Normal and abnormal motion of the shoulder

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Hence, the stress calculated when \( P = \sigma_{max} \) is the ultimate bending strength (or stress \( \sigma_f \)).

The flexural modulus of elasticity \( (E) \) of the bone specimen can also be calculated using the following formula 3:

\[
Y_{at A} = \left( \frac{P}{EI} \right) \left( \frac{a^3}{3} \right) \left( a + \frac{3L}{2} \right)
\]

where \( Y_{at A} \) is the vertical deformation at point \( A \) (Fig. 2).

\[E = \frac{Pa^3}{6LY_{at A}} \left( a + \frac{3L}{2} \right)\]

Or,

\[E = \frac{P}{Y_{at A}} \left( \frac{1}{bh^3} \right)\]

where \( a = L = 1.2 \text{ cm}. \)

Now \( Y_{at A} \) is the Instron cross-head displacement, and the initial slope of the load-deformation diagram (Fig. 2) is \( P/Y_{at A} \). Therefore, \( E \) can be calculated from equation (4).

References


Normal and Abnormal Motion of the Shoulder

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Abstract: The roentgenographic parameters of motion in normal and abnormal shoulders, including the movement of the scapula, arm angle, glenohumeral angle, scapulothoracic angle, excursion of the humeral head, and instant center of motion for abduction in the plane of the scapula, were determined in twelve normal subjects and fifteen patients. The scapula rotated externally with abduction. The ratio of the glenohumeral to scapulothoracic movement was 5:4 after about 30 degrees of abduction. The center of rotation of the glenohumeral joint for abduction in the plane of the scapula was located within six millimeters of the geometric center of the humeral ball. The average excursion of the humeral ball on the face of the glenoid in the superoinferior plane between each 30-degree arc of motion was less than 1.5 millimeters in normal subjects. Significant previous injury resulting in abnormal mechanics of the shoulder joint was associated with abnormal values for excursion of the instant center and of the humeral head. An abnormal glenohumeral-to-

scapulothoracic ratio was associated with significant pain in the shoulder. The fact that these various parameters were sensitive indicators of normal and abnormal motion raises the possibility of diagnostic clinical application.

Many authors 2,3,4,5,6,7,8,10,11,12,13 have pointed out the complexity of the shoulder and nearly a century ago 2,3 the interplay of the sternoclavicular, acromioclavicular, scapulothoracic, and glenohumeral joints was described. It has been suggested 11,12 that "true abduction" of the arm should not be in the coronal plane, but rather in the "plane of the scapula" which is angled 30 to 45 degrees anterior to the coronal plane, because in the scapular plane the inferior part of the capsule is not twisted and the deltoid and supraspinatus are optimally aligned for elevation of the arm. Inman and co-workers showed that all of the joints in the shoulder girdle move simultaneously, and that in the motion of abduction the glenohumeral joint moves twice as much as the scapulothoracic joint. Saha 13 described a "zero position" of the humeral head on the glenoid based on how much rolling and sliding takes place at the
Reference axes are taken in the humerus: \( x,y \), scapula \( x,y \), and body \( X,Y \). The line \( x \) is a perpendicular to the true axis of the humerus through \( O_h \), the center of the humeral head. The line \( y \) passes through the superior and inferior edges of the glenoid and \( z \) is the mid-line of the scapular spine. \( O_s \) is chosen at the center of the glenoid fossa and hence the \( x \)-axis passes through this point perpendicular to the \( y \)-axis.

### Materials and Methods

**Subjects Studied**

The main motion we studied was abduction of the arm in the plane of the scapula. We had twenty-seven subjects, of whom twelve were asymptomatic, normal volunteers twenty-two to sixty-three years old, and fifteen were patients seventeen to seventy-two years old who had lesions of the shoulder and were about to have arthrography. We adopted a technique similar to that of Freedman and Munro to obtain roentgenograms in the plane of the scapula with the arm in neutral rotation. An anteroposterior roentgenogram was made of each shoulder with the patient standing with the torso at a 30-degree angle to the plane of the roentgenogram. When the arm was abducted to each of the required positions, the plane of abduction was parallel to the plane of the roentgenogram and the amount of abduction was gauged with reference to the \( Y \)-axis of the body.

