one. Later (1868, 1874), he was lead by the work of Gegenbaur (1868), Guérin (1868) and Durand (de Gros) (1868) to alter his opinions and to admit that there is also an actual twisting of the bone.

One of the most outstanding pieces of work in this field was done by the French anthropologist Broca (1881). Using his own measuring device, called the Tropometer, he studied torsion in over 600 human humeri as well as in those of about 40 anthropoids and 100 various mammals and birds. He came to the conclusion that a true torsion of the humerus exists and placed its value in the adult human at 164 degrees.

Later, Le Damany (1903, 1906) reported his observations on humeral torsion in man and many lower forms. Le Damany admitted a true torsion in man of about 90 degrees, but did not agree with others that it was also present in quadrupeds and birds.

More recently occasional reports have appeared concerning torsion; the more noteworthy, perhaps, being those of Grunewald (1919), Rouffiac (1924) and C. P. Martin (1933).

The latest contributions to the problem have been made by Evans and Krahl (1945) who show the probable origin of humeral torsion to be in the alteration of the crossopterygian fin into a terrestrial type of appendage and point out a gradual increase in the degree of torsion as one follows it through a phylogenetic series. In a second paper (1945) these workers present values of humeral torsion in various races and nationalities of man. They find torsion to be greater in whites than in American Negroes, and in whites greater on the right than on the left. Their average degree of torsion for the white race is 74.4 degrees and for Negroes, 72.6 degrees.

There appears to be little doubt today that a true humeral torsion takes place in man. However, the problem of the torsion of the humerus is by no means a closed one and there are many points concerning which further information is to be desired and upon which further work might be carried out.

CHAPTER II

STATEMENT OF THE PROBLEM

Although there is a rather copious literature on the subject of humeral torsion, considerable disagreement as to the methods of expressing it, its location in the bone and its causative factors is to be observed. Some have confused torsion and rotation, while a minority group (Holl, 1891; Albrecht, 1875) have denied the presence of torsion completely. With a few exceptions (Piersol, 1930, p. 269 and Cunningham, 1943, p. 243), the standard text-books of human anatomy make little or no comment on this feature of the humerus.

No definite conclusion has been reached as to the site of torsion. Martins thought that torsion had taken place in the shaft of the humerus as did many of his followers. This assumption was based upon the twisted appearance of the humerus produced by the spiral groove. Berteaux (1891, cited by Le Damany, 1903) was one of the first to express disagreement with this view, and gave the anatomical neck of the humerus as the region in which torsion took place. Le Damany (1903) and Rouffiac (1924) point out the strong possibility that torsion might occur in the region of the proximal epiphysis of the humerus, while C. P. Martin localized the process in the surgical neck.

Various postulations have been made as to the cause of torsion. Among these, the shifting of the scapula (Holl, 1891; Fick, 1904; Grunewald, 1919; and Braus, 1929) and muscular pull (Le Damany, 1903; Rouffiac, 1924; and C. P. Martin, 1933) are the more noteworthy.

The question of the duration of the process of torsion has not been definitely settled. Although Gegenbaur, Broca and Le Damany have measured torsion in individuals of variour ages, they do not give opinions as to when the process is initiated in ontogeny or at what age it ceases. Rouffiac (1924) seems to have been the only worker to give a definite time of completion of the process.

These three aspects of torsion: its site, cause (or causes) and its duration seem to be in need of further study and clarification. The body of this work is devoted to these considerations.

CHAPTER III

MATERIALS AND METHODS

A. Humeri of Fetuses, New-born Individuals and Infants

A study of the proximal humeral epiphysis was undertaken in a series of 24 humeri taken from individuals in various stages of prenatal development, from neonati and from several young children. In most cases reliable data as to the duration of pregnancy or postnatal age were obtainable. In a few cases, where such information was not available, estimates of age were made from crown-rump measurements. Sex is known for all except the very early fetal stages.

Most of the observations on early fetal humeri were made in cleared and stained preparations. In the older, fresh specimens the humeri were removed and cleaned of the soft tissues, leaving only the periosteum intact.

It was desired to learn how much movement is possible between the bony diaphysis and the cartilaginous epiphysis in the region of the epiphyseal line in these young humeri, and to see how much of the stability of the diaphyseo-epiphyseal union is due to the surrounding periosteum. Beginning from a circular incision around the shaft, about one centimeter from the epiphyseal line, the periosteum was split by an incision which crossed the epiphyseal line and extended over onto the epiphysis. Then, with the aid of a binocular dissecting microscope, the periosteum was peeled off this end of the bone so that the margin of the epiphyseal disc was exposed. The amount of rotational and side-to-side movement possible between epiphysis and diaphysis was noted before and after the removal of the periosteum. The ease with which the epiphysis could be pulled off after the removal of the periosteum was also observed. Lastly, upon removal of the epiphysis, the shape of the exposed end of the diaphysis and the corresponding surface of the epiphysis was studied.

Measurements of torsion were made in all the young humeri with the exception of those in the cleared specimens, where, of course, this could not be done.

B. Shoulder Muscles

The muscles studied in this investigation were obtained from 42 of the cadavers used in routine dissection in the Department of Gross Anatomy of the School of Medicine, University of Maryland during the courses given from October, 1944, to April, 1945, and from September, 1945 to April, 1946.

In the problem at hand it was desired to obtain information concerning the strengths of certain muscles of the scapulo-humeral and axio-humeral groups. The muscles of the scapulo-humeral group included the Supraspinatus, Infraspinatus, Teres minor, Teres major and Subscapularis, while those of the axio-humeral group were the Pectoralis major and the

Latissimus dorsi muscles. It will be later emphasized that these muscles seemed the most likely to be involved in the production of a torsion by reason of the positions of their insertions into the humerus, and because of the nature of their functions.

The early work of E. Weber (1846) pointed out that the force exerted by a muscle was dependent upon its physiological cross-section and not its length. Upon this basis the relative forces of muscles or groups of muscles can be studied by a comparison of their cross-sectional areas. Therefore, physiological cross-sections were taken from the seven muscles mentioned above, on the right and left sides of each of 23 cadavers. Only the Pectoralis major, Latissimus dorsi and Teres major were taken from each side in a second group of 19 cadavers. The area of each muscle section was determined.

C. Method of Making Muscle Cross-sections

After the muscles had been carefully cleaned of their investing fasciae, a physiological cross-section was made in each case with an extremely thin sharp knife. It was found that good sections could be obtained by using a Bard-Parker knife, fitted with a size 22 blade. A second cut was made close to the first and parallel to it, so that a slice of muscle, about one-eighth of an inch in thickness could be removed.

Since a physiological cross-section of a muscle, by definition, is one which passes at right angles through all of its fiber bundles, it was essential to know rather exactly the origins of the muscles in question so that the incision would pass across the muscle distal to the area of origin. The areas of origin on the surface of the bone were determined by reference to the standard works on human anatomy and by a careful examination of the muscles themselves prior to sectioning.

So that the section taken from one particular muscle might be directly comparable to any other section from the same cadaver or from another cadaver, a definite site for the incision was decided upon in the case of each of the muscles studied. In general, the sections were made as described below and included all the fiber bundles of the muscle.

Supraspinatus: Section along a line joining the deepest point of the lesser scapular notch and the groove for the circumflex scapular artery on the axillary margin of the scapula.

Infraspinatus: Section along the lower part of the line described above.

Teres minor: Section through the thickest part of the belly of the muscle.

Teres major: Section through the muscle midway between the origin and insertion.

Subscapularis: Section along the line joining the deepest point of the lesser scapular notch and the infraglenoid tuberosity.

Pectoralis major: Section along a curved line, beginning at the origin of the most cranial fibers of the clavicular portion and passing down across the sterno-costal and abdominal portions to the axillary margin of the muscle.

Latissimus dorsi: Section beginning at the origin of the scapular fibers and passing across to the lateral margin. In those cases in which there was no slip arising from the inferior angle of the scapula, the section began where the Latissimus dorsi crossed the inferior scapular angle, the arm being placed parallel to the body.

As each muscle-slice was taken from the cadaver, it was placed upon a sheet of absorbent paper moistened with embalming fluid and stored in a petri dish until it was again needed.

D. Measurement of Cross-sectional Area

As will be emphasized later, there is considerable variability of the material due to individual differences of several sorts. It therefore seemed advisable to select a method of measurement of the cross-sectional area which would not further complicate the picture by introducing undue errors of a technical nature into the work. In order to point out the importance of the type of technique which one uses for area determinations and to show certain advantages of the method employed here, it may be permitted to consider a few of the techniques which have been used in the past.

One of the first ways of determining the area of a physiological cross-section in square centimeters was the indirect method of Weber (1846), who maintained that the value could not be determined directly. His method was based upon a knowledge of the length of the fleshy fibers, the weight of the muscle and its specific gravity. These terms were used in the following formula:

$$S = \frac{P}{pL}$$

in which S represents the cross-sectional area; P, the weight of the muscle; L, the fiber length; and p is the specific gravity of the muscle substance. With this formula Weber (1851) carried out calculations for all the muscles of the human body. Although his indirect estimates are in considerable disagreement with the results of more recently developed direct methods, some workers still accept Weber's values. In most cases the areas of Weber differ widely from the determinations of the writer.

Buchner (cited by Fick, 1910, p. 294) has described a simple method which gives rather rough approximations of area. A slot, two centimeters in width is cut into the end of a board and the edges of the slot are graduated in fractions of a centimeter. The muscle, previously hardened in formalin, is pressed into the slot and the cross-sectional area is easily calculated. The widths of the slot may be varied, being more narrow for smaller muscles and wider for larger ones. It can be readily understood that considerable error may be introduced by the use of this method, depending upon how loosely or firmly the muscle is packed down into the slot.

A more elaborate technique, but more exact, has been worked out by Grohmann and Fick (1902), wherein the physiological cross-section of the muscle is colored on the cut surface with a dye and pressed against a piece of paper. The print thus obtained is cut out and pasted onto a sheet of lead foil of uniform thickness. The contour is then cut out of the lead foil and weighed. Knowing the weight of one square centimeter of this foil, one can calculate the cross-sectional area of the muscle. Errors may arise in this method due to spreading of the fibers as they are pressed against the paper, from smudging or through technical errors in cutting and weighing. Reys (1915) too, has criticized methods involving the imprinting of sections on paper where flattening of the soft tissues may occur.

A technique involving the use of coordinate paper was used by Hermann (1898). Gans (1905, cited by Reys, 1915) dissociated the muscle by treatment with nitric acid and counted the fibers. Reys indirectly estimated the area by measuring the side of the muscle, the angle of insertion, and in the case of some of the more complicated muscles, the relative weights. The merits of indirect methods of determination are open to question, in view of the great discrepancies in the values obtained thereby.

Using the Kodaloid method introduced by Scammon and Scott (1927) to supplant the older paper cut-out methods, Mainland (1933) has made careful measurements of area of Masseter muscle cross-sections and considers it a very satisfactory technique. A brief description of this method also appears in the paper by Mainland and Hiltz (1933).

In this present work, where it was necessary to make measurements of cross-sectional area in over 435 muscles, a method was desired which would permit fairly rapid determinations and yet give a high degree of accuracy. A simple photographic printing procedure was finally decided upon. This method enables one to obtain sharp and accurate outlines of the muscle cross-sections on paper, from which the measurements of area can be taken.

Working under a yellow safety lamp in the photographic dark-room, the cut surface of each slice representing the physiological cross-section was placed against a sheet of number four glossy Azo printing paper. After exposure to white light for a suitable length of time, the prints were developed. This gave an accurate silhouette of each cross-section in white against a jet black background.

In order to correctly identify the silhouettes later, a convenient system of labelling the prints was devised. A series of labels was prepared by inking the names of the muscles and the identification numbers of the cadavers upon thin glass cover slips. Each sheet could thus be permanently labelled at the time of printing by placing the appropriate glass slips at the margin of the paper together with the section before exposure to white light.

The results which are obtained by the use of this method may be observed in Figure 1 which shows the set of section silhouettes obtained from the right and left sides of cadaver number 25.

The cross-sectional area of each muscle slice, as represented by the black and white photographic print was determined to one-tenth of a square centimeter by means of a Keuffel and Esser Pantograph Polar Planimeter. This instrument is an improvement on the original Amsler pattern and gives increased accuracy in the measurements of small figures.

Scammon and Scott (1927) have given a review and criticism of several methods for the determination of irregular areas. They conclude that for small areas the results of the paper cut-out method are superior to those obtained by the use of the planimeter, while even more accurate values are given by their Kodaloid method. The earlier study of the errors involved in planometric methods by Henrici (1894) showed that some error arises through faulty adjustment of the mechanism and slight irregularities in the action of the integrating wheel. However, these are relatively small and unimportant. The gross error is the personal one which is largely due to faulty guidance of the tracer around the margin of the area to be measured. However, as Henrici has pointed out, these deviations will, in general, be partly

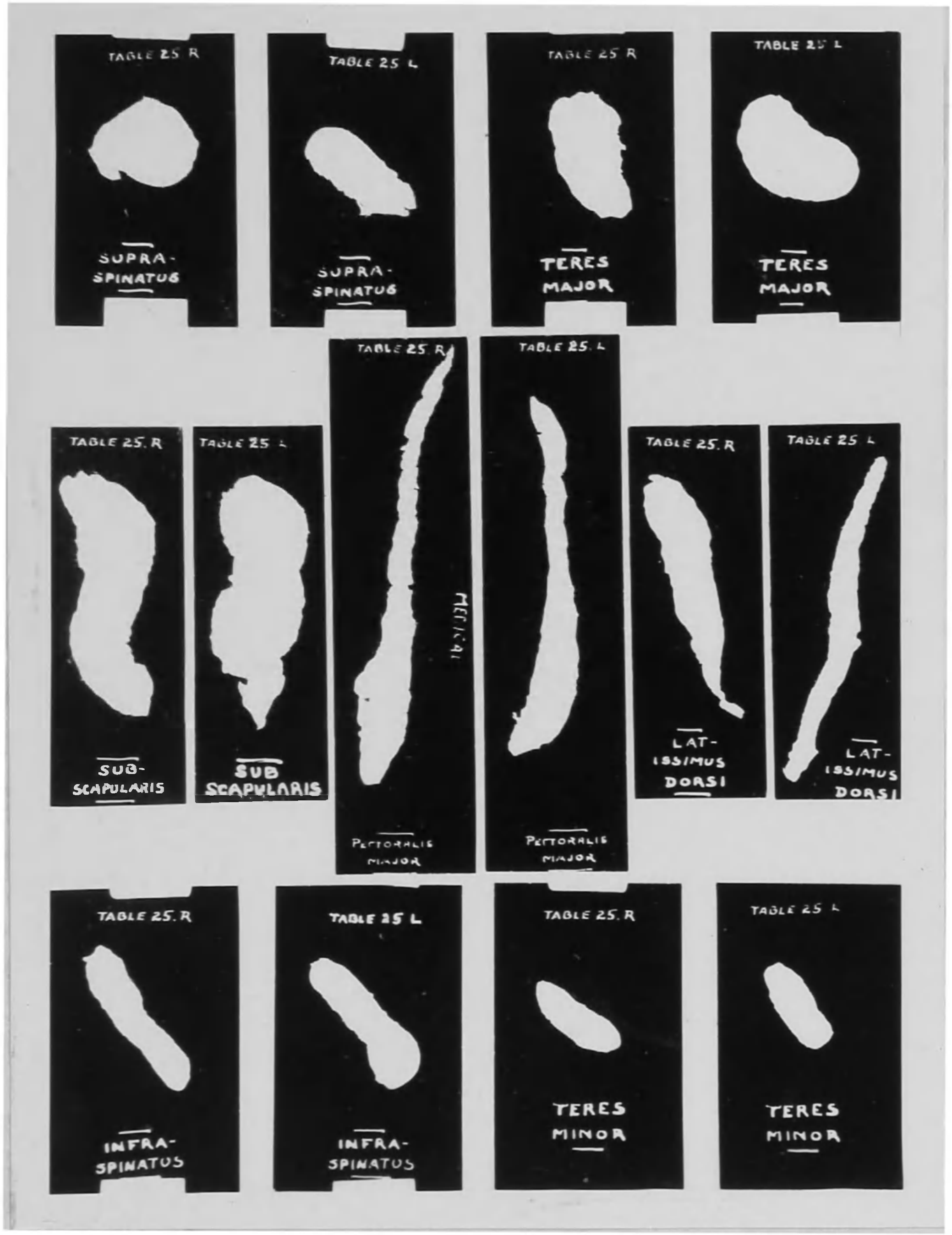


Figure 1. Set of muscle cross-section silhouettes obtained from the right and left sides of cadaver (C-25). $\times\frac{1}{2}$

positive and partly negative, so that the errors introduced will greatly cancel each other. Although it may be true that the planimetric technique becomes less accurate when used in measuring very small areas (1-3 cm^2) it appeared to be quite satisfactory in this work where the areas measured averaged about 6 cm^2.

The standard error of the planimetric technique was determined for a small (3.5 cm^2) and a large (12.7 cm^2) area. In order to eliminate the possibility of prejudice or psychological influence in taking the readings during the test measurements, the measurements were made with the assistance of a second person. The writer guided the tracer around the area to be measured, while an assistant independently read the values from the recording device. The formula employed in the determination of the standard error was the following one:

$$\sigma = \sqrt{\frac{\sum (x^2)}{N - 1}}$$

This formula permits a more critical examination of data than the one more commonly employed, wherein the sum of the squares of the deviations are simply divided by N. That the actual measurement of area as carried out in this work yields reliable values is evidenced by an extremely slight standard error of the technique which amounted to $\pm$ 0.08 for the smaller area and $\pm$ 0.09 for the larger one. In addition, it is felt that the technique, on the whole, is a rather accurate one inasmuch as excessive handling and distortion of fibers through compression and the like are not required.

The values for the areas obtained by this method were used in the calculation of muscle tension.

E. Calculation of Absolute Muscle Force

In determinations of muscle strength, one square centimeter is customarily taken as the unit of cross-section and the muscle strength per unit of cross-section area has been called the <u>absolute muscle strength</u> ("absolute Muskelkraft") by R. Fick (1910). This term is defined by him as the tension per square centimeter of muscle cross-section area under conditions of maximal volitional excitation when the joint over which the muscle passes is in the mid-position.

The value of absolute muscle strength or the <u>muscle strength</u> unit ("Muskelkrafteinheit," Fick) has been determined in various ways, both experimentally and by indirect methods. Methods of determining this unit have been described and discussed by O. Fischer (1906, cited by Fick, 1910), Fick (1910), Arkin (1941) and others. It is readily seen that anyone attempting to determine the muscle strength unit is troubled by a great number of variable factors which render it extremely difficult to arrive at a definite value. First of all, it is clear that a value for the unit must be, at best, an average one since the tension may be considerable when the muscle is stretched, but it decreases as the muscle contracts. The strength will partially depend upon the degree of coarseness of the muscle fibers. There are great differences in the arrangement of the fibers and in the amounts of connective and elastic tissue present in the muscle. Therefore, as pointed out by Mainland (1945), it is not surprising that there has been such great variation in the estimates of the value for the muscle strength unit. For example, the value of 3.6 kg. per cm^2. of cross-sectional area reported by von Recklinghausen (1920) has been corroborated recently by Arkin (1941) while Franke (1920) gave a value of 11.1 kg. per cm^2. for the flexors of the elbow. Many intermediate values have been given by various workers and for different muscle groups. The following estimates (in kg. per cm^2.) may be mentioned by way of illustration: Weber (1846), 0.836 for calf muscles; Henke (cited by Mainland, 1933), 4.0; Fischer (1906), 4.5 for calf muscles; Reys (1915), 5.25 for calf muscles; Knorz (1865), 5.9 for foot muscles; Hermann (1898), 6.24 for calf muscles; Koster (cited by Henke, 1868), 7.4 for arm muscles; Knorz (1865), 8.2 for arm muscles; Koster (quoted by Reys, 1915) 9 - 10; Johnsson (quoted from DuBois-Reymond, 1903), 10.0 for certain muscles of the superior extremity. This latter value is taken by R. Fick (1910) as a convenient number for use in the calculations. He remarks that it may appear somewhat high, but that it certainly falls within the sphere of possibility. Mainland and Hiltz (1933) also have estimated absolute muscle force on a basis of 10 kg. per cm^2. Strasser (1917) felt that the value of 10 kg. per cm^2. for absolute muscle strength was too great and should be placed at only

6 kg. per cm^2. It is apparent that a great deal of careful work must be carried out on a large number of individuals before a reliable value for the muscle strength unit will be available.

According to Fick, the effective total tension of a muscle is equal to Q x KE, where Q represents the area of the physiological cross-section and KE is the muscle strength unit. In this study in which an attempt was made to correlate muscle strength and the degree of humeral torsion, this formula was used. In view of the many estimates which have been given for the unit of muscle strength, it was difficult to decide which value should be used in this work. The value for KE in the above formula was taken as 10 kg. per cm^2. since the value, determined from a large number of individuals, has been widely used and is easily handled in the calculations. The values for muscle tension which will be given later may be readily converted to conform with those of any of the other workers by multiplying by the appropriate factor. For example, in calculating the effective total tension of a muscle whose cross-section is 7.5 cm^2., a value of 75 kg. would be obtained, based on KE = 10. To convert into the terms of Knorz for arm muscles (KE = 8.2) one multiplies by $\frac{8.2}{10}$, thus:

$$75 \text{ kg.} \times \frac{8.2}{10} = 61.5 \text{ kg.}$$

Perhaps after further work has been done on this problem, the value for the muscle strength unit will be shown to be somewhat less than 10 kg. per cm^2.

