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A Static Analysis of the Muscles Crossing the Human Shoulder Joint

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人間의 어깨 근육에 對한 靜力學的 研究

박영필

抄錄

人間의 근육에 걸리는 힘에 對한 研究는 치료나 生體工學分野에서 대단히 중요한 부분을 차지하고 있다.

本 研究에서는 팔을 前頭面(Frontal plane)上에서 0°부터 90°까지 外轉(Abduction)시킬 때 어깨 근육에 작용되는 힘을 決定하는 方法을 개발시켰다. 여기에서는 해부학, 생리학적인 데타와 벡타해석 및 수학의 방법을 사용하였으며 靜力學的으로 부정정(Indeterminant)인 問題를 풀기 위하여 Minimal Effort Principle이 사용되였다.

Introduction and Review of Previous Work

The study of force distribution in human muscles during muscular activity is of current interest. This paper presents the results of a quasi-static force analysis and describes the force distribution in the various muscles crossing the gleno-humeral joint of the shoulder girdle during rotation of the upper extremity about the anterior-posterior axis.

Much research has been conducted in an attempt to gain greater understanding of forces in human muscles and their motion. Pearson, McGinley, and Butzel[1] obtained values of force, angular velocity and angular acceleration at joints by using a dynamic analysis of the upper extremity in planar motion. Dempster[2] reviewed the anthropometry of human motion and developed techniques to use the parameters of angle, velocity, acceleration, rhythmic patterns and external force to describe movements and posture changes. Engen and Spencer[3] used motion pictures of upper extremity to identify patterns of movement, angular velocity and acceleration. Chaffin[4] approximated the human body by a series of seven links so as to compute reactive forces and torques. Passerello and Huston[5] approximated the human body by ten elliptical conical links and, aided by a systematic organization of the complex geometry, they were able to

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write equations of motion. Karas and Staplenton[6)] used kinematic methods to analyze gymnastic motion. Bouisset and Pertuzon[7)] determined the mass moment of inertia of the humero-ulnar joint of the combined forearm and hand by modeling it as either a compund pendulum or a quick-released mechanism. Basmajian[8)] reviewed electromyographic techniques and investigated electromyographic properties of some muscles involving shoulder movements. MaConall and Basmajian[9)] combined human kinesiology with electromyographic studies to investigate muscle properties and movements of the human body. Inman, Saunders, and Abbot[10)] used electromyographic techniques together with comparative anatomical and roentgenographic analyses to analyze shoulder motion. Nubar and Contini[11)] developed a minimal principle for biomechanics. By postulating that an individual muscle will, consiously or otherwise, move in such a manner as to reduce its total muscular effort to a minimum consistent with imposed conditions. Nubar[12)] made a thermodynamic study of muscle contraction energy so as to establish the total enrgy of contraction of muscle. Seireg and Arvikar[13,25)] formulated a mathematical model for evaluation of forces in the musculoskeletal system of the lower extremity. Hill[14)] discussed the thermodynamics of human muscles. Gutstein[15)] developed a generalized form of Hooke's Law for muscle elasticity without reference to the thermodynamic or myographic properties of muscles. Fenn[16)] established the relation ship between changes in muscle length and force. Bigland and Lippold[17)] described a method for obtaining the relationship between force, velocity, and integrated electrical actity in human muscles. Ramsey and Street[18)] developed a relation between length and tension of skeletal muscles and found that tension developed in a maintained state of tetany is a maximum at the resting length and decreases with decreasing muscle length. Nubar[12)] studied stress-strain relations in skeletal muscle by considering muscle tissue to be a nonlinear material which obeys a form of Hooke's Law. Troup and Chapman[19)] applied static bending moments to the trunk in the sagittal plane and calculated mean lumbar extensor muscleforces and moments. Macleish and Charley[20)] used force and radi ographic measurements during a one-legged stance to determine abduction forces and location of center of center of mass. Merchant[21)] instrumented and loaded a dried male pelvis to determine muscle force distribution. Houbar[22)] developed equations for muscle contraction by assuming that muscle tension is developed as a function of time and is propagated down the fibers with constant velocity. Parnely and Sonmebloc[23)] developed a mechanical model of a muscle utilizing force generators, nonlinear springs and dampers.