### Selection of Reference Axes

A study of the motion of the shoulder must start with a definition of the axes in each of the two moving parts (humerus and scapula) relative to the stationary part, the torso (Fig. 1). The geometric center of the humeral head \( (O_h) \) is chosen as one reference point because the curvature is sufficiently close to uniform for this purpose, and the center can be found by a simple geometric construction. The reference point for the scapula \( (O_s) \) was chosen to be the center of a line joining the limits of the glenoid fossa. On each roentgenogram the three sets of axes were drawn; the axes of the torso were designated \( X,Y \), the axes of the scapula, \( x,y \), and the axes of the humerus, \( x,y \) (Fig. 2). Because Figure 2 was drawn from a roentgenogram made with the subject facing the x-ray source at a 30-degree angle, in other words in the plane of the scapula, the \( XY \) axes are in this plane and not in the coronal plane of the body. The arm angle, glenohumeral angle, and scapulothoracic angle are defined in Figure 2.

Several roentgenograms were made for each subject, at 30-degree intervals from the dependent arm position up...
to maximum abduction in the plane of the scapula. Because of the inevitable minor variations in a sequential set of roentgenograms, a method was needed to obtain satisfactory superposition of the sets of roentgenograms. A master tracing was made of the scapula and humerus at 60 degrees of abduction (mid-range) and the axes were marked. Each of the other roentgenograms (made at 0, 30, 90, 120, and 150 degrees and at maximum abduction) was superimposed over the master tracing as closely as possible and the individual axes then were drawn. In this way, sequential patterns of movement were obtained.

Definitions of Parameters

Still referring to Figure 2, various parameters of interest can now be defined. The movement of the scapula on the thorax can be defined by following one point and one angle, that is, $O_A$ and the scapulothoracic angle ($\Theta_{ST}$). Information on the rotation of the scapula can be obtained by determining the center of rotation of the scapula for each 30-degree interval considered. The directions of measurement must be defined relative to the several axes. Also, changes in $\Theta_{GH}$ and $\Theta_{ST}$ can be related to the arm angle ($\Theta_A$), and the ratio $\Theta_{GH}/\Theta_{ST}$ can be determined.

The excursion or sliding of the humeral head on the face of the glenoid (the rise and fall of the geometric center of the ball, $O_h$) can be expressed as the parameter $e$, the distance on the y-axis that $O_h$ lies above or below the center of the glenoid ($O_c$).

The motion of the humerus on the glenoid can be described in terms of the center of rotation. The method for determining it is shown in Figure 3. For each 30-degree interval of the angle between two sequential roentgenograms of the same subject, the center of rotation for that arc of motion is the pivot point about which the humerus appears to rotate. The center of rotation of the scapula on the thorax was determined by a similar technique.

Results

A typical set of sequential roentgenograms from a normal subject (Fig. 4) illustrates the information obtained. In the relaxed position of the extremity with the subject standing, the average arm angle ($\Theta_A$) for the fifteen normal subjects was 2.5 degrees, with a range of from $-3$ to $+9$ degrees. The average scapulothoracic angle ($\Theta_{ST}$) was $-4.7$ degrees, with a range of from $-11$ to $+10$ degrees. Freedman and Munro obtained a mean value of $-5.3$ degrees, although Basmajian and Bazant stated that it invariably faced somewhat upward.