The criticisms may be brought forward that the value of 10 kg. per cm^2 is only an approximation, that it differs considerably from other values which have been obtained and that conclusions should not be based upon figures obtained through the use of such a disputed value. However, it will be made clear later, that the values for muscle tension in this work are only relative ones and the real values, therefore, are unimportant. The data for the muscle tensions might just as well have been given in terms of cross-sectional area since this is proportional to tension, but it seemed more suitable to use a unit expressing tension, since this is the point under consideration. It is obvious that any of the estimated values for the muscle strength unit might have been used since only relative strength is important here. If all the values of cross-sectional area (Q) used in plotting the data graphically are multiplied by the same factor (KE), whatever its value may be, it is clear that the resulting figures will still bear the same relationships to one another as the original values of Q. Therefore, regardless of which value for KE one chooses to accept, the conclusions which may be drawn from the data will not be altered in any way.

F. Embalming Fluids

In this department the fluid used in the embalming procedure is not the same in all cases. Three fluids are routinely used, depending upon the condition of a body when it is received. One of the three fluids is selected which, by virtue of its certain qualities, will be expected to give the optimum result. The formulae of these embalming fluids are as follows:

Fluid No. I. (Used in the majority of cases at the University of Maryland.)

Carbolic acid	4.5	parts
Glycerine	5.25	"
Alcohol (95%)	4.5	"
Formalin	3.0	"
Water	82.75	"

Fluid No. II. (Keiller's fluid)

Carbolic acid	1.5	parts
Glycerine	2.5	"
Formalin	10.0	"
Water	86.0	"

Fluid No. III. (Used routinely at the School of Medicine, Johns Hopkins University.)

Carbolic acid	47.0	parts
Glycerine	29.4	"
Formalin	11.8	"
Alcohol (95%)	11.8	"

The degree to which the muscle tissue is affected by each of these fluids with respect to swelling, shrinking, etc., is not definitely known. However, it does not seem probable that any such changes would be of great magnitude. Certainly any slight alterations which might take place in the tissues will not significantly influence the measurements taken here or in any way affect the conclusions drawn from them.

G. Humeri

The humeri used in this work were collected from the 42 cadavers mentioned above in connection with the discussion of muscles. The bones were cleaned of all soft tissues. The articular cartilages at each end of the bones were left intact. Each pair of humeri was marked with the proper identification number so that the bones could be studied in connection with the muscles of the corresponding cadavers.

H. The Measurement of Humeral Torsion

Measurements of the degree of humeral torsion were made on both humeri of each individual by means of a recently developed instrument, the Torsiometer (Krahl, 1944). The technique of measuring humeral torsion employed in this work and the lines of reference used are described in full in an earlier communication (Evans and Krahl, 1945) and need not be discussed in detail here. However, as there are certain fundamental principles involved which will have to be taken up later under "Discussion," it is necessary to dwell briefly upon the technical method here.

In order to arrive at an accurate knowledge of the degree of torsion in any particular humerus, it is essential that a clear distinction be made between rotation and torsion.

The importance of such a distinction has been emphasized recently by Krahl and Evans (1945). However, in view of the prevailing confusion of the two terms in the current literature, a restatement of this important point appears to be justified. In a number of text-books which have enjoyed wide distribution, the terms rotation and torsion are used interchangeably and at times one or the other is employed incorrectly by itself. Thus, in Gray's, "Anatomy," (1942, 24th ed., p. 66) one reads that the limbs undergo a "torsion *or* rotation" (italics mine) through an angle of 90° around their long axes. Arey, in his "Developmental Anatomy" (1940, 4th ed., p. 159) states that the limbs undergo a torsion of 90° about their long axes and Keith (1933, p. 487), likewise, speaks of the torsion which the limb undergoes. Obviously, these latter authors are referring to the well-known embryonic rotation of the limbs and not to a torsion (twisting) of the limb. Rotation implies a simple turning of the entire part, while torsion, on the other hand, signifies a twisting of one end of an object with respect to the other. In the former, all parts undergo an equal change in position; in the latter, one portion remains stationary while another is shifted.

Inasmuch as rotation concerns the humerus as a whole, any consideration of it will have to deal with the position of the whole humerus, (i.e., both proximal and distal ends) relative to the body axes. It is clear that this problem cannot be made an issue of this article. The work reported herein concerns itself exclusively with the position of the long axis of the distal end with respect to the long axis of the proximal end of the bone. In order to obtain a knowledge of this relationship, the position of the humerus relative to body axes must be completely ignored. When the position of the distal end, relative to the head is measured, the position in which the lead lies in the starting position will therefore be irrelevant.

The procedure was as follows. The head of the humerus is placed in any desirable position and its long axis is determined as indicated in Figure 2 (xx'). Through the center of the head another line is constructed which intersects the axis of the head at a right angle. Then the long axis of the distal end is determined. The angle, Υ , which can be ascertained by the aid of the Torsiometer, indicates the degree of torsion (Figure 2B).

In interpreting torsion in this manner, a postulate has been made which will be justified later by the presentation of suitable evidence. It has been postulated that the long axis of the distal end has been moved out of the position aa' (a position in which the coronoid fossa of the distal end and the greater tubercle of the head of the humerus face in the same direction--see Figure 2A) into the position bb' shown in Figure 2B. Torsion has occurred in a medial direction (see arrow).

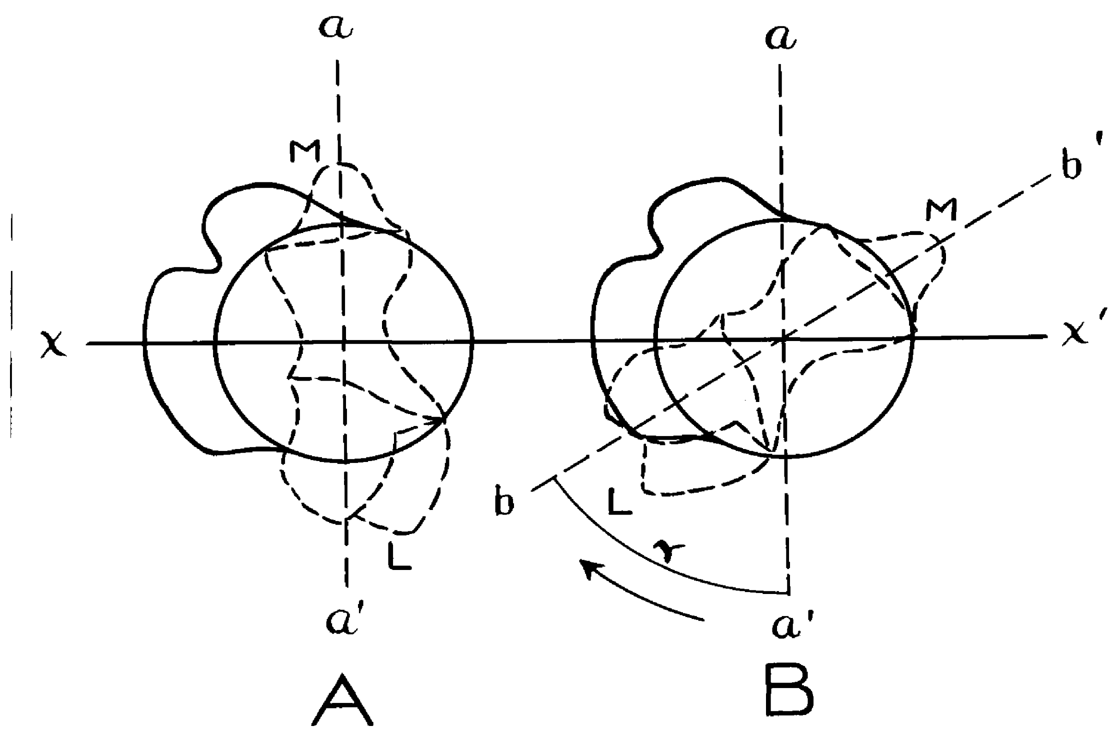


Figure 2. Left humerus seen from above with proximal (solid outline) and distal (dotted outline) ends of the bone superimposed. Lines xx' and bb' represent the long axes of proximal and distal ends, respectively. L., lateral epicondyle; M., medial epicondyle. A. illustrates the postulated starting position, i.e., prior to torsion; B. shows movement of axis bb' out of position aa' through angle γ. Arrow indicates that torsion has occurred in a medial direction.

I. Data on Cadavers Used in This Investigation

As much information as could be obtained concerning the history of each cadaver was collected. This included personal histories, hospital records, height, weight, age and, where possible, the occupation of the individual. This information was considered in the evaluation of the results where it appeared to have a bearing upon the size and condition of the muscles. These data for each subject studied are presented in tabular form in Table I.

TABLE I

General data concerning the individuals studied.

No.	Sex	Race	Age	Height (Cm.)	Weight (Kilos.)	Occupation	Cause of Death*
C-1	M	N	56	-----	48.53	Laborer	Gastric Cancer
C-2	M	N	59	165.0	55.34	---	Lobar Pneumonia
C-3	F	N	32	161.5	58.06	Maid	Uremia, H.C.D.
C-4	M	N	48	166.5	53.07	---	Lobar Pneumonia
C-5	M	N	48	177.0	59.87	Unempl.	Uremia, Nephrosclerosis
C-6	M	W	70	175.0	71.67	---	A.C.D.
C-7	M	N	40	169.5	47.17	Hostler	Pul. T.B.
C-8	M	W	60	172.5	34.93	Cook,Waiter	Pul. T.B.
C-9	M	N	56	163.0	52.16	---	Lues, Central Nervous System
C-10	M	W	83	168.0	48.53	Watchman	Cardiac Failure, A.C.D.

TABLE I (Cont'd)

No.	Sex	Race	Age	Height (Cm.)	Weight (Kilos.)	Occupation	Cause of Death*
C-11	M	N	60	171.5	52.62	---	Coronary Occlusion
C-12	M	N	67	165.0	52.16	---	Bronchopneumonia
C-14	M	N	82	167.0	48.08	---	Bronchopneumonia, H.C.D.
C-15	M	W	76	167.5	56.70	---	Chronic Myocardial Degeneration
C-16	M	W	61	159.0	40.82	---	Pul. T.B.
C-17	F	N	68	153.0	34.47	Housework	Bronchopneumonia, H.C.D.
C-18	M	N	38	170.0	39.46	---	Pul. T.B.
C-19	M	N	78	180.0	46.27	Laborer	Cardiac Failure, A.C.D.
C-20	M	N	70	177.5	55.34	---	A.C.D.
C-21	M	N	60	162.5	56.25	Unemployed	Cardiac Failure
C-22	M	W	62	182.0	60.78	Unemployed	Cerebral Hemorrhage, H.C.D.
C-24	M	W	42	167.0	46.27	Painter	Sec. Anemia, Nephrosclerosis

TABLE I (Cont'd)

No.	Sex	Race	Age	Height (Cm.)	Weight (Kilos.)	Occupation	Cause of Death*
C-25	M	W	85	157.0	55.34	Laborer	Coronary Thrombosis, A.C.D.
C-26	M	W	69	169.0	49.54	---	R.F., A.C.D., Pneumonia
C-27	M	N	45	173.0	37.27	Farmer	Pul. T.B.
C-28	M	N	37	175.0	55.90	---	Pul. T.B.
C-29	M	N	47	172.0	44.55	---	Acute Miliary Tuberculosis
C-30	M	N	72	158.0	55.00	---	Arteriosclerotic Heart Disease
C-31	M	W	60	162.0	39.55	---	M.I., Myocarditis, Gen. A.
C-32	M	N	60	162.0	48.18	---	Cardiac Failure, A.C.D.
C-33	F	W	37	147.0	39.55	Housewife	Uremia, C.G.N., P.P.C.
C-34	M	N	51	-----	46.82	---	Bronchopneumonia, G.&C.A.
C-35	M	W	65	166.0	61.36	---	Cardiac Failure, Emphysema, P.D.
C-36	M	N	53	170.5	36.36	---	Cardiac Failure, Pul. T.B.

TABLE I (Cont'd)

No.	Sex	Race	Age	Height (Cm.)	Weight (Kilos.)	Occupation	Cause of Death*
C-37	M	N	79	176.0	50.00	---	R.F.
C-38	F	N	45	157.0	28.18	---	D.M.
C-39	M	N	30	174.5	47.72	---	Chronic Pul. T.B.
C-40	M	W	51	174.0	40.90	---	Pul. T.B.
C-41	M	N	36	169.0	49.09	---	Pul. T.B.
C-42	M	W	46	179.0	49.09	Machinist, Seaman	Pul. T.B., Pulmonary Hemorrhage
C-43	M	N	46	174.0	49.54	---	Pul. T.B.
C-44	M	W	72	170.0	54.54	Pharmacist	Pneumonia, Cardiac Failure, D.M.

*Key to abbreviations: A.C.D., Arteriosclerotic Cardiovascular Disease; C.G.N., Chronic Glomerular Nephritis; D.M., Diabetes Mellitus; G.&C.A., General and Cerebral Arteriosclerosis; Gen. A., General Arteriosclerosis; H.C.D., Hypertensive Cardiovascular Disease; Maln., Malnutrition; M.I., Myocardial Insufficiency; P.P.C., Probable Portal Cirrhosis; P.D., Pulmonary Disease; Pul. T.B., Pulmonary Tuberculosis; R.F., Respiratory Failure; Sec., Secondary.

The remainder of the technical procedures employed in this investigation are best considered in conjunction with their respective topics and will appear in subsequent sections of the paper.

CHAPTER IV

OBSERVATIONS UPON THE SITE, CAUSE AND DURATION OF HUMERAL TORSION

A. The Site of Torsion

Presentation of supportive evidence from the literature and of new evidence obtained in the present study

The several views as to the site of humeral torsion may be divided into two main groups. One group, including the views of many of the earlier workers, places humeral torsion in the diaphysis, while the other centers the process near the proximal end of the bone (anatomical neck, surgical neck et cetera). While there is little or no support for the first view, there is a considerable amount of evidence in favor of the second one. The proximal epiphyseal cartilage, for reasons to be enumerated presently, appears to be the most likely site of torsion.

1. Evidence against a diaphyseal torsion

It is perhaps natural that many anatomists have located the torsion of the humerus in the shaft of the bone, for references to the twisted appearance of the shaft are numerous. Upon examination of the human humerus (or, for that matter, that of many lower mammalian types) the spiral groove is seen winding downward from dorsal to lateral around the bone, indeed making it to appear as though the shaft had been subjected to a twisting which had rotated the distal end in a medial direction. Martins, among others, gave the spiral groove of the humerus as evidence that the bone had undergone a torsion.

a. The spiral groove is not an indicator of torsion

Evidence from the literature. It must be recalled that, in life, this spiral marking lodges the Radial nerve and that the edges of the groove afford attachment to the lateral and medial heads of the Triceps brachii. The best explanation for the presence of the spiral groove appears to be found in the combined effects of the processes of pressure atrophy and tension hypertrophy of bone.

It is indeed remarkable that certain mechanical forces of a functional nature can cause increased growth and hypertrophy of bone, while others, such as pressure, can bring about an atrophy or limitation in the growth of bone. To see an excellent illustration of pressure atrophy, one has only to inspect the tortuous furrows eroded into the inner surface of the cranium by the meningeal vessels. Muscles, too, are able to bring about changes in the configuration of bone.

Osseous tissue is indeed to be regarded as a highly plastic one and a copious literature may be called upon for illustrations of this property of bone. The malleability of bone was early recognized by Sir Charles Bell (1902). The experimental studies of Demoor (1903) have demonstrated the remarkable plasticity of bone and muscle. Weidenreich (1922) too, has emphasized the moulding effects of muscle upon bone and Bernhard (1924) has shown that the prismatic shape of the tibia is due to the pressure of the anterior leg muscles. Considering this feature of bone from the standpoint of pathology, Brailsford (1945) has thrown additional light upon the mechanism through which the moulding of bone is accomplished.

That the spiral groove of the humerus represents the response of the bone to pressure and tension rather than to a twisting of the shaft receives excellent experimental support from the work of Wermel (1935 a). Tendons, moved to new positions in the limbs of rabbits, pressed deep grooves, flanked by ridges, into the surface of the bone.

Melzer (cited by Rouffiac) and Rouffiac (1924) both consider the spiral groove merely as a visible expression of muscular traction. The former supports this view by pointing out that the spiral ridges descending on either side of the Radial nerve are especially marked in very muscular subjects.

Campana (1874) has pointed out that in the eighth fetal month the humeral diaphysis, like that of most of the other long bones at that stage is smooth and rounded without a trace of ridges, depressions or crests which it has in the adult state. He continues that the later appearance of these superficial modifications is due to the mechanical action of muscular function upon the bone.

It thus appears quite likely that the spiral groove of the humerus represents a trough for the Radial nerve, the margins of which are emphasized by muscular attachments. Rouffiac (1924), in order to set apart this apparent twisting from the active process of torsion has introduced the term, false diaphyseal torsion.

Evidence from personal observation. In the present investigation the writer was able to confirm Melzer's observation that the spiral ridges flanking the Radial nerve in its descent are more marked in muscular individuals. Particular notice was made of the degree of muscular development in the cadavers studied. In nearly all cases the humeri of these subjects clearly reflected the condition of the muscles. Powerful individuals had humeri with sharp, prominent crests, while the humeri of those with poorly developed muscles were nearly smooth and the spiral markings were barely discernable. By way of illustration, two right humeri, photographed from the dorso-lateral aspect, are shown in Figure 3. Humerus A is from a young male Negro with an excellent muscular development, while humerus B is from an elderly male white subject with very small weak muscles. The marked difference in the development of the spiral ridges is clearly seen.

During the course of this work, while studying the humeri of fetal and young individuals, it was repeatedly noted that these bones were completely devoid of the sharp ridges and

Figure 3. Two right humeri photographed from the dorso-lateral aspect to show the striking difference between the prominence of the ridges along the spiral groove in a powerful individual; A, and one with poor muscular development; B.

crests which characterize the humeri of adults. During the first few years of life the straight, cylindrical appearance of the shaft is not modified to any appreciable degree. Even in the humeri of a seven year old child, the only crest which showed any degree of prominence was the lateral lip of the intertubercular sulcus. These findings corroborate those of Campana (1874) in fetal and young humeri.

If it were true that torsion occurred in the diaphysis and that the spiral groove of the humerus arose as a result of this torsion, it would be reasonable to expect that the groove would become evident soon after the initiation of torsion. This, however is not borne out by actual observation. In the last portion of this work, concerned with the problem of the duration of torsion, it was found that torsion begins quite early in development and that by the time the age of seven has been reached the process is rather more than one-half completed. Yet, by actual observation, there is no spiral groove in evidence at this time. Only later, when the muscles of the child develop into the larger, more powerful muscles of the youth, does the groove, with its accompanying ridges begin to make its appearance.

Yet another piece of evidence may be brought forward against a direct relationship between humeral torsion and the presence of a spiral groove. If the groove were a direct result of the twisting process one would expect that the angle passed through by the groove in its downward course would be equal to or at least proportional to the angle of torsion. Such a relationship could not be demonstrated, however. When the angle of the spiral groove was plotted against the torsion angle in a series of adult humeri, no direct relationship between the two values became evident. The value for the angle of the groove appeared to be merely an expression of the distance along which the Radial nerve made contact with the bone.

The only reference which the writer has been able to find regarding a quantitative relationship between the torsion angle and the angle of the spiral groove is the general statement of Howell (1939) that the twisting has not occurred to the extent that the groove suggests. The findings of the writer do not support such a view, for in the majority of humeri the angle of the spiral groove proved to be much smaller than the torsion angle and the two angles differed in some cases by as much as 32°. It is possible, however, that Howell's impression of the degree of torsion is based upon the figures of those who reckon torsion in terms of the so-called supplementary angle of torsion; a method which yields angular values in the neighborhood of 16°. The writer's method (see Figure 2 B, angle γ) gives an average value of about 74°. Therefore, the apparent conflict of views may be explainable upon the basis of the method of expressing torsion.

b. Early ossification of the humeral shaft

<u>Evidence from the literature</u>. Torsion of the humeral shaft might conceivably occur before this part of the bone

is completely ossified. However, ossification of the shaft begins early in development, the primary center appearing around the 8th week of fetal life. At birth the shaft is entirely osseous or nearly so. Thus, if torsion were to take place in the shaft, it would have to do so in great part before birth. This is not borne out by actual observation. As will be emphasized later, the ontogenetic findings of Gegenbaur (1868) and his followers show a gradual increase in torsion of the humerus with age during the earlier years of life.

Evidence from personal observation. In the study of humeri of very young subjects, it was uniformly observed that the diaphyses were completely ossified at birth. It is conceivable that some torsion might be impressed upon such a small and relatively weak shaft, even though ossified. However, the bone becomes stouter and stronger with age and should therefore become increasingly resistant to torsional forces. Yet, as will be pointed out later, the advance of torsion is a rather steady one from beginning to end. Torsion is by no means completed before birth, i.e., before the complete ossification of the shaft.