The functions of individual muscles associated with the shoulder joint were studied by several researchers (Basmajian and Latif[26)]; Wright[27)]; Shevlin and Lucci[28)]) to determine the role of specific muscles for a given motion such as swimming, golf, climbing and swing of the arm by using electromyography.

The shoulder, which is the proximal joint of the upper limb is the most mobile joint in the human body. Although the shoulder joint is the one most commonly used in human activities, it is surprizing that it has been the subject of only a few studies. Furthermore, most of the previous investigations have dealt with the magnitude of the lines, muscular forces in terms of electromyographic and kinematic analyses. The reason for this is that the mechanism of shoulder movement is much more complicated than that of any other joint in human body.

Modeling of the System

In this work force distribution in the muscles crossing the gleno-humeral joint was determined for abduction of the arm about the anterior-posterior axis from zero to ninety degrees in 10 degrees increments. The zero anatomical reference position was defined as that taken by the upper limb when hanging vertically at the side of the trunk. The anatomical character of the gleno-humeral joint was investigated and measurements were taken by dissection of a corpse. The upper limb can rotate about three axes: the transverse axis, the anterior-posterior axis, and the vertical axis. In addition the upper arm can rotate around its longitudinal axis. This study, however, was concerned with abduction of the arm and, therefore, only rotation about the anterior-posterior axis was considered.

The movement of the shoulder joint can be divided into two main types of movement: major movement and minor movement. The major movement consists of humeral movement and the minor movement consists of scapular. Humaral movement can be thought of as a combination of abduction, adduction, medial rotation, lateral rotation, flexion and extension of the forearm. Scapular movement can be thought of as the combination of forward movement, backward movement, downward movement, upward movement, and rotation of the scapula. The latter movement would involve flexion of the spinal colum. Generally, scapulo-humeral group muscles, axio-humeral group muscles, the biceps and triceps are involved in humeral movement and the axio-humerla group muscles influence scapular movement. Evaluation of the arm, in either the coronary or frontal plane, is relatively independent of the motion of the joints of the scapular complex. Therefore, only the motion of the gleno-humeral joint of the shoulder girdle was considered in this study. The other joints (subdeltoid, scapulo-humeral, acromio-clavicular, sterno-clavicular and scapulo-thoracic) were considered to be stationary since, for abduction from zero to ninety degrees, the participation of these joints in the motion is relatively minor.

The muscles were assumed to participate in the motion were following: deltoid, supraspinatus, infraspinatus, subscapularis, teres major, teres minor, pectoralis major, biceps, triceps, coracobrachialis, latissimus dorsi.

Since it was important to formulate a model using anatomical data for the points of orgin and insertion points of muscles, a few anatomical and physiological assumptions were necessary. In order to represent muscle forces as vectors it was necessary to determine the acting points of the force vectors. Therefore, muscles were assumed to have distinctive origin and insertion points and the acting forces were assumed to be along the lines that connect the two points. In many cases it was quite difficult to define the acting points because muscles are originated and inserted by regions or lines rahter than points. In the cases in which a muscle originated or inserted in a region, appropriate graphical centers of the region were chosen as acting points. In cases where the muscles originated or inserted approximately along lines, the middle of the line was chosen as the acting point. The deltoid, pectoralis major and biceps were considered to be consisted of more than one muscle fiber. The delotid was represented by three vectors and the pectoralis major and bieps by two vectors each. With these assumptions the total nmuber of muscle forces used in the analysis was fifteen. The points and thd the vectors represent of some muscle forces are shown in Figures 1 to 3.

The head of the humerus was assumed to be round and it was assumed that there was no friction between the glenoid fossa and the head of humerus. With this assumption resultant reaction forces would go through the center of the head of humerus.