In moving the extremity, in normal subjects the relationships among $\Theta_A$, $\Theta_{GH}$, and $\Theta_{ST}$ were different (Fig. 5) in the arc of motion between 0 and 30 degrees of abduction, as compared with the arc of motion between 30 and 120 degrees. In all of our twenty-seven subjects as well as in those of Inman and associates, Freedman and Munro, and Saha, results are in reasonable agreement. The average arm angle measured from our roentgenograms with the arm in approximately 30 degrees of abduction was in fact 24 degrees. For the arm angle range of 2.5 to 24 degrees, the ratio of the glenohumeral angle to the scapulothoracic angle was 4.3:1. In other words, the scapula moved only slightly compared with the humerus. The mean regression lines were drawn for the range 24 degrees to maximum abduction. For the twelve normal subjects, as well as for three patients who were found to be normal in all respects, the equations of the regression lines were: $\Theta_{GH} = 0.55\Theta_A + 12.6$ and $\Theta_{ST} = 0.44\Theta_A - 12.4$. These indicate that in that range (24 degrees to maximum arm angle) the ratio of glenohumeral to scapulothoracic motion was actually $5:4$ or 1.25:1, meaning that there was not a great deal of difference in the amounts by which they rotated. Freedman and Munro's ratio was 1.35:1 for the range 0 to 135 degrees, which is not very different from ours. Saha, however, found an average ratio of 2.34:1 for the range 30 to 135 degrees for abduction in the plane of the scapula. Our data are in contrast to the findings of Inman and associates for abduction in the coronal plane; they stated that "at the glenohumeral and scapulothoracic articulations, the ratio, from almost the beginning to the termination of the arc, is respectively two to one. . . ."

Typically, as abduction progressed the glenoid face moved medially, then tilted upward, and finally moved upward somewhat as the arm was brought to maximum elevation (Fig. 6). These motions can be expressed in terms of the center of rotation of the scapula with respect to the fixed axes in the body. From 0 to 30 degrees, the scapula rotated about its lower mid-portion, and then from 60 degrees onward the center of rotation shifted towards the glenoid, so that it was rotating about that area, result-
Sequential roentgenograms made in abduction in the plane of the scapula.

By plotting the positions of the tips of the acromion and the coracoid it was clear that the scapula twisted about its x-axis. Figure 7 shows how this was detected on a plain roentgenogram. Assume that there is rotation about \( \theta_{\text{sc}} \) in a counter-clockwise direction. The coracoid tip will move predominantly upward, while the acromion tip will move backwards in the same transverse plane in relation to the face of the glenoid. Hence, by measuring the upward movement of the coracoid with respect to the face of the glenoid, the angle of rotation can be calculated. The rotation could, of course, be about the same axis parallel to \( x \). For all subjects, patients as well as normal individuals, the acromion remained stationary with respect to the face of the glenoid except at high abduction angles when it tended to rotate slightly downwards, as would be predicted (Figs. 6 and 7). This is consistent with a counter-clockwise rotation (twisting) of the scapula on abduction of the arm that occurs in the plane of the scapula. For the fifteen normal subjects, the regression line for the twisting was: \( \theta_{\text{sc}} = 0.59\theta_{\text{an}} + 5.4 \), with a correlation coefficient of 0.83. This means that the twisting angle was 0.59 times the ...

The motion of the scapula in its own plane is defined by the position of the glenoid and the centers of rotation relative to fixed XY axes in the body. The center of rotation of the scapula begins low in the body of the scapula and progresses upwards toward the glenoid. (Asterisk denotes center of rotation for the specific intervals, 0 to 30 degrees and so on.) The outlines of the scapula corresponding to the 0 and 150-degree abduction positions are shown.
Rotation or twisting of the scapula about the x-axis is shown by the upward movement of the coracoid and little shift in the acromion relative to the face of the glenoid (left). If the scapula is viewed in the lateral projection (right), the coracoid would be seen to move upward with the acromion remaining on the same horizontal plane relative to the glenoid.

This twisting can be described as the superior angle of the scapula moving away from the body wall and the inferior angle moving into the body wall, that is, external rotation of the scapula. This is of significance when considered with the external rotation of the humerus which often occurs after 90 degrees of abduction. It now is evident that the humerus and the scapula move synchronously to some extent, so that the relative amount of rotation may be small, depending on how much the humerus rotates.

Instants centers of rotation and ball excursion: In all of the normal subjects, although there was some variation, the instant centers lay quite close to each other and to the center of the humeral ball. In contrast to this, many of the patients displayed centers of rotation which departed considerably from the center of the ball (Table I, Subjects K, O, V, W, X, Y, and Z).