Again, assuming that torsion took place in the diaphysis, even after complete ossification, perhaps through changes in the internal structure of the bone, it would be reasonable to expect to find a continuous increase in the degree of torsion throughout the life of the individual. Presumably any causative factors which would act to twist the diaphysis during infancy and childhood would continue to be effective in later years as well. However, personal investigation with Evans (1945) and evidence to be presented later in this paper indicate that the process of torsion is no longer active after the attainment of maturity. This, too, speaks against a torsion in the shaft of the humerus.

c. Mechanical qualification of the diaphysis for resisting torsion

Evidence from the literature. Further evidence against a torsion of the shaft may be obtained from an examination of the structure of the bone. The thick and strong compacta found in the shaft of the humerus makes it seem unlikely that torsion would occur there, for tremendous muscular or other forces would be necessary to produce a twist. Hultkrantz (1897) has emphasized that the outline of a section taken from about the middle of the humerus is nearly an isoceles triangle with rounded corners and he has pointed out that the humeral shaft meets its requirements by being well qualified to resist pure pressure and torsion tensions. To be sure, torsional forces sufficiently powerful to fracture the shaft of the humerus are developed at times under certain conditions. Kasuya (1930), Masumura (1931) and Tochihara (1931) have described humeral fractures resulting from baseball pitching. To this cause Eliason (1925) and Scudder (1938) add the muscular exertion of hand-wrestling and Key and Conwell (1942) and Geckeler (1943) also give violent muscular action as an etiological factor in shaft fractures. However, these are extreme instances and do not represent the normal situation.

d. Absence of spiral fibers

If torsion, indeed, occurs in the humeral diaphysis, it could reasonably be expected that the finer structures of the shaft would reflect the twisting by exhibiting a spiral arrangement. If structures at the histological level were arranged parallel to the long axis of the bone when it was first laid down, a twisting of one end of the shaft with respect to the other should pull any linearly arranged structures out of line. The extent of this shifting would be proportional to the degree of torsion so that the course of the fibers would give one a clear idea of the direction and of the amount of twisting that had taken place.

i. Evidence from the literature

Campana (1874) seems to have been the first to report upon the course of the fibers in the humerus and he could find no evidence of a spiral arrangement. Botez (1926), in making a review of the literature on bone architecture, was unable to find published evidence of twisted fibers in the humerus. More recently in "Piersol's Human Anatomy" (1930) it is stated that no spiral fibers have been found in the bone.

Benninghoff (1925, 1927, 1930), using his method of producing split-lines, studied the course taken by the fiber bundles in the general lamellae of the superficial layers of the compacta and of the arrangement of osteones in the deeper layer. After the splits had been made and stained, he sectioned the bones and found that the direction of splitting is determined by the local fibrous structure, being parallel to the fiber bundles and to the osteones. After removing the superficial layers of the bone by decalcification, Benninghoff applied his method to a study of the osteones located more deeply. He concluded that, in long bones, the course of both the fiber bundles of the general lamellae and of the osteones is parallel to the long axis of the bone, with some deviations at the roughened areas where tendons are attached.

ii. Evidence from personal observation

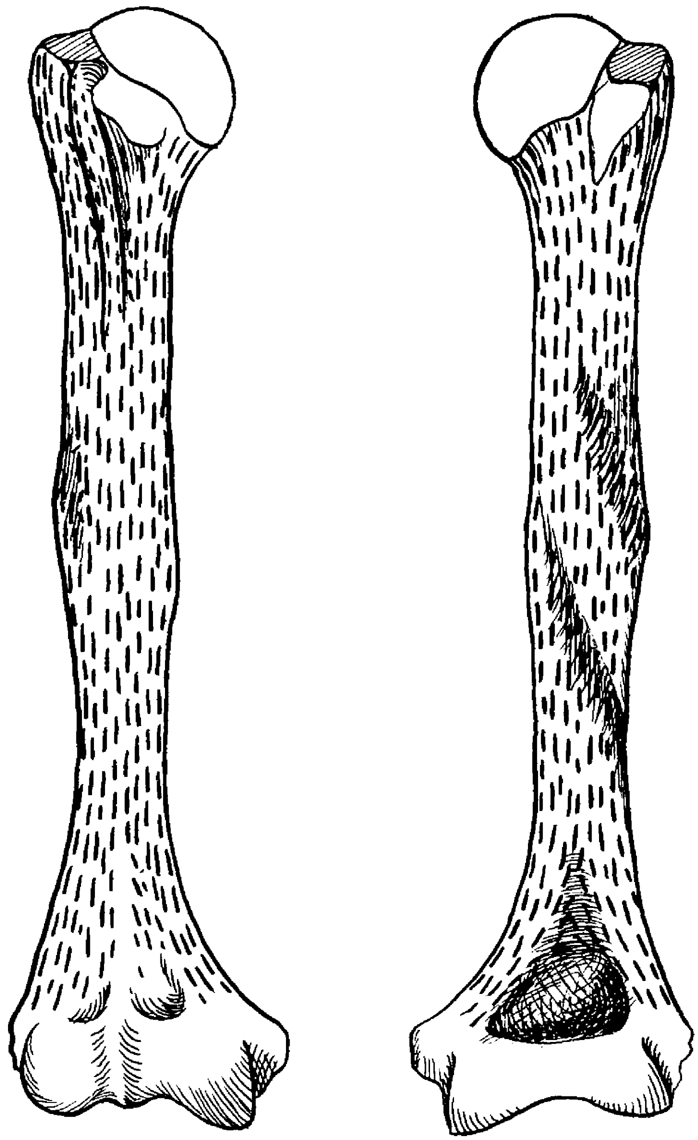
The findings of previous workers gives one a rather definite impression that the fibrous structures in the humerus do not take a spiral course. Nevertheless, the physician finds that spiral fractures of the humerus are not rare and occasionally a dried humerus is seen to crack spontaneously along an irregular line. It would be quite convenient to explain these observations on the basis of a spiral pattern of the finer structures in the bone. Therefore it was decided to reinvestigate the arrangement of the fibers in the shaft of the humerus to see whether the earlier work could be confirmed and to make more complete the evidence concerning the site of torsion.

Two methods of study were particularly practicable and demonstrative. One was the technique of making split lines to show the direction of the fibers. The other involved splitting the humeri longitudinally and observing the course taken by the cracks thus produced.

The direction of fibers as revealed by split lines in the humeral diaphysis. Benninghoff (1925) has used an ingenious method for showing microscopically the course of the finer structures in bone. A modification of this technique was found to serve the writer's needs admirably.

Several humeri were partially decalcified by treatment with a 10 percent solution of hydrochloric acid for a period of about 15 hours, then rinsed in tap water to remove the acid. Using a large sharp pin, a large number of pricks were made over the surface of the shaft at close intervals. As each prick was made, India ink was applied to the tiny split with a fine pen. The ink, running along the split, marked it permanently and clearly indicated the direction of the more superficial fibers at that particular site.

When all the split lines had been marked, the bones appeared similar to the one illustrated in Figure 4. Here a humerus, prepared in the manner described above, is shown



A B

Figure 4. A partially decalcified humerus in which split lines have been visualized by the application of India ink. A and B are ventral and dorsal views, respectively, of the same humerus.

from both the ventral and dorsal aspects. It will be observed that the splits, in general, form long parallel rows. The rectilinear arrangement is disturbed somewhat at areas where muscles have fibrous attachments to the bone, and again at the distal end where the shaft is flattened and flares out to either side. However, there is no place where the direction of the splits can be taken to indicate a spiral course of the fibers in the superficial lamellae of the bone.

The course taken by cracks made in the humeral diaphysis. Several humeri were obtained from embalmed and fresh specimens. After the bones had been thoroughly cleaned, small cuts were made through the compacta at the proximal end of the shaft by means of a small circular saw. The cuts were spaced at intervals of about 90 degrees around the shaft. By means of a small sharp chisel and mallet a crack was started at each saw cut. The extension of the cracks along the bone was facilitated by the insertion of small wedges. Cracks produced in these moist specimens proceeded rather directly along the shaft. The same procedure was attempted in dried, degreased specimens, but with little success. The brittle bone fragmented readily and satisfactory cracks could not be obtained.

In the fresh and embalmed bones, the majority of the cracks pursued a rather direct course from one end of the shaft to the other. Small deviations occurred occasionally, but on the whole the splits were straight and even. Some of the cracks were intentionally directed across the spiral groove, yet they did not deviate to follow the groove, but continued along their original courses.

There were a few instances in which the cracks took a spiral or erratic course. These, however, did not seem to follow any definite plan, but spiralled in a clockwise direction in some humeri and counter-clockwise in others.

In these investigations, neither split lines in the superficial lamellae of the bone nor cracks through the entire compacta gave any indication of a spiral arrangement of the finer structures in the bone. These observations are offered as further evidence against a diaphyseal torsion of the humerus.

It is felt that the evidence just presented seriously weakens the case for a torsion in the shaft of the humerus. The presence of a spiral groove, creating the illusion of a twisted humerus, is probably accounted for in greater part by the ability of the bony surface to react to stimuli of pressure and of tension. The characteristic contours of the humerus are not in evidence at birth, but only develop later during the vigorous muscular activity of youth. The spiral ridges flanking the spiral groove are more marked in muscular subjects. In addition, the writer was unable to demonstrate a relationship between the degrees of torsion and the angle through which the radial groove spirals in its descent along the humerus. One must conclude that the spiral groove is not a result of torsion, but represents merely the position of the Radial nerve and the attachments of muscles. The early ossification of the shaft and its subsequent growth and strengthening would represent a serious obstacle to a diaphyseal torsion, yet humeral torsion, beginning before birth and continuing long afterwards, proceeds steadily and without interruption. Further, the absence of additional torsion after maturity makes a twisting of the shaft seem unlikely. The strength and thickness of the compacta makes the humerus well suited to withstand torsional stresses. Lastly, spiral fibers in the compacta of the shaft which might reflect a previous twisting have not been demonstrated. It therefore becomes obvious that one must look to some other portion of the bone as a site of torsion.

2. Evidence for a torsion at the proximal epiphyseal line.

While there is little or no reason to seriously consider the diaphysis as the site of humeral torsion, one can draw evidence from many lines of investigation which show beyond any reasonable question that the torsion must occur in the region of the epiphyseal cartilage. Information which helps to prove the theory of a proximal epiphyseal torsion may be assembled from gross anatomical and histological findings, from clinical observations and the study of pathological conditions, as well as from experimental studies.

In assuming a torsion in the epiphyseal plate, one must first decide whether one or both of the cartilages are involved in the process. An examination of the shapes or contours of the two epiphyses where they meet the diaphysis makes it appear more likely that the proximal end of the bone is the one chiefly concerned. Obviously a rounded epiphysis could more easily twist about the long axis of the shaft without seriously altering the contour of the bone than could a flattened one. Because of the flattened nature of the distal end of the humerus, a twisting of the distal epiphysis with respect to the shaft would not be easily accomplished.

Furthermore, one would expect the epiphysis which fuses last and which shows the more active growth to be best suited as a site of torsion. Growth in length stops relatively early at the distal epiphyseal cartilage. Various estimates of the age at which epiphyseal fusion occurs have been given. A listing of the various figures would only serve to illustrate the confusion which exists on this point. Probably the most reliable data are given in the work of Todd and his associates. This information for the bones of the limbs has been compiled by Mainland (1945), mainly from Todd's figures which are based upon a large number of radiographic studies of healthy American children. According to these figures, complete fusion of the distal humeral epiphysis to the shaft takes place at about 14½ years in boys and slightly earlier in girls. Assuming an epiphyseal torsion and the continuance of torsion until about the age of 20 years, it is evident that the distal humeral epiphysis will not be involved to a very great degree in the process.

The union of the proximal epiphysis takes place much later. This is in agreement with the principle of Beclard which states that of the two extremities of a long bone, that towards which the nutrient artery is directed is the first to fuse with the diaphysis. According to Mainland's table, mentioned above, the proximal epiphysis unites at 20 years in males and about six months earlier in females. As one might expect, the greatest amount of growth occurs at that end of the bone at which the epiphysis unites last. In the case of the humerus the greatest growth in length takes place from the proximal epiphysis, and although estimates vary, its rate there may be from three to five times that at the distal end. This more active growth center should be better able to keep pace with the advance of torsion, supplying the necessary adjustments to the shifting parts.

a. Physical characteristics of the epiphyseal plate

Although the humeral shaft is ossified at birth, the epiphyses are still largely cartilaginous at this time. While the centers of ossification in the ends of the bone are developing, there remains between epiphysis and diaphysis a zone of cartilage known as the epiphyseal plate. Just before maturity the diaphyseo-epiphyseal junction is represented by a mere line, but it is considerably wider during the early years of life. This has been repeatedly stated by such workers as Cohn (1924), Eliason (1925) and Key and Conwell (1942).

It has been noted that the osseous shaft is strong, rigid and is well suited to withstand torsional forces. A close examination of cartilage, on the other hand, shows it to be a tissue having mechanical properties quite different from those of bone. The epiphyseal cartilage represents a relatively soft part of the bone until the time of fusion. Key and Conwell (1942) have pointed out that the epiphyseal cartilage is especially soft during the period of active growth. The cartilaginous disc between epiphysis and diaphysis, therefore represents a zone which is weak with regard to the resistance of torsional forces. Such forces would be expected to effect a deformation of this softer area more readily than at any osseous portion of the bone.

To find an example of the ease with which cartilage may be twisted one has merely to recall the intermittent torsions to which the costal cartilages are subjected during respiratory movements. While it is true that a long piece of cartilage such as costal cartilage can be more easily twisted than a flattened disc of the same material, the epiphyseal line in the very young individual is represented by a cartilage plate of considerable thickness.

b. Evidence deduced from the structure of the epiphyseal cartilage

In an absolute sense cartilage is less resistant to tension and pressure than bone and seems to be better qualified to withstand pressure than tension. Its ability to resist torsion is very slight as evidenced in the example of the costal cartilages. A consideration of the histological structure of hyaline cartilage helps to explain the mechanical properties of the tissue.

The fluid-filled cells of the chondrones are able to offer resistance against pressures, the elastic matrix provides the characteristic resiliency of the cartilage, while the collagen fibrils tend to take up tensile stresses, aided considerably by the surrounding perichondrium. The fibrils run in various directions and form a complicated interlacing structure, but their orientations have not been adequately mapped. In general, they appear to be arranged eccentrically about the chondrones. It is seen that the components of hyaline cartilage, while arranged to resist pressure and tension, are not able to efficiently resist torsional stresses.

Although the entire cartilage is less resistant than bone, one may perhaps further narrow the region of relative weakness to the portion of the cartilage plate which is immediately adjacent to the end of the diaphysis. Here, growth takes place in the columns of cartilage cells. Mitotic figures are prominent at the distal ends of the columns, while degenerative changes take place at the base (end towards the diaphysis) with subsequent calcification of the cartilage matrix. It appears likely that torsion might occur quite readily in such a transitional zone. There is little organized resistance against stresses and the actively multiplying cells are perhaps best qualified to bring about the necessary accommodations to a turning of the head about the shaft. Indeed, it is emphasized by Bennett and Bauer (1938) that the newly formed columns of bone at the metaphyseal end of the diaphysis mark the weakest part of a long bone.

c. Clinical evidence

There is considerable clinical evidence to support the view that the proximal epiphyseal disc of the humerus represents a relatively weak region. Clinical reports also bear out the contention that the level of greatest weakness in the cartilage is immediately adjacent to the end of the diaphysis.

Bennett and Bauer (1938) state that in the majority of fractures of the epiphyses in young children the fracture line passes through the juxta-diaphyseal zone mentioned above, rather than through the cartilaginous tissue distal to the metaphyseal end of the shaft. This transitional zone corresponds to the fourth layer of the epiphyseal disc described by Aitken (1938). He too attests to its weakness and concurs with Bennett and Bauer in finding that epiphyseal fractures are carried through this particular part of the epiphyseal disc, leaving the remainder of the plate intact. This receives further confirmation by Poland (1901) and Eliason (1925) who state that in such separations the cartilage plate is usually carried away with the epiphysis. It is of especial interest that Aitken considers this type of fracture as belonging to Type I. This type comprises those fractures which are caused by shearing or twisting forces.

Separations of the proximal humeral epiphysis are not at all infrequent. Its percentage occurrence among humeral injuries varies considerably in the reports found in the clinical literature. Mauck (1929), for example, found only three cases of epiphyseal separation among 112 fractures occurring about the upper end of the humerus, while Eliason (1925), in a study of 67 cases of humeral epiphyseal separations found nine or 13.4% of them to be located at the proximal epiphysis. Among epiphyseal fractures Aitken (1938) finds that those of the proximal humeral epiphysis rank fifth, while Poland (1901) states that they are first in order of occurrence among the single epiphyses. Undoubtedly there is more than one reason for the variations of opinion with regard to this point. It has been estimated by Hutchinson (cited by Platt, 1901) that probably 50% of the cases of this epiphyseal injury have been incorrectly diagnosed as dislocations of the shoulder. Whatever the actual percentage occurrence of this injury may be, it is certain that it occurs rather frequently and, as one might expect, separations all take place before the time of epiphyseal union.

Here again, there is considerable difference of opinion. Each author gives a slightly different age range in which he feels that proximal humeral epiphyseal separations occur. It was formerly believed that most separations occurred in infancy. To be sure, they sometimes occur as birth injuries, but if one reviews the reports of such workers as Lucid (1899), Poland (1901), Eliason (1925), Mauck (1929), Jones (1932), Roberts (1932), Howard and Eloesser (1934), Aitken (1938), Scudder (1938), Key and Conwell (1942) and Geckeler (1943), it is seen that most of the age estimates overlap in the second decade of life. Of the five patients with proximal humeral epiphyseal separations reported by Howard and Eloesser, two were 16 and the others were 14, 15 and 19 years of age.

It may be asked why epiphyseal separations occur principally in the second decade of life rather than in earlier years when the association between epiphysis and diaphysis is not as close and the cartilage plate is thicker and softer. The occurrence of such separations in infants at the time of birth has been mentioned. However, there seems to be little doubt that the majority of such separations take place at a considerably later time. The above question is rather difficult to answer, but a partial explanation, at least, may be found in the work of Howard and Eloesser (1934). They studied the positions of insertion of the Pectoralis major, Latissimus dorsi, Teres major, Teres minor and Subscapularis muscles upon the adult humerus and made a similar examination in a still-born fetus. A scale drawing of each bone was made with the muscle insertions indicated. Then, with a formula of proportions the muscle positions of the fetus were enlarged proportionately and transposed to the drawing of the adult bone. This study yielded quite interesting results. It showed strikingly the low level of the attachment of the tubercular muscles in the infant, the low level of the upper borders of the Pectoralis major, Latissimus dorsi and Teres major muscles in the infant and the relatively low level of the surgical neck of the humerus in the growing child. It was found that surgical neck fractures occur typically from the latter part of infancy until the end of the first decade and that they occur relatively lower than such fractures in the adult. They relate this to the low insertion of the muscles and to the low level of the transition between cancellous and dense cortical bone that exists in the shaft of the growing humerus. The Teres minor, Infraspinatus, Supraspinatus and the Subscapularis muscles apparently change their relative levels of attachment and come to lie at a higher level above or in the immediate vicinity of the epiphyseal line. At the same time, the Pectoralis major, Latissimus dorsi and Teres major muscles move their upper borders of insertion near to the base of the tuberosities and narrow the true surgical neck. Howard and Eloesser reason that these factors, together with the gradual proximal progress of the dense cortical bone of the shaft protect the upper shaft and place the strain in the neighborhood of the epiphyseal line so that in the second decade of life epiphyseal separations result more frequently. They feel that such slips or separations, occurring in infancy, are secondary to underlying diseases affecting this region of the bone.

The factors which produce epiphyseal separations appear to have some bearing upon the present problem. Although many separations occur as a result of direct violence, such as falls or blows upon the shoulder, a great number of them may be attributed to ligamentous stress or to forces developed in violent muscular contractions. It is of interest to note the circumstances which give rise to proximal epiphyseal separations in the humerus. Lucid (1899) and Eliason (1925) state that fractures through the epiphysis may occur as a result of strain or sudden wrenching of the arm during childbirth. The latter author also gives forcible traction on the arm upward and outward as a cause of epiphyseal separations. He cites a case wherein a nurse or mother jerks a child by the hand as it stumbles or trips. While the arm is thus held, the child's weight swings downward and the arm is rotated. Aitken (1938) finds that separations may sometimes result from indirect violence when a torsional force is produced by a fall upon the elbow or outstretched hand. One notices a basic similarity among these causative factors. Nearly all involve some type of twisting, torsional or rotational force.

Later on it will be shown that the humeral rotators are attached in such a way that when acting simultaneously, they tend to cause a rotation of the shaft with respect to the proximal epiphysis. Not only is the epiphyseal cartilage a relatively weaker part of the bone, but, as will be shown presently, a certain degree of motion is actually permitted between the epiphysis and diaphysis. Now, within the range of normal movements and of normal muscular activity the shifting of the parts is not of sufficient magnitude to disrupt the union. However, if the twisting forces transgress a certain maximum, the torsion may become so great as to result in the displacement of the shaft from the epiphysis.

The cases just cited to not represent the normal circumstances, for such tremendous forces are not often created nor do they occur with any degree of frequency. Nevertheless, it may be readily conceived that frequent stresses of this type of more moderate dimensions (developed during normal muscular activity or perhaps through ordinary muscle tonus), although too weak to produce displacement, might have a formative influence upon the growth of the bone of such a sort that new bone would be laid down in a spiral fashion.

d. Evidence from experimental work

Under abnormal conditions, at least, torsions will occur in the region of the epiphyseal line. Le Damany (1906) operated upon the hind limbs of young rabbits in such a way that the hip joint was dislocated. Metal pins were passed through the epiphyses and shaft of the femur, all in the same plane, to serve as reference points. After several months the animals were sacrificed and the relationships of the metal pins were noted. It was found that the abnormal forces exerted upon the femur due to the disruption of the normal mechanics of the hip joint had caused shiftings in the pins so that they were no longer all in the same plane. That the torsion did not take place in the shaft was shown by the fact that the reference pins in the shaft had retained their original positions. However, the relative positions of the epiphyseal pins on the one hand and the shaft pins on the other hand had shifted, indicating that a real torsion had taken place between the shaft and head of the bone. Although this torsion was produced under abnormal circumstances, the obvious inference is that when torsion occurs normally in the body, the process is similar and takes place in the epiphyseal cartilage.

e. Evidence from pathological conditions

One of the best pieces of evidence that torsion occurs at the epiphyseal cartilage is obtained from a study of the bones of rachitic and achondroplastic individuals. Le Damany (1904 b) has reported torsion angles for the humeri of such individuals. In cases of rachitic humeri, where the bone is unusually soft and vascular near the epiphyseal cartilage, he found average values of 120, 98 and 85 degrees in three pairs of humeri. However, in two achondroplastic humeri, where premature epiphyseal fusion had occurred, he found an average torsion angle of only 30 degrees. Apparently the unusual softness at or near the diaphyseo-epiphyseal junction allowed torsion to proceed beyond the normal limits, while early closure of the epiphyseal line precluded the possibility of further torsion.

f. Evidence from personal observations

The foregoing considerations of the structure and properties of cartilage and the clinical evidence of the relative instability of the diaphyseo-epiphyseal junction argue forcefully for an epiphyseal torsion. Nevertheless, it appeared highly desirable to learn more about this plate of cartilage, to determine the degree of motion permitted at the epiphyseal line and to study the factors limiting the movements. It also seemed profitable to examine closely the configuration of the adjacent surfaces of the epiphysis and diaphysis to see whether the contours were such that a turning of the epiphysis might readily occur. Through these and other observations, additional evidence in support of a torsion at the level of the proximal epiphyseal cartilage has been obtained.