Also, only quasi-static motion of the upper limb was considered. That is, it was assumed that the center of rotation of the upper limb remained stationary throughout the rotation. The center of rotation of the humerus was determined by measuring the change in position of eight selected points on the humerus as it rotated 0 to 90 degrees. Of course, the center of rotation does not remain entirely constant but changes slightly throughout the motion. Therefore, an analysis was conductedto determine the sensitivity of the motion of the location of the center of rotation by performing a number of analyses with different centers of rotation.

The whole upper extremity (upper arm, lower arm and hand) was considered to be

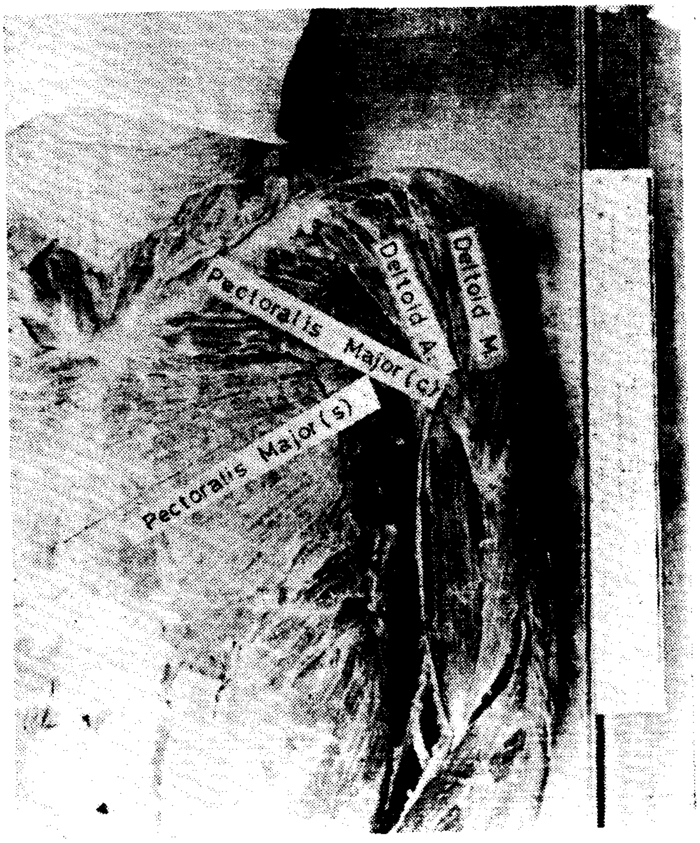


Fig. 1. Intact Muscles (Anterior View)

A : Deltoid Middle B : Deltoid Anterior
C : Pectoralis Major (c) D : Pectoralis Major (s)

Fig. 2. Vector Representation of Some Muscles (Front)

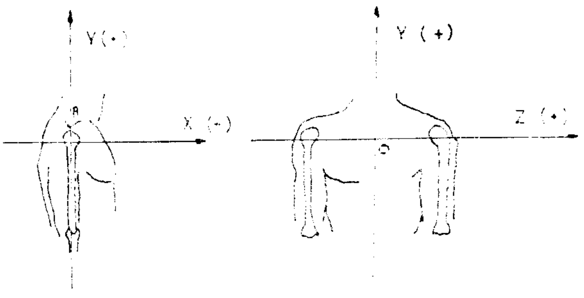
a rigid link. An external force, representing a weight, was concentrated at the center of the hand. The segment weight and the external force were taken to be a net applied weight for the system.

Figure 4 describes the coordinate system used and Table 1 lists the coordinates, in millimeters, of the origin and insertion points of each muscle force vector used in this analysis. Table 2 gives some geometric properties (length, effective radius, effective area) of the muscle.

The above data were collected from the cadaver of 25 years old normal male. After finding the insertion and origin points in the position of zero abduction, the lengths, direction cosines and moment arms of every muscle were calculated for every abducting position to 90 degrees interval by fixing the origin point and rotating the insertion point with respect to the center of rotation. Table 3 shows the anatomical data for muscles at reference posture of 0 degree abducting position.

The changes in muscle length with change in rotation angle is shown in Figure 5 for the muscles which increase in length and in Figure 6 for the muscles which decrease in length.