In order to assign a value which was descriptive of the instant center patterns, the center of the humeral head was located and the distance from it to each instant center was measured. The distances were then averaged and scaled up or down to correspond to an average humeral-head diameter of forty-four millimeters. The average instant center value for the normal subjects was 6.0 ± 1.8 millimeters. An abnormal value for instant center was one that was located ten millimeters or more from the center of the ball.

The ball excursions showed an interesting feature. From 0 to 30 degrees, and often from 30 to 60 degrees, the humeral ball moved upwards on the glenoid face by about three millimeters. Thereafter it remained constant, moving only one millimeter or at most two millimeters upward or downward between each successive position. For the normal individuals the average movement from position to position was 60.0 ± 9.0 millimeters.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Maximum Arm Angle (Degrees)</th>
<th>Glenohumeral to Scapulothoracic Ratio</th>
<th>Instant Center (mm)</th>
<th>Excursion of Ball on Glenoid (mm)</th>
<th>Clinical Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average of Normals</td>
<td>150</td>
<td>1.25 ± 0.25</td>
<td>6.0 ± 1.85</td>
<td>1.09 ± 0.475</td>
<td>Normal volunteers</td>
</tr>
<tr>
<td>K</td>
<td>156</td>
<td>1.00</td>
<td>8.7 A*</td>
<td>1.2</td>
<td>Old GH dislocation (normal volunteer)</td>
</tr>
<tr>
<td>N</td>
<td>150</td>
<td>1.87</td>
<td>4.4</td>
<td>1.2</td>
<td>Normal volunteer</td>
</tr>
<tr>
<td>CL</td>
<td>112</td>
<td>1.00</td>
<td>7.1</td>
<td>4.0 A</td>
<td>Rotator-cuff tear</td>
</tr>
<tr>
<td>E</td>
<td>150</td>
<td>0.99 A</td>
<td>4.8</td>
<td>1.0</td>
<td>Shoulder pain; normal arthrogram</td>
</tr>
<tr>
<td>H</td>
<td>137</td>
<td>1.14</td>
<td>6.5</td>
<td>0.8</td>
<td>Rotator-cuff tear</td>
</tr>
<tr>
<td>J</td>
<td>147</td>
<td>1.36</td>
<td>6.6</td>
<td>1.0</td>
<td>Painful shoulder; previous injury</td>
</tr>
<tr>
<td>M</td>
<td>155</td>
<td>1.15</td>
<td>10.7 A</td>
<td>2.0 A</td>
<td>Shoulder pain; normal arthrogram</td>
</tr>
<tr>
<td>O</td>
<td>156</td>
<td>1.38</td>
<td>11.2 A</td>
<td>1.45</td>
<td>Rotator-cuff tear</td>
</tr>
<tr>
<td>Q</td>
<td>137</td>
<td>0.99 A</td>
<td>4.2</td>
<td>0.8</td>
<td>Rotator-cuff tear</td>
</tr>
<tr>
<td>R</td>
<td>152</td>
<td>2.24 A</td>
<td>8.2</td>
<td>1.1</td>
<td>Shoulder pain; normal arthrogram; arthritis in cervical spine</td>
</tr>
<tr>
<td>T</td>
<td>128</td>
<td>0.68 A</td>
<td>4.0</td>
<td>0.6</td>
<td>Rotator-cuff tear</td>
</tr>
<tr>
<td>U</td>
<td>99</td>
<td>0.72 A</td>
<td>4.9</td>
<td>1.0</td>
<td>Shoulder pain; normal arthrogram; degenerative arthritis GH joint</td>
</tr>
<tr>
<td>V</td>
<td>123</td>
<td>0.83 A</td>
<td>12.1 A</td>
<td>2.7 A</td>
<td>GH dislocation</td>
</tr>
<tr>
<td>W</td>
<td>164</td>
<td>0.93 A</td>
<td>10.8 A</td>
<td>2.2 A</td>
<td>Rotator-cuff tear</td>
</tr>
<tr>
<td>X</td>
<td>129</td>
<td>1.41</td>
<td>14.2 A</td>
<td>4.0 A</td>
<td>Rotator-cuff tear</td>
</tr>
<tr>
<td>Y</td>
<td>99</td>
<td>0.236 A</td>
<td>13.25 A</td>
<td>2.2 A</td>
<td>GH dislocations</td>
</tr>
<tr>
<td>Z</td>
<td>148</td>
<td>0.826 A</td>
<td>12.7 A</td>
<td>2.2 A</td>
<td>Painful shoulder; previous injury</td>
</tr>
</tbody>
</table>