1. The contribution of the periosteum to the security of the diaphyseo-epiphyseal joint and the mobility of the humeral epiphysis upon the diaphysis

Considerable emphasis has been placed, thus far, upon the relative weakness of the humerus in the region of the proximal epiphyseal cartilage, yet it must not be supposed that this joint is entirely unstable. While this cartilaginous zone is not as strong as the shaft of the bone, nevertheless, it must be able to withstand a considerable amount of shearing and torsional force from external violence and from muscular pull. In the course of this investigation it became clear that the cohesive force which aids in holding the epiphysis and diaphysis together is not in itself sufficient to prevent displacement of the epiphysis in the presence of forces which are developed about this region during normal physical activity. The diaphyseo-epiphyseal junction of the immature individual must depend in great measure for its security upon the periosteal membrane, as previously noted by Le Damany (1906) and Rouffiac (1924), for the periosteum sweeps across from the diaphysis to the epiphyseal margin and binds these two portions of the bone together rather firmly. Although, as already mentioned, the weaker epiphyseal cartilage might readily yield to torsional forces, it is not inconceivable that a strong, unyielding periosteum bridging this zone might constitute a serious impediment to the progress of torsion. The behavior of the periosteum in cases of fracture and epiphyseal separation has been described in considerable detail in books and articles on fractures by such authors as Poland (1901), Eliason (1925), Aitken (1938) and Key and Conwell (1942). The physical qualities of the periosteum and the degree of intimacy of the membrane with the bone in young and old bones was early noted by John and Charles Bell (1827) and has been emphasized subsequently by many writers. The ability of periosteum to resist tension has been studied quantitatively by Moore (1928). Yet, one is not able to decide from this abundant literature whether the periosteum renders the diaphyseo-epiphyseal junction immobile or whether, through its elasticity, the membrane may permit a slight amount of rotational movement to occur. Therefore, further information concerning the properties and relations of the periosteum, particularly in the epiphyseal region, was sought.

The humeri studied were those of the fetuses and neonati used in the study of the diaphyseal cone, to be reported presently. Unfortunately, a series of humeri, graded in age from birth to maturity, was not available for examination.

After the muscles, joint capsule et cetera had been removed and while the bones were still in the fresh condition, the security of the diaphyseo-epiphyseal joint was studied. (As stated by Mainland (1945), preserved specimens do not adequately show strength or weakness of periosteal attachments, as do fresh ones.) With the periosteum intact, an attempt was made to move the proximal epiphysis from side to side and to twist it medially and laterally. In the fetal humeri especially, there was a surprising amount of movement between the head and shaft. When the epiphysis was held in a fixed position in the Torsiometer and the shaft was rotated under it until further twisting was arrested by periosteal tension, it was found that from five to ten degrees of movement were possible. In the humeri of new-born individuals, there was somewhat less freedom of movement, but the weakness of the union was still strikingly indicated.

The next step in the procedure was to strip off the periosteum, beginning on the diaphysis and passing over to the epiphysis, in order to determine in a general way how much of the stability at the epiphyseal line was due to periosteal tension and how much was due to cohesive forces in the cartilage. In every case the membrane was found to peel off quite readily. Sometimes it could be pulled along over the bone like a sleeve without being first cut longitudinally in strips. Although the periosteum yielded readily along the shaft, considerable tension and even sharp dissection was necessary to free it from the epiphysis. Once the periosteum was removed, very little effort was required to unseat the epiphysis. Indeed, in most fetal humeri, great care had to be exercised so that the epiphysis would not be pulled away with the periosteum. The connection was slightly more secure in the new-born and circumnatal specimens which had been denuded of periosteum. When an attempt was made to twist the epiphysis or to move it from side to side, a very slight effort was sufficient to shear off the head which usually yielded with a slight pop or snap. The break was a clean one in each case and no cartilage remained on the end of the diaphysis.

It may be concluded from these observations that: (a) the proximal diaphyseo-epiphyseal junction in the humerus of the very young individual is by no means a stable one, (b) whatever stability exists in this region is due, in great part, to the presence of the investing periosteum, (c) the periosteum is, however, less firmly attached to the diaphysis than it is to the epiphyseal cartilage and to the epiphysis, and (d) separations, therefore, occurred in the humeri of infants at the level of the junction between diaphysis and epiphyseal cartilage, i.e., at the level given by Aitken (1938) and others in cases of epiphyseal separation in the living.

These observations upon the periosteum greatly reinforce other arguments which suggest that the region in which humeral torsion takes place is the diaphyseo-epiphyseal junction. Although the head is not permitted extensive movements of a rotational sort upon the shaft, the important point to be remembered is that a certain amount of motion is possible. Assuming a torsional force acting normally in the body, capable of producing this sort of movement repeatedly and predominantly in the same direction, it does not seem unreasonable to suppose that such an active growth center might be capable of responding to forces constantly acting to produce a torsion, by depositing the newly forming structural particles along the lines of this torsional force and thus give the finished organ a twisted shape. According to this notion, then, the torsion observed in the adult humerus would be the sum total of innumerable smaller torsions accompanied by continual readjustment and rearrangement of the cell columns in the actively growing layer of the epiphyseal cartilage.

ii. The diaphyseal cone

A point seldom considered in connection with humeral torsion is the manner in which the epiphysis and diaphysis are fitted together. It is obvious that a simple abutment of the approximating surfaces would not suffice to preserve the integrity of the joint in the presence of large shearing forces. Relatively powerful muscles are pulling in opposite directions above and below the proximal epiphyseal line of the humerus. In addition to torsional tensions, there must also be considerable shearing force exerted here. Steindler (1935) states that in bones, it is unlikely that torsional stresses ever occur without being accompanied by a certain amount of shearing. If the approximating surfaces of the diaphysis and epiphysis were flat and in the horizontal plane, it can be seen that opposing muscular forces might easily shear off the epiphysis, particularly in young individuals where there is a cartilage interposed. This sometimes does occur and has already been discussed, but in such cases the force involved far surpasses normal values. A more efficient arrangement might comprise two irregular surfaces which fit closely together and by interlocking offer greater stability to the joint. One can conceive of certain types of interlocking joints which, while stabilizing the union, might also inhibit or entirely prohibit a rotation of one part about the other. Therefore, the manner in which the epiphysis and diaphysis are fitted together becomes a rather important consideration in the present problem.

When the humerus of a young person is macerated so that the proximal epiphysis can be lifted off, it is seen that the configuration of the proximal end of the diaphysis and that of the adjacent surface of the cap-like epiphysis constitute a mechanical device which is admirably suited to the requirements of a region about which torsional forces are constantly playing. The line of junction of the two parts is not at all flat. The clinical literature, in particular, repeatedly emphasizes this fact. The texts and shorter articles of Lucid (1899), Platt (1901), Poland (1901), Cohn (1924), Eliason (1925), Piersol (1930), Brailsford (1934), Aitken (1938), Scudder (1938), Key and Conwell (1942) and many others describe in some detail the manner in which the epiphysis of the humerus is fitted upon the shaft. The proximal end of the shaft is raised into a conical elevation of varying height with its apex more or less centered with respect to the long axis of the bone. The corresponding surface of the epiphysis, on the other hand, is concave so that it fits like a cap on the convex end of the shaft. This "dove-tailed" arrangement therefore tends to offset shearing forces brought to bear upon the region, while offering no serious resistance to a turning of the head upon the shaft. The diaphyseal cone thus constitutes a kind of pivot on which the head may turn without being readily dislocated.

A brief examination of the proximal end of the humeral diaphysis of a young individual or of a longitudinal section through the epiphyseal region in a mature humerus should be sufficient to convince one of the presence of a diaphyseal cone. Comparing the young and old bones, one may notice that the cone in the mature bone is higher than in the younger one. This, too, has been emphasized by Eliason (1925) and Aitken (1938). But even on points seemingly so obvious and easy to observe there exists disagreement between different authors. Eliason (1925), for instance, points out that the low or flat surface of the proximal end of the humerus in younger individuals makes it difficult to maintain a reduction after an epiphyseal separation has occurred, but that in later youth the conical shape of the bone makes it easier to hold a reduction in position. This is not in agreement with Scudder's belief that reductions are more easily maintained in younger children, an opinion which rests on Scudder's observation that the diaphyseal cone is higher in early than in late childhood. Moreover, an example is not wanting which shows that even in the same book views are presented which are the very opposite of one another. For example, it is found that Aitken, writing Chapter VI of Scudder's text-book on fractures, holds the view that the diaphyseal cone becomes higher with increasing age, while Scudder himself, in Chapter XXVIII of the same book is evidently of the opposite opinion. He states that in youngsters the epiphyseal line or surface is more or less rounded or conical, while in the older child it is more nearly a horizontal plane.

In view of the mechanical role which a conical end on the diaphysis might play in the process of humeral torsion, it seemed advisable to check the statements of the workers cited above, by actual observation. By simply studying the configuration of the proximal end of the humeral diaphysis in a series of individuals covering an age range from the third month of fetal life to 20 years, it could be conclusively shown that there is a definite increase in the conical elevation with advancing age.

The material studied included 23 humeri of fetal and very young individuals. Since humeri of children and adolescents were not easily accessible to the writer, recourse was had to scale drawings and radiographs of a total of 32 humeri of individuals ranging in age from birth to 20 years. These were obtained from the works of Platt (1901), Cohn (1924), Eliason (1925), Piersol (1930), von Lanz and Wachsmuth (1935), Scudder (1938) and Moseley (1945).

The proximal epiphyseal line presents its greatest width when the humerus is viewed from its ventral aspect. The diameter at the epiphyseal line was taken to represent the base of the cone. The height of the cone was therefore the distance from this line to the highest point of the elevation. Measurements on fetal and young humeri were made with vernier calipers, while those on radiographs and drawings were made with a millimeter scale graduated in 0.5 mm. Of course there was a great variation in the size of the humeri studied and some of the radiographs and drawings of humeri in books and special articles were not presented in the natural size. Therefore, in order that all values for the height of the cones might be strictly comparable to one another, a relative term, the index of cone height was calculated. Heights of the diaphyseal cones were expressed as percentages of the base line and where there was more than one humerus for any particular age, the average value was taken. These values for the 55 humeri in this series are arranged according to the age of the individual in Table II. The relationship of the age of the individual to the height of the diaphyseal cone is shown graphically in Figure 5.

It is seen that the cone is raised rapidly at first, and in relative terms has completed over one-half of its elevation at the time of birth. During the first few years of life the height of the cone with respect to the width of the base increases more slowly and finally becomes stationary near the age of 20 years. The curve will be seen to resemble closely those which are often obtained in graphic representations of biological processes. The data were plotted without regard to race or sex of the individual or to the side from which the humerus was taken. In addition, there is a certain amount of individual variation and a small technical error involved. Considering all these factors it is perhaps surprising that the relationship comes out so clearly. The meaning of the graph is clear and certain conclusions may be drawn from it. There can be no doubt that there is a relative growth in height of the cone with respect to the line representing its base. The cone is well in evidence by the time that coordinated contractions of the humeral rotators

TABLE II

Tabulation of data concerning width of humerus at the proximal epiphyseal line, cone height, cone index, and index averages for age groups. Includes values for fresh specimens (K-#) and measurements of published radiographs and scale drawings (indicated by name of author).

Designation	Age	Width (mm.)	Height (mm.)	H/D x 100	Group Averages
K(F-10)R	12 wks.	3.0	0.	----	----
K(F-20)L	20 wks.	5.2	.8	15.4	
R	20 wks.	5.8	.8	13.8	14.6
K(F-23)R	25 wks.	7.5	1.4	18.7	18.7
K(F-1)R	34 wks.	10.1	2.6	25.7	25.7
K(F-17)L	35 wks.	11.0	2.5	22.7	19.5
R	35 wks.	10.4	1.7	16.3	
K(F-6)L	36 wks.	10.5	2.8	26.7	26.8
R	36 wks.	10.4	2.8	26.9	
K(F-3)L	38 wks.	13.0	4.1	31.5	
R	38 wks.	12.8	4.3	33.6	32.2
K(F-14)L	38 wks.	11.7	3.9	33.3	
R	38 wks.	11.5	3.5	30.4	
K(F-4)L	40 wks.	9.9	2.9	29.3	
K(F-2)L	40 wks.	11.1	3.1	27.9	
R	40 wks.	11.5	2.9	25.2	
K(F-5)L	40 wks.	13.2	4.9	37.1	
K(F-13)L	40 wks.	9.6	2.5	26.0	29.4
K(F-19)L	40 wks.	11.5	4.0	34.7	
R	40 wks.	11.1	3.8	34.2	
L. & W.[1]	40 wks.	11.5	2.5	21.7	
Moseley	40 wks.	10.0	2.5	25.0	
					BIRTH
Eliason	5 days	7.5	2.5	33.0	33.0
Cohn	7 wks.	16.0	4.5	28.1	28.1
Scudder	8 wks.	16.0	4.5	28.1	
K(F-22)L	2.5 mos.	15.4	4.3	27.9	26.5
R	2.5 mos.	15.1	3.8	25.1	
Cohn	5 mos.	18.0	6.0	33.3	33.3

[1] Lanz and Wachsmuth

TABLE II (Cont'd)

Designation	Age (Postnatal)	Width (mm.)	Height (mm.)	H/D x 100	Group Averages
Scudder	14 mos.	19.0	6.0	31.6	31.6
Moseley	15 mos.	16.5	5.5	33.3	33.3
K(F-15)L Scudder	18 mos. 18 mos.	27.4 19.5	8.4 5.5	30.7 28.2	29.5
K(F-16)L Cohn	2 yrs. 2 yrs.	19.9 19.5	7.7 8.0	38.7 41.0	39.9
Cohn Moseley	3 yrs. 3 yrs.	25.5 13.5	8.5 5.0	33.3 37.0	35.2
Scudder Eliason	4 yrs. 4 yrs.	19.0 23.5	6.5 8.5	34.2 36.2	35.2
Cohn	4 yrs.,7 mos.	28.0	11.0	39.2	39.2
Scudder Moseley	6 yrs. 6 yrs.	12.5 21.0	4.5 8.5	36.0 40.2	38.3
Scudder Cohn	7 yrs. 7 yrs.	18.5 36.0	6.5 15.0	35.1 41.7	38.4
Cohn Scudder	8 yrs. 8 yrs.	31.0 14.0	14.5 4.5	46.7 32.1	39.4
Cohn	11 yrs.,6 mos.	33.0	14.0	42.4	42.4
Platt Eliason	12 yrs. 12 yrs.	33.0 27.0	13.5 11.0	41.0 40.7	40.9
Eliason	14 yrs.	30.0	12.5	41.7	41.7
Moseley	15 yrs.	19.5	7.0	35.9	35.9
Poland	17 yrs.	27.0	10.0	37.0	37.0
Cohn	17 yrs.,6 mos.	31.0	11.0	35.5	35.5
Poland	18 yrs.	17.0	6.0	35.2	35.2
Cohn Piersol	20 yrs. 20 yrs.	26.0 28.0	10.0 12.5	38.4 44.6	41.5

Note: The values of width and height for humeri in the K series are the actual values measured. Since many of the radiographs and drawings were reduced in varying degree for publication, the values following the names of authors are only relative ones.

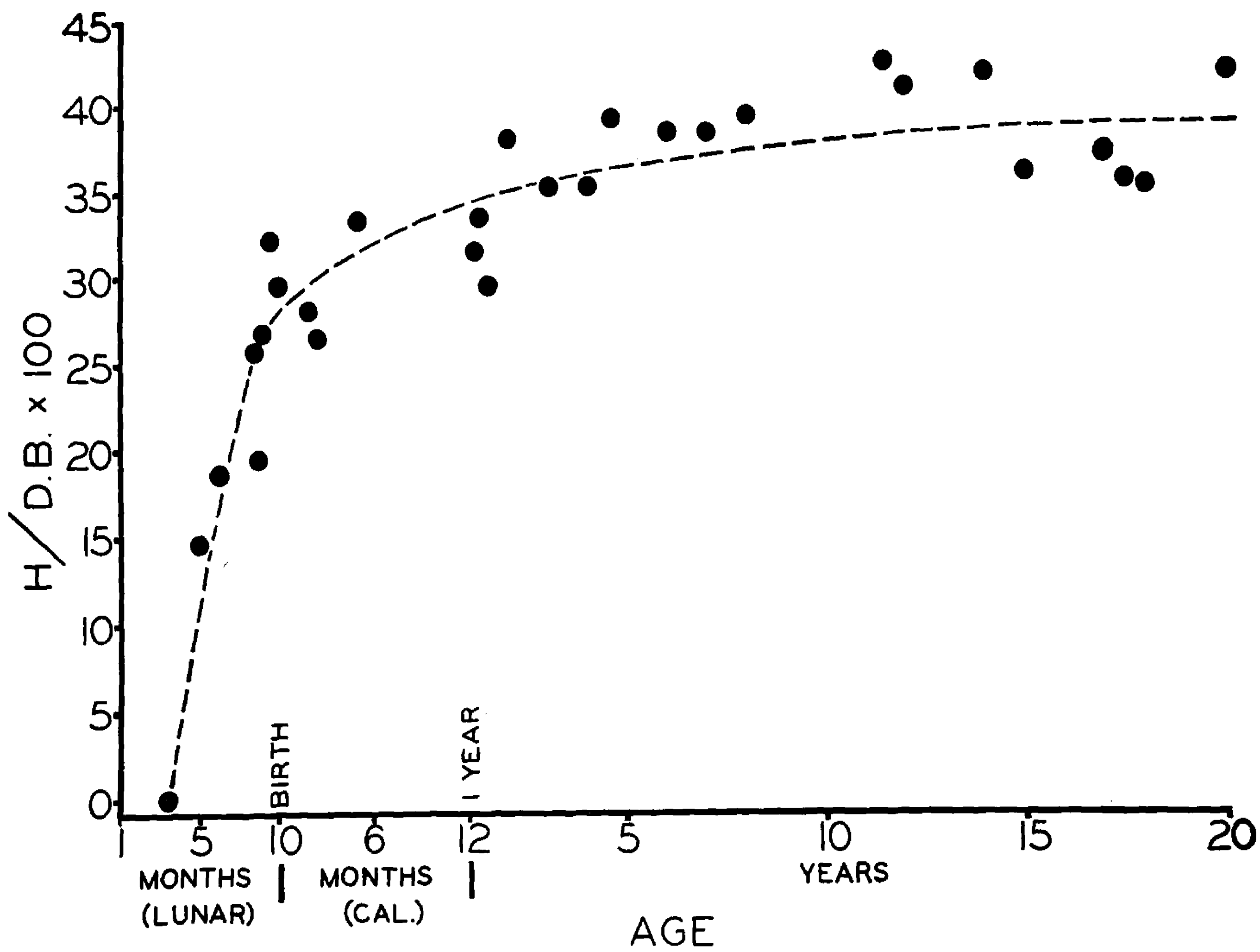


Figure 5. Graph showing the rate of growth of the diaphyseal cone at the proximal end of the humerus of man. Data obtained from a study of 55 humeri of fetal, newborn and young individuals.

occur and its growth is retarded and finally completed by the time of epiphyseal union.

iii. The coincidence of the dates of epiphyseal fusion and the cessation of torsion

Although the problem of the duration of torsion is taken up at some length in a later chapter, certain conclusions which are reached in that part of the work have a very direct bearing upon the subject now under consideration. It therefore seems expedient to anticipate this later portion somewhat and mention some of the conclusions reached therein.

If, according to the author's theory, the ability of the bone to be twisted depends upon the presence of a weaker cartilaginous part, it follows that the disappearance of such a zone should preclude the possibility of any further twisting. Evidence suggesting that this assumption is correct was presented by Krahl and Evans (1945) who found no increase in the degree of humeral torsion with age in adults (i.e., after the bone had become completely ossified). Yet, it has been conclusively shown that torsion increases steadily during the early years of life.

In order to definitely establish the time when torsion is completed it is necessary to measure the degree of torsion in a large series of humeri representing a broad range of age. Insofar as the author is aware, such a study has never been made. The results of the study described in the concluding chapter of this work show that there is close agreement between the time of epiphyseal fusion and the time at which the progress of torsion is halted. This nice correlation appears to be one of the best pieces of evidence in support of the theory of a proximal epiphyseal torsion of the humerus.

Resumé

The evidence presented in this chapter demonstrates that there is little or no foundation for the assumption of a twisting or torsion of the humeral diaphysis, while there is convincing evidence that the process is localized in the proximal epiphyseal cartilage. The spiral groove of the humerus cannot be attributed to a twisting of the shaft, but is merely the natural response of bone to pressure of a nerve whose course is a spiral one and to tension exerted by muscles. The early ossification and rigidity of the shaft and the absence of a spiral arrangement of fibers oppose a diaphyseal theory of torsion. On the other hand, the weaker disc of epiphyseal cartilage permits slight movements. These movements, though restricted by the periosteum, if frequently repeated, may induce a gradual twisting at this active growth center. The diaphyseal cone affords a pivot about which the epiphysis may turn without danger of being sheared off. Lastly, the diaphyseo-epiphyseal joint is shown to be the site of torsion through the coincidence of epiphyseal closure and the cessation of torsion.

B. The Causes of Humeral Torsion

1. The problem

The greater part of the work which has been done on the torsion problem has been of a descriptive and statistical nature. The early writers were primarily concerned with torsion as an aid in the problem of the homology of fore- and hind limbs. Also, a few theories have been offered to explain the phenomenon of torsion. With the exception of a few who showed that torsion is a progressive process during growth of the individual, most investigators have studied, rather, the shape of the bone as affected by torsion, the latter being evidenced by the crossed axes of the ends of the bone. While information of this sort is indeed desirable and necessary towards a solution of the problem, it is felt that greater emphasis must be placed upon humeral torsion as a dynamic, changing process, expressing the response of a plastic and reactive structure to mechanical forces brought to bear upon it.

The writer has arrived at the conclusion that the mechanism involved in the production of humeral torsion is represented by a number of muscles which are attached to the humerus in such a manner that when they contract, torsional forces are exerted upon the humerus. The idea that muscle action is the cause of humeral torsion is not altogether new; it has been suggested by other authors such as Le Damany (1903 b), Rouffiac (1924) and more recently by C. P. Martin (1933).

Experimental studies on the production of abnormal torsions in the limbs of animals have supplied evidence that torsion is a result of the action of muscular forces (see Appleton, 1922, 1923; Wermel, 1935; Murray, 1936). Krahl and Evans (1945) have expressed their agreement with the ideas on the cause of torsion given by Le Damany and Rouffiac, but it is felt that further evidence is urgently needed to prove this hypothesis and especially its applicability to the human humerus. The following account is an attempt to contribute such evidence, by attacking the problem from a somewhat different viewpoint and with a new method.

2. The muscular apparatus

In the light of what has been said in the previous chapters about the localization of humeral torsion and about the direction in which torsion takes place, the question arises whether there exists a muscle or a group of muscles which is capable of effecting a turning of the shaft against the epiphysis in a medial direction. It is evident that muscles which can cause such a twisting must be medial rotators and they must be attached to the shaft in a region distal to the epiphyseal cartilage. Muscles fulfilling these requirements do actually exist; they are a group of medial rotators which may be called collectively the infra-epiphyseal medial rotators and which are represented by three muscles; the Teres major Latissimus dorsi and Pectoralis major (see Figure 6, E, F, and G, and Figure 8, C).

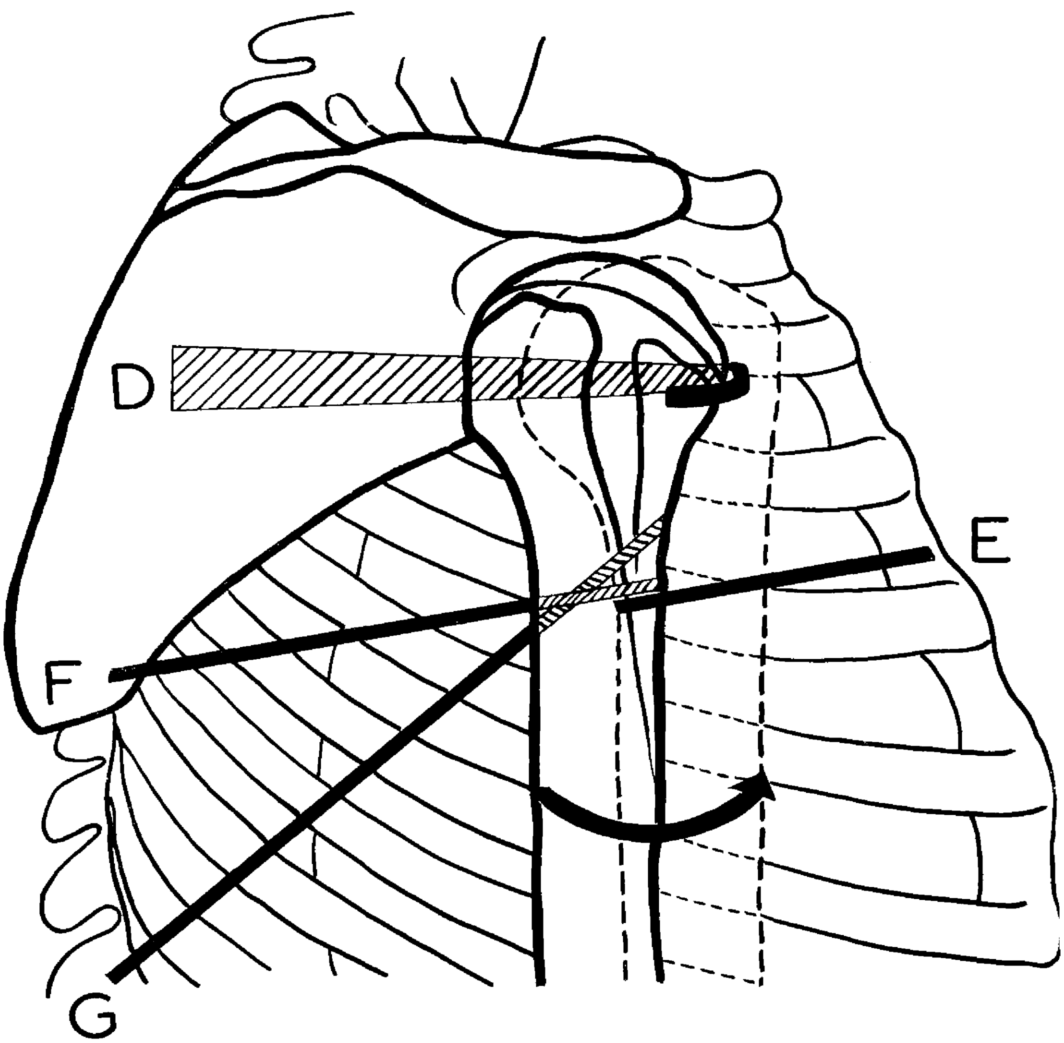


Figure 6. Diagrammatic sketch of right shoulder, seen from dorso-lateral, indicating positions of the medial rotators of the humerus. D, Subscapularis; E, Pectoralis major; F, Teres major; G, Latissimus dorsi. Humerus in solid outline shows position after 36° lateral rotation from normal; dotted humeral outline represents position after 60° medial rotation from normal. (Based upon a figure in von Lanz & Wachsmuth, 1935)

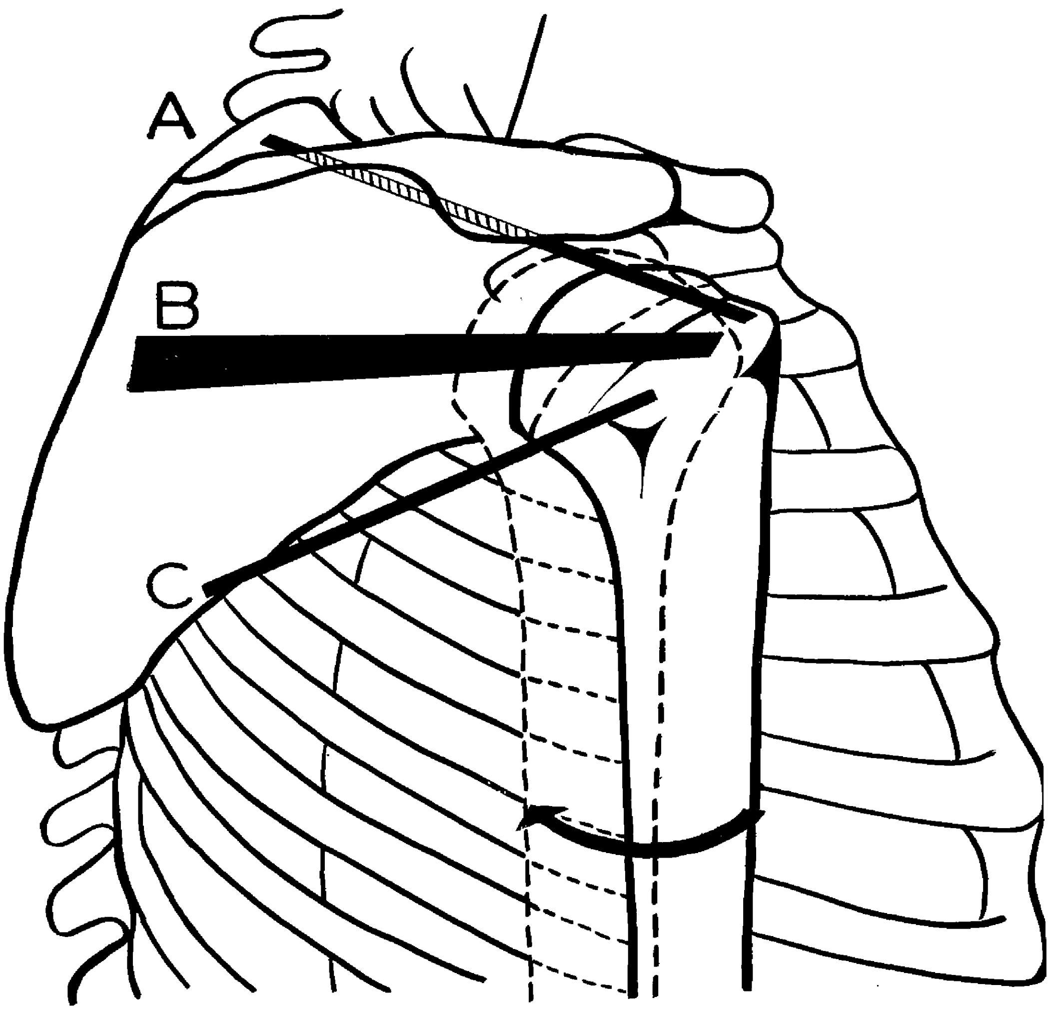


Figure 7. Diagrammatic sketch of right shoulder region, seen from dorso-lateral, with the lateral rotators of the humerus indicated by three black bands. A, Supraspinatus; B, Infraspinatus; C, Teres minor. The humerus in solid outline represents the position after 60° medial rotation from normal; dotted humeral outline represents position after 36° lateral rotation from normal. (Based upon a figure in Von Lanz and Wachsmuth, 1935)

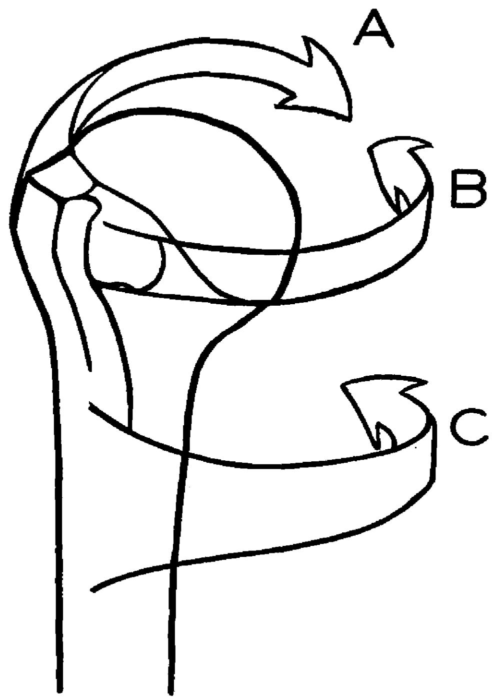


Figure 8. Diagram showing the positions of the humeral rotators and the direction of their pull. A, short lateral rotators; B, Subscapularis; C, Pectoralis major, Latissimus dorsi and Teres major.

The problem is, however, more complex than would appear at the first glance. In the first place, if medial rotation is to produce a medial turning of the humeral shaft with respect to the epiphysis, it is necessary that the medial rotatory force act against another force which tends to either rotate the proximal epiphysis laterally or at least fix it so that it cannot participate in the medial rotation. There is a group of muscles—the short lateral rotators (see Figure 7 and Figure 8, A)—all of which are inserted upon the epiphysis and might supply this required lateral rotatory force.

But it must be considered that whenever a medial rotation is willed, the lateral rotators are relaxed and that therefore in the act of willed medial rotation, there would be very little, if any, resistance to the medial rotators and therefore no occasion for creating a torsion.

Even more serious is a second consideration. It has been recognized for a long time that the chief action of the group of muscles which has been called, with special reference to this problem, the infra-epiphyseal medial rotators, is not that of medial rotation. Their main function is that of adduction in the shoulder joint, some of them (Latissimus dorsi and Teres major) acting also as extensors, the Pectoralis major acting also as a flexor. But whenever these muscles do become involved in a willed act of medial rotation, e.g., when contracting against strong resistance, they are not allowed to act alone, applying medial rotatory force only upon the shaft. There exists a special medial rotator muscle, the Subscapularis (Figure 6, D and Figure 8, B), the chief action of which is medial rotation. This muscle is attached, like the short lateral rotators, to the epiphysis of the humerus and represents the direct antagonist to the lateral rotators. The strength of the Subscapularis is approximately equal to the sum total of the strength of the three lateral rotators.[1]

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1. The average difference in cross-sectional area of the short lateral rotators and the Subscapularis in 46 shoulders was only about 1 cm^2., according to data for cadavers 1-25 in Table III under B.

This is the muscle which is chiefly engaged in a willed act of medial rotation.[2] By virtue of its insertion into the epiphysis of the humerus the Subscapularis muscle cannot be concerned in turning the shaft with respect to the epiphysis. Moreover, if the Subscapularis or supra-epiphyseal medial rotator is considered in relation to the infra-epiphyseal rotators, it is evident that these two classes of muscles represent a perfect mechanism for accomplishing a coordinated medial rotation of both head and shaft.

From these considerations it becomes evident, that in a willed act of medial rotation of the humerus there is no occasion for twisting forces to act upon the shaft of the humerus alone. If the infra-epiphyseal rotators are at all contracting in such an act, their action is accompanied by a contraction of the chief medial rotator and coordination in the medial rotation between head and shaft results.

If one wishes to find situations in which medial torsional forces are exerted upon the humerus, attention must be directed to movements other than pure medial rotation. One must consider the various arm movements in which rotation is not willed, yet in which rotational forces are set up incidental to these other movements. It is under such circumstances that the three infra-epiphyseal medial rotators become of importance in an explanation of the causes of a medial

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2. Duchenne (1867) has applied to the Subscapularis muscle the special designation: medial rotator of the humerus.

turning of the humeral shaft against its proximal epiphysis. While it is true that these muscles are primarily adductors, extensors and flexors, it is also true that whenever they pull upon the shaft in order to adduct, flex or extend the shoulder joint, they must at the same time, by reason of their insertions, exhibit a strong tendency to rotate the shaft medially. But when we intend to carry out a movement of adduction, flexion or extension, the chief medial rotator muscle, the Subscapularis, does not contract. On the contrary, if we intend to carry out a lateral rotation simultaneously with adduction, flexion or extension, the short lateral rotators may be contracted at the same time that the infra-epiphyseal rotators try to force a medial rotation. It follows that willed acts of humeral adduction, flexion or extension are accompanied by an unwilled tendency to rotate the shaft medially against the proximal epiphysis. Upon such occasions when unwilled forces tend to produce a medial rotation of the humeral shaft, they necessarily lack the coordinating assistance of the Subscapularis or are even opposed by an actual lateral rotation of the proximal humeral epiphysis. Since such acts of unwilled medial rotation of the shaft occur many times every day, it becomes evident that the Pectoralis major, Latissimus dorsi and Teres major are the muscles responsible for the medial twist of the shaft against the head of the humerus.

3. The angle of torsion and muscle strength

It is now necessary to test the assumptions made in the preceding pages. In searching for the solution of this problem, it appeared likely that a definite relationship might exist between the angle of torsion and the force which the three infra-epiphyseal medial rotator muscles are capable of exerting in trying to rotate the shaft against the epiphysis of the humerus. The more powerfully developed these three muscles are, the greater might be the angle of torsion. Since the angle of torsion can readily be measured (Krahl, 1944; Evans and Krahl, 1945; Krahl and Evans, 1945), it remained to find a proper method of measuring the strength of a muscle and expressing it numerically.

Methods of measuring the strength of muscles have been worked out by a number of authors (Arkin, 1941; Schmier, 1945; and others); different investigators have interpreted differently what constitutes muscle strength, and even where the same interpretation and method was used, the results of different authors are greatly at variance.[3] It is, however, generally conceded that the size of the area of a physiological cross-section of a muscle is the most fundamental factor in determining the force with which it can act. For the present purpose it would be sufficient to use the area of the

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3. Methods of determining the value of absolute muscle strength are discussed by such authors as O. Fischer (cited by Fick, 1910), Fick (1910), Arkin (1941) and Mainland (1945).

muscle cross-section as an adequate expression of muscle strength. In order to render the figures of the writer comparable to those published by other students of muscle mechanics, it seemed, however, convenient to make certain simple adjustments.

The force which a muscle is capable of exerting when it contracts may be expressed as tension, i.e., as the maximum load which a muscle is just able to lift. This maximum load can be experimentally measured and various methods (which will not be discussed here) have been devised to ascertain it. From the value of the tension of a muscle and the cross-sectional area of the same muscle, the muscle strength unit (Muskelkrafteinheit, Fick, 1910) can be calculated and expressed in kg. per cm^2. The value of this unit has been calculated for a variety of muscles by a large number of investigators (Weber, 1846; Knorz, 1865; Henke, 1868; Henke, cited by Mainland, 1933; Koster, cited by Henke, 1868; Koster, cited by Reys, 1915; Hermann, 1898; Johnsson (quoted by DuBois-Reymond, 1903; Fischer, 1906; Fick, 1910; Reys, 1915; Strasser, 1917; Franke, 1920; von Recklinghausen, 1920; Arkin, 1941), but hardly two of them ever arrived at the same figure. The values range between a minimum of 0.836 kg. per cm^2. and a maximum of 11.1 kg. per cm^2. Fick chose a value of 10 kg. per cm^2. since it is easily handled in calculations and he felt that, although the value seemed somewhat high, it certainly fell within the sphere of possibility. More recently, Mainland and Hiltz (1933) have also estimated muscle force upon a basis of 10 kg. per cm^2.

Knowing the physiological cross-sectional areas of the muscles in question and assuming the muscle strength unit to be 10 kg. per cm^2., the total tension or strength of the muscle equals the cross-sectional area in square centimeters, multiplied by 10. The values recorded under "Muscle tension" in the following tables have been obtained in the manner just described (Area of physiological cross-section in cm^2. x 10 kg. per cm^2. = Tension in kg.). As such, they are comparable to the values of muscle strength published by other authors. The question as to whether or not the value of 10 kg. per cm^2. is the correct figure for the muscle strength unit is irrelevant in connection with the present problem since muscle tension or strength is taken here only as a relative value.

The method of measuring the cross-sectional areas of the muscles in the embalmed cadaver has already been described in a previous chapter. It remains now to investigate the relationship between muscle strength and the angle of torsion.

4. Results

The angle of torsion of the humerus and the areas of physiological cross-sections of the three muscles (Pectoralis major, Latissimus dorsi and Teres major) which have been assumed to produce a medial torsion of the humerus, were measured in altogether 42 cadavers, making a total of 84 humeri with their respective muscles. The values of the cross-sectional areas of the individual muscles are recorded in

Table III, C-1 to C-25 under A and in Table III, C-26 to C-44.[4]

In Table IV, in the order of the specimen numbers, the values for the torsion angles are presented under A; values for the sum total of muscle tensions of the three infra-epiphyseal medial rotators (Pectoralis major, Latissimus dorsi and Teres major) for both left and right sides of each of the 42 cadavers appear under B.

In Table V, the 84 individual humeri have been arranged in the order of magnitude of the torsion angles and the total muscle tension of the three infra-epiphyseal medial rotators has been recorded for each humerus. From this table it will be immediately noticed that there exists no strictly orderly gradation in the values of muscle strength. When the values of torsion were plotted against the values of muscle strength, the graph showed such a wide scattering of the points that no very certain conclusions were possible.

In order that these data may be properly evaluated, however, several considerations must be made. In the first place, even if there existed a constant relation between torsion angle and muscle strength, of the kind stated above, the

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4. In two cases (C-1 and C-21) the left Latissimus dorsi muscles were not measured since they had been removed or damaged by students before sections could be taken. These missing values were supplied by using the value for the right Latissimus dorsi of the same specimen. It was felt that these substitutions could be made without introducing an appreciable error into the values for the totals, since the average difference in cross-sectional area of the Latissimus dorsi muscles of the remaining individuals was only 0.7 cm^2.