* Designates a value outside of one standard deviation of the normal.
position was only 1.09 ± 0.47 millimeters. It was expected that there would be a correlation between the instant center and the ball excursion, and this was borne out when the abnormal values were compared (Table I).

Only seven shoulders from our series of twenty-seven subjects showed distinctly greater instant centers and excursions than the remainder. Analysis of the seven abnormal and one borderline abnormal shoulder was revealing (Table I). All had either a previous glenohumeral dislocation (Subjects V and Y), a rotator-cuff tear (Subjects CL, W, and X), or significant shoulder pain associated with a previous history of injury (Subjects M and Z).

Three (Subjects H, Q, and T) of the seven patients with rotator-cuff tears documented by arthrogram did not have abnormal values for ball excursion and instant center, and one of these (Subject Q) was also noted to have a significant tear of the rotator cuff at the time of surgery.

All of the three patients with a previous glenohumeral dislocation (Subjects K, V, and Y) had abnormal values for the instant center and only one had a normal value for ball excursion. This sixty-one-year-old patient had been asymptomatic for thirty-six years following a glenohumeral dislocation.

In the analysis of the ratios of glenohumeral to scapulothoracic angle in the ten individuals with abnormal ratios, none were patients. Two had previous glenohumeral dislocations (Subjects V and Y), three had rotator-cuff tears (Subjects Q, T, and W), and one had roentgenographic changes compatible with degenerative arthritis of the glenohumeral joint (Subject U), one had cervical osteoarthritis (Subject R), and two had significant shoulder pain associated with a history of injury to the shoulder joint (Subjects Z and E). One individual with an abnormal value was an asymptomatic volunteer (Subject N). All but one of these ten subjects had significant shoulder pain or neck and shoulder pain. The five subjects with abnormal glenohumeral-to-scapulothoracic ratios, but normal values for instant center and ball excursion, included one with degenerative osteoarthritis of the glenohumeral joint (Subject U), two with rotator-cuff tears, and one with no known shoulder symptoms (Subject N).

A normal value for the glenohumeral-to-scapulothoracic ratio was not significant because four subjects with rotator-cuff tears (Subjects CL, O, W, and X), one subject with previous glenohumeral dislocation (Subject K), and one with normal motion values and a painful shoulder (Subject M) had normal glenohumeral-to-scapulothoracic ratios.

It may be concluded that if a patient has an abnormal instant center value (more than ten centimeters) and in addition an abnormal ball excursion (more than 1.5 millimeters), a significant previous injury has occurred resulting in abnormal mechanics of the shoulder joint.

An abnormal glenohumeral-to-scapulothoracic ratio was associated with significant disease, but a normal ratio of this kind did not rule out significant disease of the shoulder joint.

**Discussion**

The measurements which have been described depended primarily on the selection of reference axes drawn in the thorax, scapula, and humerus. With careful roentgenographic and graphic techniques these axes could be drawn accurately and reproducibly. The glenohumeral-to-scapulothoracic ratio in abduction motion was found to be 5:4 after 30 degrees of abduction was reached. It is emphasized that for a given arc of motion, this means that the humerus moves 5 degrees on the glenoid, while the scapula moves 4 degrees on the thorax. In contrast, a study of Figure 5 reveals that the absolute angles $\theta_{\text{UH}}$ to $\theta_{\text{CT}}$ are in about a two-to-one ratio. The reason for this difference is that from 0 to 30 degrees most of the movement is glenohumeral, elevating that line, while there is lowering of the scapulothoracic line for the motion from 30 degrees upwards. This may explain the discrepancy mentioned at the outset.