TABLE III

Cross-sectional Areas of Pectoralis major, Teres major
Latissimus dorsi, Supraspinatus, Infraspinatus, Teres minor and
Subscapularis muscles. Values are expressed in square centimeters

No.	A: P. maj.		A: T. maj.		A: Lat. d.		B: Suprasp.		B: Infrasp.		B: T. min.		B: Subscap.	
	R	L	R	L	R	L	R	L	R	L	R	L	R	L
C-1	5.6	4.8	9.3	5.7	4.0	---	5.1	3.7	3.3	3.6	2.8	2.2	9.1	7.5
C-2	17.3	16.2	15.9	15.0	8.4	5.9	6.9	6.8	6.9	5.4	4.7	5.0	19.4	16.5
C-3	11.5	9.4	7.0	12.3	7.5	7.4	4.6	4.5	7.1	5.9	3.2	3.4	13.4	12.7
C-4	9.9	9.3	7.0	7.1	7.7	7.9	5.0	5.6	4.9	5.2	2.6	2.3	13.9	10.2
C-5	6.1	5.2	5.8	5.4	4.9	4.9	4.5	4.4	5.3	4.8	3.0	3.3	9.2	9.0
C-6	9.1	6.7	12.7	12.5	10.6	9.7	4.3	5.4	5.1	4.6	3.7	4.1	15.1	15.5
C-7	10.6	7.9	7.2	6.6	6.4	5.4	4.9	6.4	5.6	4.8	2.3	2.3	13.6	10.4
C-8	2.5	2.3	4.3	2.5	2.1	2.7	5.2	3.0	3.9	3.0	2.0	1.6	6.4	5.9
C-9	10.3	13.4	9.6	11.8	6.5	7.4	3.2	3.7	2.9	5.8	2.5	2.0	7.7	13.3
C-10	4.0	5.7	4.6	3.9	3.8	3.0	3.3	3.5	3.3	3.8	2.4	1.4	10.9	7.5

TABLE III (Cont'd)

	A						B							
No.	P. maj.		T. maj.		Lat. d.		Suprasp.		Infrasp.		T. min.		Subscap.	
	R	L	R	L	R	L	R	L	R	L	R	L	R	L
C-11	6.1	5.6	6.6	4.9	5.0	4.2	3.9	2.3	4.5	3.7	2.9	2.3	9.7	7.7
C-12	5.2	6.5	14.4	12.1	8.7	9.3	4.2	4.2	6.2	5.4	3.7	3.5	10.8	13.3
C-14	8.5	8.7	6.8	11.7	6.7	6.8	5.0	6.2	4.4	5.4	2.8	2.0	12.0	8.3
C-15	6.9	7.7	7.0	4.2	4.1	4.2	3.4	2.0	3.3	3.8	2.3	1.5	6.7	5.9
C-16	1.4	2.5	3.5	6.0	3.3	2.5	1.8	1.4	2.1	2.2	.9	.8	5.0	6.3
C-17	4.9	5.2	5.7	5.3	4.4	4.1	3.4	3.1	5.0	3.8	1.7	2.2	10.9	10.0
C-18	4.6	4.1	4.2	3.4	5.3	6.1	3.4	4.8	6.3	4.9	1.8	2.0	8.3	10.5
C-19	5.9	3.1	7.5	7.3	3.3	3.4	2.8	3.0	3.5	3.7	1.6	2.1	10.1	10.2
C-20	5.6	6.4	5.1	4.2	4.6	3.9	3.9	3.9	5.4	4.5	1.7	1.5	10.7	11.0
C-21	9.2	11.6	8.7	7.3	6.6	---	3.1	3.7	5.8	3.9	1.9	1.7	9.2	6.9
C-22	8.1	3.7	6.0	5.1	6.1	5.0	4.1	3.5	3.5	3.7	3.8	1.8	8.6	10.4
C-24	5.9	5.6	7.4	7.6	5.1	6.1	4.7	4.8	4.1	5.1	1.8	1.3	10.5	11.3
C-25	7.7	6.9	5.0	5.8	6.0	4.9	4.7	3.6	3.4	3.8	1.9	1.9	9.9	10.8

TABLE III (Cont'd)

Cross-sectional Areas of Pectoralis major, Teres major and Latissimus dorsi

No.	Pectoralis major		Teres major		Latissimus dorsi	
	R	L	R	L	R	L
C-26	5.7	5.1	3.9	4.6	3.0	3.9
C-27	5.7	4.0	4.4	5.7	3.7	3.6
C-28	12.6	9.2	9.3	6.3	7.7	5.8
C-29	4.6	5.5	7.4	7.4	3.0	3.8
C-30	9.0	9.6	8.2	7.6	7.8	8.5
C-31	4.3	3.4	3.5	3.2	4.2	4.2
C-32	6.3	7.2	7.9	4.2	5.3	5.7
C-33	3.7	4.4	2.5	3.2	2.9	3.0
C-34	7.3	5.4	7.7	8.3	6.2	4.6
C-35	9.8	6.9	6.4	8.5	6.5	6.3

TABLE III (Cont'd)

No.	Pectoralis major		Teres major		Latissimus dorsi	
	R	L	R	L	R	L
C-36	3.2	2.7	5.2	3.8	3.0	3.0
C-37	12.1	10.7	6.5	8.6	6.8	7.4
C-38	2.0	1.7	1.5	1.4	1.1	0.9
C-39	7.1	6.3	7.3	7.7	5.3	5.2
C-40	3.7	3.2	3.9	3.2	3.1	3.0
C-41	7.1	7.4	7.7	6.2	4.6	4.0
C-42	5.6	4.3	5.2	4.4	3.0	3.1
C-43	6.7	6.2	2.9	4.2	5.3	5.6
C-44	7.1	9.0	7.5	7.2	5.5	8.4

TABLE IV

Humeral torsion and muscle tension data

No.	A Torsion Angle		B Muscle Tension (Kg.)*	
	Right	Left	Right	Left
C-1	89	58	189	145
C-2	85	85	416	371
C-3	80	83	260	291
C-4	61	67	241	243
C-5	66	65	168	155
C-6	85	73	324	289
C-7	71	78	242	199
C-8	79	86	89	75
C-9	65	82	264	326
C-10	65	74	124	126
C-11	69	71	177	147
C-12	84	82	283	279
C-14	84	80	220	272
C-15	77	77	180	161
C-16	80	84	82	110
C-17	83	82	150	146
C-18	78	88	141	136
C-19	57	66	167	138
C-20	83	80	153	145

*Tension values represent total of Pectoralis major, Teres major and Latissimus dorsi, expressed in kilograms. (Tension = Physiological cross-sectional area x 10 Kg./cm^2.)

TABLE IV (Cont'd)

No.	A Torsion Angle		B Muscle Tension (Kg.)	
	Right	Left	Right	Left
C-21	79	79	245	255
C-22	70	78	202	138
C-24	71	76	184	193
C-25	84	83	187	176
C-26	75	82	126	136
C-27	75	75	138	133
C-28	73	86	296	213
C-29	72	79	150	167
C-30	73	67	250	257
C-31	61	73	120	108
C-32	80	87	195	208
C-33	73	84	91	106
C-34	77	67	212	183
C-35	81	76	227	216
C-36	78	79	114	95
C-37	72	75	254	197
C-38	86	86	46	40
C-39	60	73	197	192
C-40	82	82	107	94
C-41	74	87	194	176
C-42	84	84	138	118
C-43	74	73	149	160
C-44	72	74	201	246

TABLE V

Humeral torsion and muscle tension data for each humerus and set of muscles, arranged according to degree of torsion

Number and Side	Race	Sex	Age	Torsion Angle	Muscle Tension (Kilograms)
C-19 R	N	M	78	57	167
C-1 L	N	M	56	58	145
C-39 R	N	M	30	60	197
C-4 R	N	M	48	61	246
C-31 R	W	M	60	61	120
C-10 R	W	M	83	65	124
C-5 L	N	M	48	65	155
C-9 R	N	M	56	65	264
C-19 L	N	M	78	66	138
C-5 R	N	M	48	66	168
C-4 L	N	M	48	67	243
C-30 L	N	M	72	67	257
C-34 L	N	M	51	67	183
C-11 R	N	M	60	69	177
C-22 R	W	M	62	70	202
C-11 L	N	M	60	71	147
C-24 R	W	M	42	71	184
C-7 R	N	M	40	71	242
C-29 R	N	M	47	72	150

TABLE V (Cont'd)

Number and Side	Race	Sex	Age	Torsion Angle	Muscle Tension (Kilograms)
C-37 R	N	M	79	72	254
C-44 R	W	M	72	72	201
C-6 L	W	M	70	73	289
C-30 R	N	M	72	73	250
C-28 R	N	M	37	73	296
C-33 R	W	F	37	73	91
C-31 L	W	M	60	73	108
C-39 L	N	M	30	73	192
C-43 L	N	M	46	73	160
C-10 L	W	M	83	74	126
C-41 R	N	M	36	74	194
C-43 R	N	M	46	74	149
C-44 L	W	M	72	74	246
C-26 R	W	M	69	75	126
C-27 R	N	M	45	75	138
C-27 L	N	M	45	75	133
C-37 L	N	M	79	75	197
C-24 L	W	M	42	76	193
C-35 L	W	M	65	76	216
C-34 R	N	M	51	77	212
C-15 L	W	M	76	77	161
C-15 R	W	M	76	77	180

TABLE V (Cont'd)

Number and Side	Race	Sex	Age	Torsion Angle	Muscle Tension (Kilograms)
C-36 R	N	M	53	78	114
C-22 L	W	M	62	78	138
C-18 R	N	M	38	78	141
C-7 L	N	M	40	78	199
C-29 L	N	M	47	79	167
C-36 L	N	M	53	79	95
C-21 R	N	M	60	79	245
C-21 L	N	M	60	79	255
C-8 R	W	M	60	79	89
C-32 R	N	M	60	80	195
C-16 R	W	M	61	80	82
C-3 R	N	F	32	80	260
C-14 L	N	M	82	80	272
C-20 L	N	M	70	80	145
C-35 R	W	M	65	81	227
C-17 L	N	F	68	82	146
C-9 L	N	M	56	82	326
C-12 L	N	M	67	82	279
C-40 R	W	M	51	82	107
C-40 L	W	M	51	82	94
C-26 L	W	M	69	82	136
C-17 R	N	F	68	83	150

TABLE V (Cont'd)

Number and Side	Race	Sex	Age	Torsion Angle	Muscle Tension (Kilograms)
C-20 R	N	M	70	83	153
C-3 L	N	F	32	83	291
C-25 L	W	M	85	83	176
C-12 R	N	M	67	84	283
C-33 L	W	F	37	84	106
C-42 R	W	M	46	84	138
C-42 L	W	M	46	84	118
C-16 L	W	M	61	84	110
C-25 R	W	M	85	84	187
C-14 R	N	M	82	84	220
C-2 R	N	M	59	85	416
C-2 L	N	M	59	85	371
C-6 R	W	M	70	85	324
C-8 L	W	M	60	86	75
C-38 R	N	F	45	86	46
C-38 L	N	F	45	86	40
C-28 L	N	M	37	86	213
C-32 L	N	M	60	87	208
C-41 L	N	M	36	87	176
C-18 L	N	M	38	88	136
C-1 R	N	M	56	89	189

chance of it becoming visible in Table V would be a slight one. The material from which the values recorded in Table V were taken, is entirely lacking in uniformity and individual cases are not strictly comparable with one another. There is, however, one major requirement in making such a study a real source of information. When it is desired to study the effect of muscle strength upon humeral torsion, one should know, for best results, the state of the muscles, which existed during the period of active torsion. As will be shown in the next chapter, torsion stops at about the age of 19 years. For optimum results our material should, therefore, consist of subjects not much older than 19 years. But it so happens that material of this kind is very scarce in an anatomical department and is usually not at all available. With this thought in mind, it is advisable to separate the material into at least two groups; one of which comes closer to an optimal condition and a second one which is of no use and must be eliminated. This second group consists of subjects whose muscles cannot be expected to give even approximately correct information about the state of the muscles which prevailed at the time when torsion was taking place. In this category are included all subjects who died at an advanced age when the muscles had become atrophic partly from disuse (Chor and Dolkart, 1936; Solandt, 1942) and partly from the normal effects of old age, and furthermore, such subjects who died from wasting diseases of long duration. Consequently, all data were eliminated which were taken from individuals 65 years of age or over (cadavers: 6, 10, 12, 14, 15, 17, 19, 20, 25, 26, 30, 35, 37 and 44; total: 14). Likewise, data of those who died of Tuberculosis (cadavers: 7, 8, 16, 18, 27, 28, 29, 36, 39, 40, 41, 42 and 43; total: 13) or other wasting diseases (cadavers: 33 and 38) were eliminated.[5] In addition, one humerus (cadaver 1, right) was taken out since it had been fractured and had healed with an artificial medial twist of the distal fragment.

The elimination of these 59 humeri and muscle groups markedly reduces the amount of data, but one is thereby assured of greater reliability of the remaining values. The torsion angles of the remaining 25 humeri and the corresponding values of muscle strength (total tension in kg.) of the infra-epiphyseal medial rotators are recorded in Table VI and in graphic form in Figure 9. Although even this selected material is still lacking in uniformity, such differences as do exist between the individual cases were not able to veil the actual relationship between muscle tension and humeral torsion. Figure 9 shows that the lowest values of muscle tension correspond to the smallest torsion angles, while the highest values of muscle tension are found in the individuals who have the largest torsion angles.

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5. The degree of emaciation of such subjects may be readily visualized from height and weight measurements. The thirteen victims of Tuberculosis averaged 5 ft., 9 in. in height and only 97 lbs. in weight, while similar averages for the 14 aged subjects (65 years or over) were 5 ft., 7 in. and 116 lbs.

TABLE VI

Values of humeral torsion and muscle tension after elimination of unsuitable cases

Number & Side	Race	Sex	Age	T. Angle	Tension (Kg.)
C-1 L	N	M	56	58	145
C-31 R	W	M	60	61	120
C-4 R	N	M	48	61	246
C-9 R	N	M	56	65	264
C-5 L	N	M	48	65	155
C-5 R	N	M	48	66	168
C-34 L	N	M	51	67	183
C-4 L	N	M	48	67	243
C-11 R	N	M	60	69	177
C-22 R	N	M	62	70	202
C-11 L	N	M	60	71	147
C-24 R	W	M	42	71	184
C-31 L	W	M	60	73	108

TABLE VI (Cont'd)

Number & Side	Race	Sex	Age	T. Angle	Tension (Kg.)
C-24 L	W	M	42	76	193
C-34 R	N	M	51	77	212
C-22 L	W	M	62	78	138
C-21 R	N	M	60	79	245
C-21 L	N	M	60	79	255
C-32 R	N	M	60	80	195
C-3 R	N	F	32	80	260
C-9 L	N	M	56	82	326
C-3 L	N	F	32	83	291
C-2 L	N	M	59	85	371
C-2 R	N	M	59	85	416
C-32 L	N	M	60	87	208

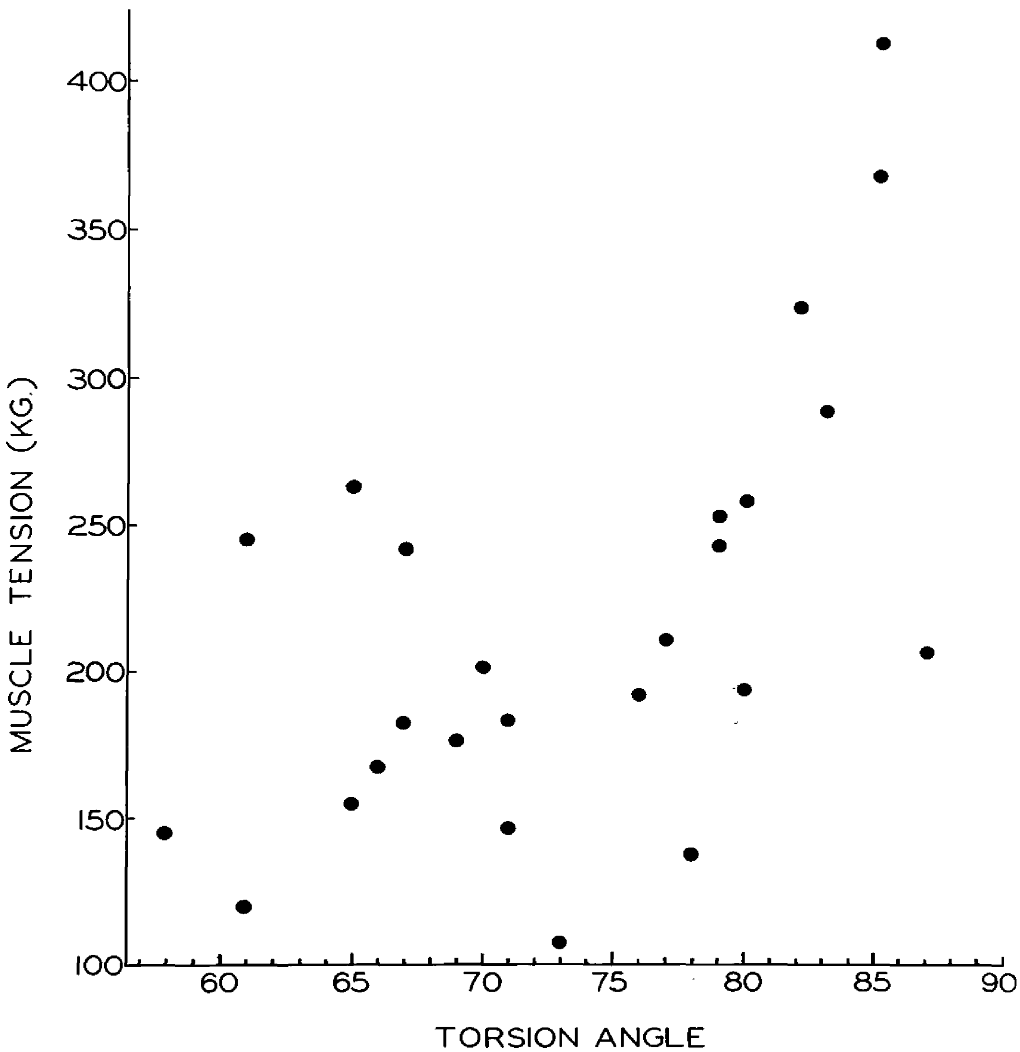

Figure 9. Graphic presentation of the data in Table VI, to show the relationship between the degree of humeral torsion and values for the tension of certain humeral rotators.

These observations show that the relationship existing between torsion and muscle strength not only does not conflict with the assumed causation of humeral torsion by the rotational forces of Pectoralis major, Latissimus dorsi and Teres major, but on the contrary furnishes strong evidence in favor of it. The movements during which the twisting force acts upon the shaft are those of willed adduction, flexion and extension of the shoulder joint, performed by the three muscles just mentioned. During such movements, each one of these muscles has a tendency to rotate the shaft against the will of the individual and therefore against the proximal epiphysis which is held in place by the contraction of the short lateral rotators.

C. The Duration of the Torsion Process

Although the problem of humeral torsion has stimulated considerable interest and has been investigated by a large number of individuals, little has been written concerning the duration of the torsion process. Since a study of the duration of torsion seemed likely to shed light upon the problem of the site and cause of torsion, a consideration of this aspect of torsion has been undertaken.

Broca (1881) and Rouffiac (1924) have made brief mention of the matter. Broca's data indicate that torsion ceases in adolescence, while Rouffiac feels that it continues until the age of 22 years. Some, as already mentioned, have studied humeral torsion in fetuses and new-born individuals; others in young children and adolescents, while yet others have centered their interest upon torsion in the adult. Gegenbaur (1868, 1898, 1910) and several other later workers have shown that torsion increases with age in young individuals and have thus proven the reality of torsion. Recently, Krahl and Evans (1945) have reported that torsion is no longer in progress in the adult. However, a complete survey of humeral torsion, from its early beginning to its culmination at some later time has not yet been undertaken.

In assuming opposing muscular forces as the mechanism which produces torsion, one must go back to the time in the history of the individual when these forces are first exerted. One must likewise follow the progress of development and growth to determine whether or not an event occurs which might render these forces ineffective and thereby bring the process of torsion to a close.

1. The initiation of the torsion process

Presumably, the process of torsion may begin as soon as the humerus is established and its rotator muscles become functional. The works of Bardeen and Lewis (1901) and Lewis (1902) on the development of the arm have shown that in a human embryo of about 7 weeks there is considerable muscular development. Every muscle found in the adult arm can be recognized at this stage and each contains muscle fibers. The cartilaginous humerus has the adult shape, but is somewhat thicker in proportion to its length. At this stage the distribution of the motor and sensory nerves from the brachial plexus is similar to that found in the adult.

Although it is essential to know when the structures involved in the production of torsion are first present, it is more important in this study to know when they take up an active role. Hooker (1942) has emphasized that the development of the functional capacity of an individual organ or system tends to lag behind the morphological development of that organ or system.

The expectant mother first perceives the vague shiftings and twitches of the fetus during the fourth month of pregnancy, but it is certain that fetal movements have their origin much earlier.

Information concerning early muscular contraction was obtained by consulting some of the more important works on fetal activity. Windle and Fitzgerald (1937) and Fitzgerald and Windle (1942) state that the human nervous and muscular systems have reached degrees of maturity compatable with function prior to the eighth week of intra-uterine life. By stimulating an embryo of 8 weeks, they elicited quick movements of the limbs and trunk. In a series of articles reporting careful observation on a large number of human fetuses of various ages, Hooker (1936, 1939, 1942, 1944) has described early fetal reflex activities elicited by controlled tactile stimuli as well as spontaneous fetal movements. Shortly after

8 weeks menstrual age he secured fetal responses to tactile stimulation. These responses consisted of trunk and neck flexures accompanied by extension of both arms. At $9\frac{1}{2}$ weeks the responses were more marked, but were of the same type. In fetuses of about $11\frac{1}{2}$ weeks developmental age, in addition to more complicated head and body responses, unilateral stimulation also brought about arm movements of a new character. The arms were slightly rotated outward, then sharply inward so that the half-flexed forearms were at first separated, then approximated as if to clap the hands. At about this stage, spontaneous movements were observed. Although spontaneous movements occurred later than those elicited by stimulation, they were similar in nature.[6]

These observations disclose the time at which coordinated movements of the humeral rotators may first be seen. On the basis of studies of human fetal behavior, therefore, it seems likely that the muscular forces responsible for the production of humeral torsion, however feeble, may initiate the twisting

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6. The above observations were made immediately after delivery of the fetus, however one may assume that the fetus was already approaching a hypoxic state at the time when the responses were elicited. The observations of Fitzgerald et al. (reported by Windle and Becker, 1940) of fetuses, prior to removal from the uterus, give evidence that the liveliness and high degree of individuality of fetal movements in utero, are markedly reduced with the interruption of the placental circulation; movements are more sustained and tonic and require stronger stimuli. It may be that muscular contractions of the type which is assumed to produce torsion could be seen, under ideal conditions, at an age slightly earlier than $11\frac{1}{2}$ weeks.

process as early in life as the eleventh fetal week.

2. The determination of the duration and time of completion of the torsion process

In order to study the progress of torsion throughout the development and growth of the individual, one needs to know the humeral torsion angles of a large number of individuals of known age. The series should extend over a wide span of years.

One might expect that if all the torsion values for various ages were collected from the literature and combined, one could arrange the values according to age and follow the progress of torsion in a graphic presentation of the data. However, when one attempts to do this, several difficulties are encountered.

It will be recalled that the same method of expressing humeral torsion was not employed by all investigators. Gegenbaur sometimes recorded torsion angles as complementary (obtuse) angles and sometimes as supplementary (acute) angles. Le Damany measured the obtuse angle and subtracted 90 degrees therefrom, while Broca gave all values as complementary or obtuse angles. Consequently, if one were to compile and tabulate the values of these workers it would be necessary to first convert all values in such a way that those of one author would be comparable with values reported by the others.

Furthermore, there has been no uniform method of measuring torsion and various lines of reference at the distal end of the humerus have been used by the several authors. This has led to considerable confusion. For example, while Le Damany used the articular axis of the elbow joint as a reference line, Gegenbaur used the bicondylar line and Broca, the so-called transverse line, which is a line parallel to the articular axis. Broca has calculated that values for torsion angles obtained by the use of the bicondylar line are six degrees greater than those determined with the articular axis. Therefore, further adjustments would have to be made in order to make values of various authors comparable.

Even after these adjustments have been made, there is considerable difference between the values given by different authors for a particular age. The explanation for this is not easily found. Perhaps the great variability of the material together with inadequate samples would account for the discrepancies in some cases. That there are significant racial and national differences in humeral torsion has been shown by Broca, in particular. It is not unreasonable to assume that the osteological material studied by a German author would be predominantly of German origin, while that studied by French workers would be mainly from French individuals. If this assumption be valid, an additional source of discrepancy is introduced.

Although Broca was a reputable anthropologist and apparently a careful and critical worker, the portion of his work containing tabulations of the torsion values which he observed was published posthumously. Conclusions from Broca's data were drawn by Manouvrier, and while only one serious error or misstatement has been noticed in the latter's report, one is prompted to be cautious in accepting all the data and conclusions as being absolutely correct.

In view of the differences in technique, lines of reference, disparity of values et cetera of the various authors, it was decided to assemble a set of data from personal observations for the purpose of studying the relationship of the torsion angle and the age of the individual.

Consequently, the torsion angles were measured in a series of humeri of fetal, new-born, young and adult individuals of known age. These figures were supplemented by a series of values published by Krahl and Evans (1945), obtained in the same manner and with the same instrument used in the present work. The entire series comprises a total of 374 humeri, of which 21 are of fetuses and neonati, 40 cover the range from birth through the age of 24 years and 313 are humeri of individuals from 25 to 91 years of age. The fetal and neonatal humeri are from the group mentioned previously under the discussions of the diaphyseal cone and periosteum; 190 are from the series of Krahl and Evans, while the remaining humeri are from the research and loan osteological collections of the Department of Gross Anatomy of the School of Medicine, University of Maryland. The torsion values for all humeri are tabulated according to ascending order of age in Table VII.

A graphic representation of the values recorded in Table VII is to be found in Figure 10. In this graph, values of

TABLE VII

Tabulation of humeral torsion angles, arranged according to age of individual. Included are torsion values for fetuses, neonati, children and adults.

Source*	Age (wks.) (Prenatal)	Torsion Angle R	Torsion Angle L	Average (R + L)	Age Average	Class Average
K(F-20)	20	42	--	42.0	42.0	42.0
K(F-21)	22 - 24	37	57	47.0	47.0	47.0
K(F-1)	34	46	61	53.5	53.5	55.5
K(F-17)	35	52	63	57.5	57.5	
K(F-6)	36	54	55	54.5	54.5	
K(F-3)	38	59	65	62.0	61.8	59.3
K(F-14)	38	66	57	61.5		
K(F-2)	40	80	72	76.0		
K(F-4)	40	49	56	52.5		
K(F-5)	40	--	55	55.0	65.0	65.0
K(F-13)	40	--	77	77.0		
K(F-19)	40	66	63	64.5		

*K(F-#) indicates personal observations on fetal and newborn individuals; K(#), K(A-#) or K(B.L.#), data on material in the research and loan collections of the Department of Gross Anatomy; K. & E., data from Krahl and Evans, 1945; K(C-#), data from cadavers used in a previous portion of this work.

TABLE VII (Cont'd)

Source	Age (Postnatal)	Torsion Angle R	Torsion Angle L	Average (R + L)	Age Average	Class Average
K(F-22)	2½ mos.	72	68	70.0	70.0	70.0
K(1043)	18 mos.	61	61	61.0	61.0	61.0
K(A-6)	4 yrs.	62	60	61.0	61.0	61.0
K(1346)	7 yrs.	55	70	62.5	62.5	62.5
K(85)	18 yrs.	76	88	82.0	82.0	82.0
K(A-8)	19 yrs.	76	70	73.0		
K(A-1)	19 yrs.	60	76	68.0	69.7	69.7
K(465)	19 yrs.	70	66	68.0		
K(192)	20 yrs.	81	80	80.5	73.5	73.5
K(A-13)	20 yrs.	63	70	66.5		
K(116)	21 yrs.	69	78	73.5	73.5	73.5
K.&E.	22 yrs.	79	80	79.5		
K.&E.	22 yrs.	74	66	70.0	74.9	74.9
K(975)	22 yrs.	79	83	80.5		
K(78)	22 yrs.	65	74	69.5		
K.&E.	23 yrs.	72	62	67.0		
K(A-2)	23 yrs.	83	84	83.5	75.0	75.0
K(357)	23 yrs.	67	76	71.5		
K(401)	23 yrs.	73	83	78.0		

TABLE VII (Cont'd)

Source	Age (Years)	Torsion Angle		Average (R + L)	Age Average	Class Average
		R	L			
K(A-14)	24	79	78	78.5	76.3	76.3
K(A-24)	24	70	78	74.0		
K(A-9)	25	67	69	68.0	68.8	(25 - 29) 71.9
K.&E.	25	74	77	75.5		
K.&E.	25	59	51	55.0		
K.&E.	25	77	70	73.5		
K.&E.	25	74	70	72.0		
K(A-23)	26	71	77	74.0	74.0	
K(A-11)	27	75	74	74.5	79.0	
K(341)	27	80	87	83.5		
K(A-4)	28	64	63	63.5	75.5	
K(15)	28	88	87	87.5		
K.&E.	29	66	68	67.0	70.0	
K.&E.	29	70	67	68.5		
K.&E.	29	78	80	79.0		
K(201)	29	75	56	65.5		
K.&E.	32	80	79	79.5	75.8	(30 - 34) 74.4
K(C-3)	32	80	83	81.5		
K(A-21)	32	64	69	66.5		
K.&E.	33	77	64	70.5	71.8	
K.&E.	33	78	68	73.0		

TABLE VII (Cont'd)

Source	Age (Years)	Torsion Angle		Average (R + L)	Age Average	Class Average
		R	L			
K.&E.	34	86	78	82.0	75.0	(30 - 34)* 74.4
K.&E.	34	76	60	68.0		
K(507)	35	60	70	65.0		
K.&E.	35	87	88	87.5		
K.&E.	35	86	83	84.5		
K.&E.	35	82	76	79.0	79.1	
K(H-7)	35	77	74	75.5		
K(742)	35	82	81	81.5		
K(16)	35	81	81	81.0		
K.&E.	36	80	83	81.5		
K(47)	36	73	78	75.5	73.2	
K(132)	36	57	68	62.5		
K.&E.	37	73	77	75.0		
K.&E.	37	75	87	81.0	72.2	(35 - 39) 76.9
K.&E.	37	61	60	60.5		
K.&E.	38	82	78	80.0		
K.&E.	38	83	71	77.0		
K(C-18)	38	78	88	83.0		
K(487)	38	84	83	83.5	78.2	
K(A-3)	38	79	81	80.0		
K(A-12)	38	78	76	77.0		
K(226)	38	71	64	67.5		
K.&E.	39	80	77	78.5	78.5	

*Continued from preceding page.

TABLE VII (Cont'd)

Source	Age (Years)	Torsion Angle		Average (R + L)	Age Average	Class Average
		R	L			
K.&E.	40	80	75	77.5		
K.&E.	40	67	53	60.0		
K.&E.	40	59	57	58.0		
K.&E.	40	68	65	66.5		
K.&E.	40	79	73	76.0	70.5	
K.&E.	40	65	67	66.0		
K.&E.	40	81	75	78.0		
K.&E.	40	84	72	78.0		
K(C-7)	40	71	78	74.5		
K.&E.	41	66	56	61.0		
K.&E.	41	76	59	67.5	68.3	
K(275)	41	81	72	76.5		
K.&E.	42	86	79	82.5		(40 - 44) 70.7
K.&E.	42	73	74	73.5		
K.&E.	42	69	55	62.0		
K.&E.	42	68	68	68.0	70.0	
K.&E.	42	62	56	59.0		
K(C-24)	42	71	76	73.5		
K(217)	42	67	76	71.5		
K.&E.	43	80	73	76.5	77.3	
K.&E.	43	81	75	78.0		

TABLE VII (Cont'd)

Source	Age (Years)	Torsion Angle R	Torsion Angle L	Average (R + L)	Age Average	Class Average
K(168)	45	64	73	68.5		
K.&E.	45	76	75	75.5		
K(137)	45	72	71	71.5		
K(459)	45	76	87	81.5	70.3	
K(83)	45	59	63	61.0		
K(177)	45	56	71	63.5		
K(433)	45	71	70	70.5		(45 - 49) 71.8
K.&E.	48	79	82	80.5		
K.&E.	48	80	87	83.5		
K.&E.	48	82	82	82.0		
K.&E.	48	70	63	66.5	73.7	
K(C-4)	48	61	67	64.0		
K(C-5)	48	66	65	65.5		
K(249)	50	78	80	79.0		
K(322)	50	72	69	70.5		
K.&E.	50	61	62	61.5		
K.&E.	50	71	79	75.0	74.4	
K(211)	50	73	87	80.0		
K(55)	50	84	77	80.5		
K.&E.	52	72	78	75.0		(50 - 54) 75.3
K.&E.	52	83	82	82.5	77.5	
K.&E.	52	82	68	75.0		
K.&E.	54	71	73	72.0		
K.&E.	54	81	73	77.0	74.5	

TABLE VII (Cont'd)

Source	Age (Years)	Torsion Angle		Average (R + L)	Age Average	Class Average
		R	L			
K.&E.	55	82	72	77.0		
K.&E.	55	84	72	78.0		
K.&E.	55	73	84	78.5	72.9	
K.&E.	55	64	56	60.0		
K.&E.	55	67	75	71.0		
K.&E.	56	79	72	75.5		
K.&E.	56	81	77	79.0		
K(C-1)	56	--	58	58.0	71.5	
K(C-9)	56	65	82	73.5		
K.&E.	57	83	68	75.5	75.5	(55 - 59) 74.4
K.&E.	58	84	81	82.5		
K.&E.	58	79	77	78.0	75.7	
K.&E.	58	69	64	66.5		
K.&E.	59	78	82	80.0		
K.&E.	59	62	63	62.5		
K.&E.	59	86	83	84.5	78.0	
K(C-2)	59	85	85	85.0		

TABLE VII (Cont'd)

Source	Age (Years)	Torsion Angle R	Torsion Angle L	Average (R + L)	Age Average	Class Average
K.&E.	60	72	68	70.0		
K.&E.	60	83	71	77.0		
K.&E.	60	87	79	83.0		
K.&E.	60	87	83	85.0	78.1	
K(C-8)	60	79	86	82.5		
K(C-11)	60	69	71	70.0		
K(C-21)	60	79	79	79.0		
K(C-16)	61	80	84	82.0	79.3	(60 - 64) 76.5
K(A-15)	61	72	81	76.5		
K(C-22)	62	70	78	74.0	74.0	
K.&E.	63	76	68	72.0	72.0	
K.&E.	64	86	79	82.5	72.0	
K(167)	64	64	59	61.5		
K.&E.	65	87	87	87.0		
K.&E.	65	81	69	70.0		
K.&E.	65	87	81	84.0		
K.&E.	65	77	71	74.0	75.6	(65 - 69) 75.4
K.&E.	65	70	66	68.0		
K(475)	65	65	74	69.5		
K(350)	65	79	74	76.5		

TABLE VII (Cont'd)

Source	Age (Years)	Torsion Angle R	Torsion Angle L	Average (R + L)	Age Average	Class Average
K.&E.	66	82	85	83.5	75.3	(65 - 69)* 75.4
K(208)	66	68	66	67.0		
K(C-12)	67	84	82	83.0	83.0	
K.&E.	68	76	58	67.0	74.8	
K(C-17)	68	83	82	82.5		
K.&E.	69	71	74	72.5	72.0	
K.&E.	69	71	72	71.5		
K.&E.	70	84	74	79.0	79.4	(70 - 74) 73.9
K.&E.	70	84	72	78.0		
K.&E.	70	82	84	83.0		
K(C-6)	70	83	80	81.5		
K(C-20)	70	85	73	79.0		
K(A-7)	70	82	78	80.0		
K(215)	70	69	81	75.0		
K.&E.	71	80	67	73.5	70.5	
K.&E.	71	71	64	67.5		
K.&E.	73	68	68	68.0	67.2	
K.&E.	73	79	64	71.5		
K.&E.	73	63	61	62.0		
K(61)	74	66	60	63.0	63.0	

*Continued from preceding page.

TABLE VII (Cont'd)

Source	Age (Years)	Torsion Angle R	Torsion Angle L	Average (R + L)	Age Average	Class Average
K.&E.	76	82	74	78.0		
K(C-15)	76	77	77	77.0	79.5	
K(A-18)	76	84	83	83.5		
K(B.L. 3)	77	78	83	80.5	80.5	(75 - 79) 77.0
K.&E.	78	84	86	85.0		
K.&E.	78	68	75	71.5	72.7	
K(C-19)	78	57	66	61.5		
K(60)	79	78	80	79.0	79.0	
K.&E.	80	76	88	82.0	82.0	
K(C-14)	82	84	80	82.0	82.0	(80 - 84) 77.8
K(C-10)	83	65	74	69.5	69.5	
K(C-25)	85	84	83	83.5	83.5	(85 - 89) 83.5
K(A-17)	91	74	75	74.5	74.5	(90 - 94) 74.5

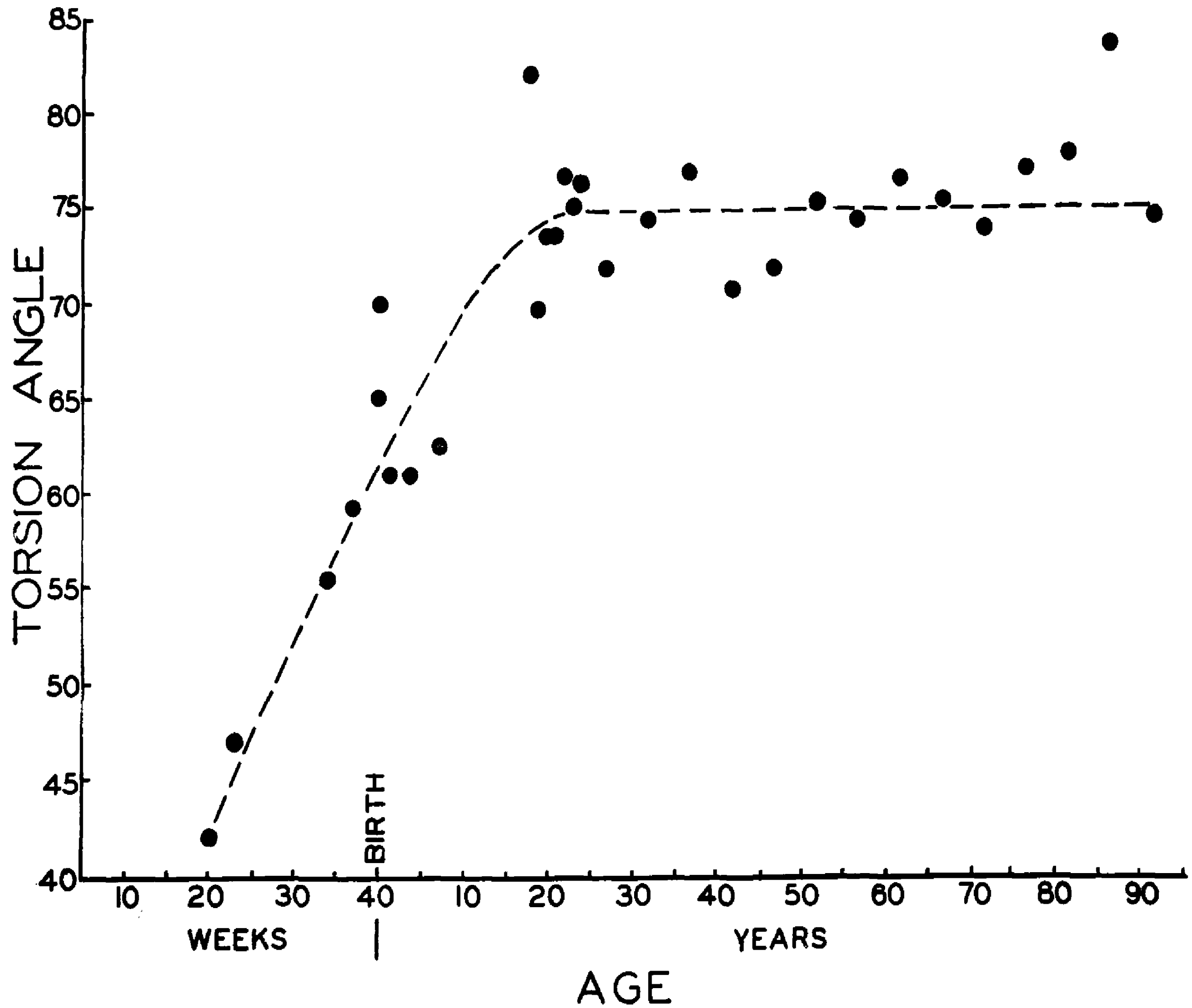

Figure 10. Graphic presentation of the data in Table VII showing the relationship of the age of the individual to the degree of torsion of the humerus

torsion angles have been plotted against the age of the individuals from whom the humeri were taken. Up to the age of 25 years (exclusive) each point represents the average of the values of torsion angles of all individuals of the same age. From 25 to 91 years, the entire material, comprising 313 humeri, was divided into classes of five years each; accordingly, each point represents the average of all individuals within a five-year group. Each average value for a five-year group was plotted against the midpoint of the five year interval upon the age scale. Inspection of the graph will show that in the region representing adult age a few points exhibit a pronounced deviation from the main level; such points, as will become apparent from a perusal of Table VII, represent only a few humeri or perhaps only a single pair. They should probably not be weighted as heavily as those representing the average value for a large number of humeri.

It will be noted from Figure 10 that an active torsion is in progress during the latter half of fetal life. During the period from 20 weeks until birth the torsion angle increases rapidly, rising from 42 degrees to over 60 degrees in this interval. Torsion continues through early childhood and youth and begins to approach the adult average in the neighborhood of 18 to 20 years. Thus, the work of those who have reported an increase in humeral torsion during development and childhood is corroborated. Although there is considerable variability of the material and additional data are to be desired for some ages, it is clear from Figure 10 that there is first a period of rapid increase in torsion, followed by a protracted one in which there is no further torsion. Between the two, there is a rather sharply defined period around 18 to 20 years in which the torsion process is brought to a close.

The results of the study of the duration of torsion permit one to draw a conclusion which deserves special emphasis at this time. Stated briefly in a previous section, this point is now considered fully. Earlier, in the section in which the site of torsion was considered, evidence was assembled which strongly suggested the proximal epiphyseal cartilage as the site of the twisting. If one accepts the view that the humerus can be twisted in this region by reason of its greater plasticity and relative weakness, then it must logically follow that the removal or disappearance of this softer zone should result in the prohibition of further torsion. In other words, when the humerus is at last completely ossified; when the cartilage is no longer present, then one should see the complete cessation of torsion. According to reliable data, the proximal humeral epiphysis becomes fused to the diaphysis at about 19½ to 20 years, varying somewhat according to sex. With this information in mind, one is struck by the close agreement between the age of epiphyseal fusion and the time of conclusion of the torsion process, as estimated from Table VII and Figure 10. In the opinion of the writer, this can only be taken as additional support of the view that humeral torsion takes place at the level of the proximal epiphyseal cartilage.

Summarizing the results on the duration of the torsion process, it may be stated that spontaneous movements involving forces assumed to be responsible for humeral torsion, are initiated early in fetal life. When torsion values for a large series of individuals are arranged according to age, the data show, at first, a progressive increase in humeral torsion. The process begins early in the fetal period (probably at $11\frac{1}{2}$ weeks or slightly earlier) and proceeds steadily until the age of 18 to 20 years. In connection with what has been said earlier concerning the site of the torsion process, it appears highly significant that the age of epiphyseal closure and the age at which torsion ceases are in such close agreement.

CHAPTER V

DISCUSSION

Although the concept of a humeral torsion has existed in some form or another for perhaps centuries, the approach to a clear understanding of the phenomenon has been impeded by many misconceptions and misinterpretations. Charles Martins, who probably did more than any other worker to stimulate interest in the problem, did not at first believe in a real torsion, but only a virtual twisting of the humerus. Estimates as to the degree of torsion were inaccurate in the beginning and it was not until techniques of measurement had been devised and refined that comparative studies of torsion were made possible. The findings of Gegenbaur and his contemporaries demonstrating the reality of torsion, represented an important advance and formed a foundation for much of the later research. Nevertheless, there were some who confused torsion and rotation and were led to deny the existence of a torsion. A few admitted a humeral torsion in primates, but not in quadrupeds. The abundance of literature which has appeared since the turn of the century has greatly increased our knowledge of torsion so that today, it is perhaps the best known feature of the humerus and is a subject of interest to anatomists and anthropologists alike. Nevertheless, conflicting opinions still prevail on some points.