There is a surprising degree of conformity between the humeral head and the glenoid in the frontal scapular plane. Therefore, as long as there is a compressive force acting, the glenohumeral articulation would be expected to be stable, and the humeral head will rotate on a more or less fixed center with little, if any, excursion. For the normal shoulder this was found to be the case. The upward excursion occurring in the early range of motion would probably be due to an initial sag of the ball in the dependent position. Excessive excursion, along varying centers of rotation, would occur if the conformity of the joint were lost or if the component of shear force acting upward or downward were excessive. The latter situation could arise due to an imbalance of forces caused by muscle tears or if pain disturbed the muscle coordination.

The fact that these various parameters seem to be sensitive indicators of motion means that they can be of diagnostic use. For instance, as an adjunct to arthrography, a motion study may indicate whether or not there is a rotator-cuff tear producing abnormality of motion.

Note: We are grateful for a grant from Mr. and Mrs. Steven C. Clarke, Jr., in support of this work, and to Dr. Robert L. Patterson, Jr., for his guidance. We thank Mr. Ray Scala and Dr. Bernard Ghelman for carrying out the radiography. Mrs. Margaret Ehrman greatly assisted with the organization and analysis of the material.

**References**

Electromyography before and after Surgery for Hip Deformity in Children with Cerebral Palsy

A COMPARISON OF CLINICAL AND ELECTROMYOGRAPHIC FINDINGS


ABSTRACT: Twenty-three ambulatory children with spastic diplegic cerebral palsy were evaluated clinically and by electromyography before and after hip-muscle surgery. The stretch tests originally designed to distinguish specific muscle tightness and spasticity were found to be non-specific when tested by electromyography. Ambulatory electromyograms using needle electrodes and telemetry generally showed decreased activity in the released muscles and, on occasion, changes in activity in muscles not operated on. These unanticipated changes after release may explain some of the unpredictability of results of such procedures in cerebral palsy.

Currently children with cerebral palsy and a spastic gait are evaluated by observation of their gait and by a series of stretch tests. Unfortunately, surgical treatment based on these criteria may produce unpredictable results. We hoped that electromyography during the stretch tests and during gait might clear up some of the confusion and aid in planning operative procedures that would give predictable results. Initial work in this area was done by Sutherland and associates.

Methods and Clinical Material

From January 1971 to August 1974, twenty-three ambulatory children (Cases 1 to 23) with spastic diplegic cerebral palsy, five to eighteen years old, were evaluated and treated for their crouched walking posture (walking with flexed hips and knees and internally rotated thighs). Their functional class of gait and use of apparatus as well as the findings by clinical stretch tests, gait examination, and gait films were recorded (Table I and Chart VI).

In each patient, electrodes of fifty-micrometer nylon-shielded copper wire were inserted in the rectus femoris, gluteus maximus, gluteus medius, lateral hamstrings, medial hamstrings, gracilis, adductor longus, and iliacus, assuming iliacus activity to be similar to that of the psoas and hence representative of the activity of the iliofemoral. Our testing system permitted only eight muscle tests per run. We therefore selected the eight muscles that we considered to be the most significant hip or knee muscles affecting gait. Prior to the selection, we tested four children with cerebral palsy and found that the activity of the tensor fasciae femoris roughly paralleled that of the gluteus medius during gait and that of the hip flexors during stretch tests. Furthermore, this preselection study showed that the activity of the vastus muscles roughly paralleled that of the rectus femoris during gait. Precise definition of the contribution of these and other muscles should, of course, await testing systems with twelve or more testing channels.

The following stretch tests were carried out while recordings were made: straight-leg-raising, hip flexion with knees flexed, adductor stretch with hips and knees flexed, 'Thomas test', external rotation of the extended hip, external rotation of the flexed hip, Phelps-Baker 'gracilis' test (extension of the knee with the hip flexed in extension and abduction), and prone flexion of the knee with the hip extended (prone rectus test of Duncan or Ely). These tests were carried out in a standardized fashion for both the clinical and the electromyographic evaluations. Each patient was first positioned in the testing posture and then slow stretch was applied for four seconds as indicated by a