A. Starting Point and Direction of Torsion

As mentioned above under "The Measurement of Humeral Torsion", the angle γ is considered to express correctly the degree of torsion. The selection of this angle, among several other possible angles, may seem arbitrary. There are in particular two angles, in addition to γ, either of which might be claimed to express correctly the amount of torsion. These are the angles α and β, which are indicated in Figure 11. Some workers such as Martins (1857), Gegenbaur (1868), Broca (1881), Lambert (1892), Hultkrantz (1897) and others have given the obtuse angle, α as the angle of torsion

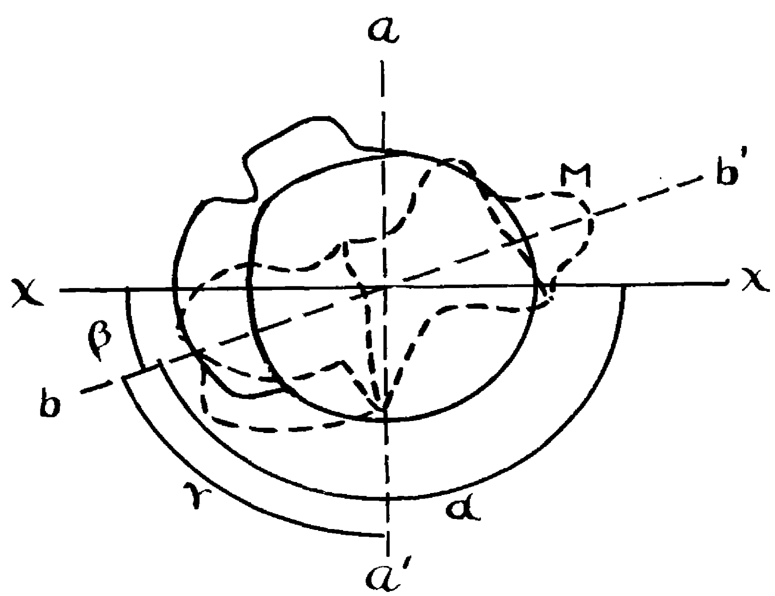

Figure 11. Superimposed proximal and distal ends of a left humerus. Lines xx' and bb' represent the long axes of proximal and distal ends, respectively. Line aa' denotes starting position of torsion, postulated by the writer. Angles α, β, and γ are torsion angles as measured by various authors.

(complementary angle of torsion), while Schmid (1873), Fick (1904) and others have given the acute angle, β (supplementary angle of torsion). A third group, including Le Damany (1903 a and b), Strasser (1917) and the writer, are of the opinion that the angle γ represents the true angle of torsion. Assuming that a subject has been selected in whom the angle γ is 70°, those who select β as the angle of torsion would record, in the same individual, a torsion of 20°, while using α as the angle of torsion, one would obtain a torsion of 160° (90° + 70°).

In an attempt to decide which of these three angles correctly expresses the degree of torsion, it must be kept in mind that a very important problem is involved here; a problem which was not yet fully recognized in the writer's earlier papers on this subject, but which deserves special emphasis. In selecting the correct angle it is necessary to determine which position of the distal end (with respect to the proximal end) was the primary position and therefore served as the starting point. In choosing γ as the angle of torsion, one would postulate that primitively the distal end was directed so that the coronoid fossa of the distal end faced in the same direction as the greater tuberosity of the proximal end. If one chooses, with Broca, the angle α , then the assumption has been made that the starting point was a position of the distal end in which the medial epicondyle faced in the same direction as the greater tuberosity of the proximal end. If one selects the angle β to express the amount of torsion, as

Fick did, the starting point must have been a primitive position of the distal end relative to the proximal end in which the lateral epicondyle points in the same direction as the greater tuberosity.

It will be immediately obvious to the reader that the postulation of any one of these three positions as the primitive position from which torsion started, must profoundly affect the opinion concerning the direction in which torsion took place. If angle α or angle γ are believed to express torsion, then it must be assumed that the distal end has been twisted around in a medial sense. But if β is assumed to be the correct value, then it follows that torsion took place in a lateral sense.

The question of the direction in which torsion occurred can be definitely settled with the aid of the data presented in Table VII. It has been shown that in early fetal stages the angle γ is 42°, that it gradually increases and finally, in the adult, attains a value of about 74°. This gradual increase is clearly seen in the series of diagrams shown in Figure 12. It is demonstrated that the long axis of the distal end advances steadily from its fetal position to approach, in the adult, the position of the long axis of the proximal end; i.e., torsion has taken place in a medial direction.

While the above considerations lead definitely to a settlement of the direction of torsion, they do not decide which position of the distal end relative to the proximal end existed in the primitive state. It might have been, as would

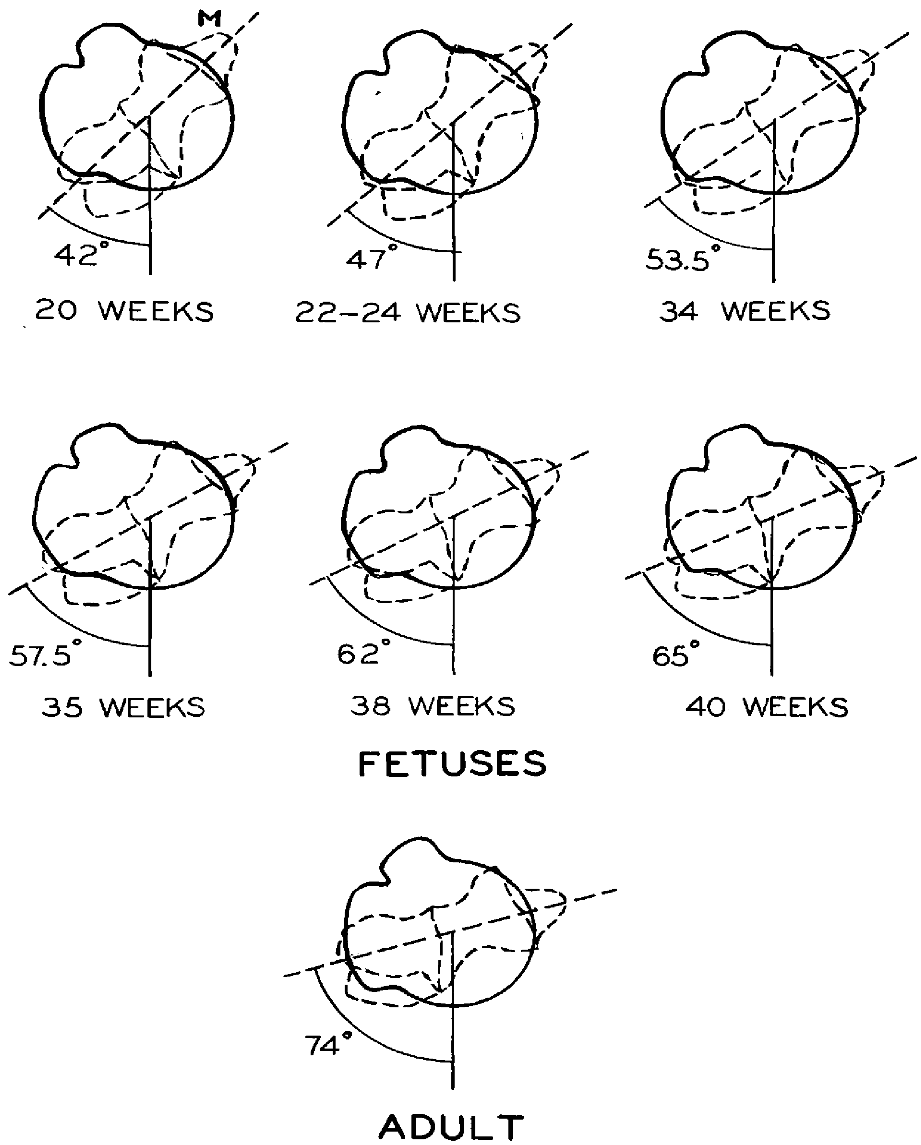

Figure 12. Series of diagrams showing relative positions of proximal and distal ends of humeri in fetuses from 20 to 40 weeks and in the adult. Note the gradual shifting of the distal axis in a medial sense.

follow from Broca's interpretation, the position in which the medial epicondyle points in the direction of the greater tuberosity; or it might have been, based upon the angle γ , a position where the coronoid fossa faces in the direction of the greater tuberosity. Strictly speaking, this problem is not within the province of the present article since it has no direct bearing on the work presented here. Yet it can be stated with some certainty that in man the primitive position is one in which the long axis of the distal end makes an angle of 42° with the line aa' of Figure 11. There are, however, good indications that even this primitive position, as it is found in the early embryonic stages of man, represents only one stage on the way from a position even more close to the line, aa'; for in the primitive reptiles, humeri have been found in which the angle γ is less than 10° and in a modern reptile, Alligator mississippiensis, the angle is about 15°. Ornithorhynchus has an average humeral torsion angle of about 14°. These values come very close to the value of 0° which would have prevailed in an animal in which the primitive position corresponded to that of the line, aa'.

B. Primary and Secondary Torsion

The considerations presented in the previous paragraphs indicate that a distinction must be made between primary and secondary torsion (Evans and Krahl, 1945; Krahl and Evans, 1945), corresponding to Le Damany's (1903 b) inherited and acquired torsion. This would mean that the apparent torsion already existing when the ossification of the humerus begins, is not caused by real torsional processes in man, but is present as the result of inherited patterns; this is the primary torsion of man's humerus. The progressive torsion noted first by Gegenbaur (1868), Broca (1881) and others and studied more accurately in this paper (see Figure 10) is the real or secondary torsion which is caused by torsional forces acting during man's ontogenetic development.

As seen in Figure 10 the youngest stage examined by the writer is that of the 20-week human fetus; in this, the average torsion angle is found to be already 42°, representing as was mentioned, the primary or inherited torsion angle.

Although humeri of younger fetuses have not been measured by the writer, it does not appear likely that torsion would progress so rapidly or to such a great extent during the first one-half of intra-uterine life as to produce a 42° torsion. This idea receives support from the literature. The average torsion angle of two 10-week fetuses reported by Le Damany was 45°, while Gegenbaur found angles of 48°, 47° and 46° in three fetuses aged 16, 17 and 18 weeks, respectively (values adjusted so as to be comparable with those of the writer). Allowing for a slight discrepancy due to differences in technique et cetera, these values may be taken as representing, within rather narrow limits, the condition in very young fetuses. The degree of humeral torsion found at 10, 16, 17 and 18 weeks is, therefore, essentially the same as that seen in the fetus at 20 weeks. Since a mechanism capable of producing the torsion is not active until at least 10 or 11 weeks, one must conclude that this "initial" torsion is the result of intrinsic factors which determine the original form of the developing humerus, as it has been taken over from our lower ancestors.

One is therefore able to place the value for the primary torsion in the neighborhood of 42° to 45°. Superimposed upon this inherited torsion is the secondary or ontogenetic torsion which is produced through the influence of extrinsic factors. The torsion angle which is measured in the adult humerus, therefore, represents the total of both primary and secondary torsion.

C. The Epiphyseal Cartilage as the Center of Torsion

In the light of all the evidence which is at hand, it appears that the concept of a torsion in the humeral diaphysis must be abandoned. The only foundation for such a view is the spiral contours of the shaft, which indeed make it appear to be twisted, but it has been shown that this is entirely illusory and that the characteristic markings are due to other causes. On the other hand, there is a wealth of evidence drawn from many fields of investigation which points unmistakably to the proximal epiphyseal cartilage as the site of torsion.

D. The Ossification of the Epiphyseal Cartilage and the Cessation of Torsion

If the torsion process actually depends upon the presence of a cartilaginous zone in the bone, it should be expected that with the disappearance of the cartilage and the complete ossification of the bone, no further torsion can take place. The actual situation agrees entirely with this expectation.

Todd's extensive studies indicate that fusion of the proximal humeral epiphysis with the shaft is complete at the age of 19½ years in females and at the age of 20 years in males. As shown in Figure 10, this is approximately the range of age at which humeral torsion stops.

E. Anthropological Measurements of Humeral Torsion

An observation is to be made from the study of the duration of torsion which should be of especial interest to the anthropologist. When one desires to determine the average torsion angle for a particular ethnic group or nationality, one must be careful to select for study only humeri of mature persons, i.e., humeri in which epiphyseal union is complete, for humeri of younger individuals will give an erroneous idea of the degree of torsion.

F. The Diaphyseal Cone

The contour of the line of junction between the proximal epiphysis and the diaphysis has been of especial interest to the author. Aside from its general anatomical interest, this interlocking arrangement has considerable practical importance. That it is of particular interest to a physician is shown by the fact that there is scarcely a text-book or special article dealing with fractures and epiphyseal separations which does not describe in some detail the configuration of the proximal diaphyseo-epiphyseal junction and its significance. All agree that separations are not observed after epiphyseal fusion, but in young people, where a break may still occur through the plate of cartilage, the conical end of the diaphysis lessens the likelihood of a complete displacement of the epiphysis from the shaft. When complete separations have occurred, the cone tends to secure the parts and to maintain them in proper alignment after reduction of the fracture.

Although the diaphyseal cone is of clinical importance, the writer is not aware that this anatomical arrangement has ever been considered in connection with humeral torsion. It seems certain that if the adjacent surfaces were flat the incidence of epiphyseal separations would be much greater than it is. The contractions of the movers of the humerus and external stresses must create considerable shearing force at times and this is certainly true of the humeral rotators. The cone and cap arrangement is able to offset the shearing force in most cases, but it can be seen that it would not seriously hinder a torsion occurring at that level. Rather, it would favor such a movement by acting as a pivot. (See Callender, 2nd Ed., Fig. 594, p. 587.)

It is difficult to say just what controls the formation of a diaphyseal cone, but one may assume that the factors which govern its development and growth will not differ greatly from those which are believed to determine the form of bones in general. The shape of the cartilaginous model of a bone develops under the aegis of an intrinsic growth pattern and foreshadows the form of the adult bone. But the many alterations and refinements which give to the bone its final contours seem to be the result of many and varied extrinsic mechanical forces. Since the proximal end of the diaphysis is at first flat and not conical, the formation of a diaphyseal cone is perhaps best explained as a response to mechanical factors.

The chief mechanical stresses, as far as the formation of a diaphyseal cone is concerned, are probably those of torsion and shearing. As noted earlier, one force is not likely to occur without the other. The size of the cone is to be correlated with the shearing stress since its effectiveness in offsetting such a force will largely depend upon its height. On the other hand, the tendency of the epiphysis and diaphysis to move against one another under torsional stresses would have a moulding influence upon the bony projection and determine its conical shape.

In agreement with this interpretation is the fact that the height of the cone increases as the strength of the muscles increases. In the third fetal month, the proximal end of the shaft is flat. At that time, whatever muscular contractions occur cannot be very strong ones, but as prenatal activity increases and the contractions become more powerful, there is a greater tendency for the shaft to be dislocated and there is likewise a rapid elevation of the cone. At first, the surface shows a slight convexity, then it becomes pointed at or near the center. In terms of the index of cone height $\left(\frac{\text{height of cone}}{\text{diameter of cone}} \times 100\right)$, the cone has accomplished about 75% of its elevation by the time of birth. Thereafter, the increase in height is less rapid and the value becomes stationary around the age of 10 to 12 years. Of course, there is subsequently still an absolute increase in the height of the cone with the further growth of the bone, but since this is accompanied by an increase in the width of the bone, there is no further relative increase. Apparently, the proportions of the cone reach a relationship in youth which supplies adequate stability to the union of the epiphysis and shaft. The cone is then able to successfully offset shearing forces under most circumstances, while it is not able to resist seriously the torsional forces which may be impressed upon this part of the bone.

G. The Torsion Angle and the Shape of the Thorax

It has been shown, in the section on "Torsion Angle and Muscle Strength" that the incidental rotatory action of the infra-epiphyseal medial rotators may be the cause of the torsion of the humerus.

In this connection it is interesting to note that Hultkrantz (1897), Fick (1904), Mollison (1917), Grunewald (1919) and Braus (1929) believed that the ontogenetic increase in the torsion of the humerus is caused by the dorso-ventral flattening of the thorax and the dorsal migration of the scapula accompanying it. Hultkrantz was of the opinion that a dorsal shifting of the scapula, causing the glenoid cavity to face more laterally, would result in a lateral rotation of the humerus; in compensation for this, a medial torsion of the humerus would bring the forearm and hand back into the position in which they are used in man. Mollison (1917) devised a mechanical model to demonstrate this theory (see illustration in Braus, 1929, Bd. I, p. 281). In confirmation of this reasoning, Hultkrantz found that in 12 skeletons with kyphotic deformities and a laterally compressed thorax, the torsion angles of the humeri were smaller than in normal individuals.

At present, the writer has no personal experience regarding these observations by Hultkrantz. If they are correct, however, two possibilities may be considered. The dorsal shifting of the scapula may be a causative factor of torsion, added to that of the action of the infra-epiphyseal medial rotators, the two factors working independently towards the same final goal. On the other hand, it may be that one of them acts indirectly through the intermediary action of the other one.

In the latter case, the following consideration seems of interest. In a laterally flattened thorax, the Latissimus dorsi and Pectoralis major act upon the humerus primarily in a dorso-ventral direction and as a result of this situation, are for the most part extensors and flexors. In a dorso-ventrally flattened thorax, the pull of these muscles upon the humerus has a more frontal direction, thereby increasing the tendency of these muscles to rotate the humerus medially. It is possible, therefore, that the dorsal shifting of the scapula, after all, effects the twisting of the humerus only by the intermediation of the action of the same muscles which have been associated with this effect in the present article.

SUMMARY AND CONCLUSIONS

1. The humerus of man was studied from the view-points of the locality, causes and duration of the processes which result in the torsion of this bone.

2. A distinction is made between torsion and rotation of the humerus. The term torsion is used in the sense of a twisting of the distal against the proximal end of the bone, while rotation is understood to mean a turning of the humerus as a whole (both proximal and distal ends) around the long axis of the bone.

3. There are three different angles which may be used to express the degree of torsion. In making a choice between them, a decision must be made as to which, of the many possible relative positions of the distal and proximal ends, is the position from which torsion has started, i.e., the position before any torsion whatsoever has occurred. The position selected is the one in which the coronoid fossa faces in the same direction as the greater tuberosity of the humerus (Figure 11).

4. A tracing of the gradual increase in torsion during ontogenetic development proves that from this assumed starting position, torsion has taken place in a medial direction (Figure 12). The gradually increasing angle between the axis of the distal end and the plane of its original position is the torsion angle (designated herein as τ).

5. In fetuses 20 weeks old, the torsion angle was found to be 42°, on the average. This was the lowest value of the torsion angle found in the human humerus and was considered as representing the primary torsion of the humerus in man, i.e., the torsion inherited from man's lower ancestors, as contrasted to the secondary or acquired torsion which the humerus undergoes during ontogenetic development, under the influence of extrinsic factors.

6. Measurements of the torsion angle at different ages were made in a series of humeri of which 21 were taken from fetuses and neonati, 40 covered the range from birth through the age of 24 years and 313 were from subjects 25 to 91 years of age. These show that, starting from a value of 42° in the 20-week fetus, the torsion angle at first increases at a rapid rate, reaching 47° at 22 to 24 weeks, 54° at 34 weeks, 58° at 35 weeks, 62° at 38 weeks and 65° at birth. Between 18 and 20 years, the torsion angle reaches about 74° which represents the average (permanent) value of torsion in the human adult humerus; the torsion process ceases at an age between 18 and 20 years.

7. In the light of abundant evidence that torsion takes place in the region of the proximal epiphyseal cartilage, the older notion that the humeral shaft is twisted must be abandoned.

8. A study of fetal humeri leads to the conclusion that it is mainly the periosteum which lends stability to the proximal diaphyseo-epiphyseal joint.

9. On the other hand, it was found that the periosteum does not prevent rotation of the shaft against the epiphysis. Careful measurements of these rotational movements with the periosteum in place showed that, from its normal position, the shaft can be rotated against the epiphysis by a maximum angle of 10°.

10. The fact that torsion stops almost exactly at the age at which complete ossification and disappearance of the epiphyseal cartilage takes place is in excellent accord with the claim that the proximal epiphyseal cartilage represents the torsional center.

11. A device is present at the proximal end of the diaphysis which, under normal conditions, is able to successfully offset shearing forces which are set up at the diaphyseo-epiphyseal joint through muscular activity and external forces. It exists in the form of a cone-shaped elevation which fits into a cup-like depression in the epiphysis. While resisting shearing forces, this cone does not hinder rotational movements at the joint, but rather serves as a pivot for such movements.

12. Measurements of the diaphyseal cone in humeri of various ages show that, from a flat surface in the early fetus, a conical elevation rises rapidly during later development and postnatal growth. With advancing age, and concomitant with an increase in muscle strength, there occurs a change in the proportions of the cone so that there is a relative increase in cone height with respect to the base.

This proportion, expressed as the index of cone height, attains its maximum value in the neighborhood of 10 to 12 years. Thus it may be said that there occurs a relative and an absolute increase in the height of the cone.

13. A technique for finding the cross-sectional areas of muscles with the aid of a photographic procedure has been devised.

14. The major cause for the twisting of the humerus is to be found in the action of three muscles; the Pectoralis major, Latissimus dorsi and Teres major, which are inserted into the shaft distal to the epiphyseal cartilage.

15. By reason of the manner in which they are inserted, these three muscles have the peculiarity of attempting to rotate the shaft medially against the proximal epiphysis during willed movements of adduction, flexion or extension of the shoulder joint. In such movements, a medial rotation of the humerus is not willed and the epiphysis is either fixed by the short supra-epiphyseal rotators or may even be rotated laterally by the short lateral rotators.

16. In accord with these considerations is the fact that in adults a high value of the torsion angle is associated with more powerful muscles, while in subjects with less powerful muscles the values of the torsion angles are low.

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