E : Detoid Posterior F : Subscapularis
G : Teres Major H : Latissimus Dorsi
Fig. 3. Vector Representation of Some Muscles (Back)



Reference points : O is jugular notch of the sternum.
A is acromion process of the scapular.
Fig. 4. General coordinate of shoulder muscle.

Table 1. Origin and Insertion Points of Muscles (mm)

i	Name of Muscles	Origin			Insertion		
		X	Y	Z	X	Y	Z
1	Deltoid anterior	70	87	145	8	-46	217
2	Deltoid middle	0	104	189	8	-46	217
3	Deltoid posterior	-50	70	130	8	-46	217
4	Supraspinatus	-40	85	94	0	73	208
5	Infraspinatus	-70	-5	98	0	76	201
6	Subscapularis	-65	10	147	30	85	186
7	Teres major	-70	-46	116	7	0	185
8	Teres minor	-70	-12	126	-5	60	213
9	Pectoralis major (s)	72	-56	0	9	0	197
10	Pectoralis major (c)	72	34	48	9	0	197
11	Biceps long	15	94	191	15	-297	198
12	Biceps short	10	60	181	15	-297	198
13	Triceps	-20	34	173	-20	-259	220
14	Coracobrachialis	10	60	181	10	-29	198
15	Latissimus dorsi	-70	-209	19	7	-10	189

Table 2. Length and Cross Sectinal Area of Muscles

i	Name of Muscles	Length (mm)	Radius (mm)	Area (mm^2)
1	Deltoids anterior	164.8	13.53	578.9
2	Deltoid middle	151.8	23.87	1790.5
3	Deltoid posterior	156.0	17.50	962.9
4	Supraspinatus	104.9	16.71	877.3
5	Infraspinatus	148.7	21.48	1450.3
6	Subscapularis	107.6	22.28	1564.6
7	Teres major	113.2	19.10	1145.9
8	Teres minor	132.6	11.93	446.8
9	Pectoralis major (s)	214.0	17.51	962.8
10	Pectoralis major (c)	165.1	11.14	447.6
11	Biceps long	375.1	12.73	509.3
12	Biceps short	362.6	11.14	389.9
13	Triceps	291.0	20.37	1303.8
14	Coracobrachialis	91.8	11.94	447.6
15	Latissimus dorsi	270.8	22.42	1564.6

Mathematical Analysis

Using the physiological model developed, force and moment equilibrium equations can be written at the center of rotation

$$\begin{aligned} &\Sigma F_{xi}+R_x=0 \\ &\Sigma F_{yi}+R_y=F_W \\ &\Sigma F_{zi}+R_z=0 \qquad i=1,2,\cdots,15 \end{aligned} \tag{1}$$

and

$$\begin{aligned} &\Sigma M_{xi}+R_{Rx}=M_W \\ &\Sigma M_{yi}+M_{Ry}=0 \end{aligned} \tag{2}$$

Table 3. Anatomical Data for Muscle at Reference Posture

i	Name of Muscles	Distance from Origin to Inser. (mm)			Moment arm from Center of Rotation (mm)		
		X	Y	Z	Lx	Ly	Lz
1	Deltoid anterior	62	135	-71	8	-120	30
2	Deltoid middle	-8	149	-28	8	-120	30
3	Deltoid posterior	-58	115	-88	8	-120	30
4	Supraspinatus	-40	0	-97	0	17	6
5	Infraspinatus	-70	-80	-104	0	8	15
6	Subscapularis	-95	-84	-39	32	12	0
7	Teres major	-77	-46	-69	7	-69	2
8	Teres minor	-65	-75	-88	-5	-10	27
9	Pectoralis major (s)	63	-55	-197	9	-67	11
10	Pectoralis mijor (c)	63	33	-149	9	-67	11
11	Biceps long	0	375	8	15	-371	14
12	Biceps short	-5	362	-20	15	-371	14
13	Triceps	0	288	-42	-20	-318	26
14	Coracobrachialis	0	90	-18	10	-103	12
15	Latissimus dorsi	-77	-198	-168	7	-81	4

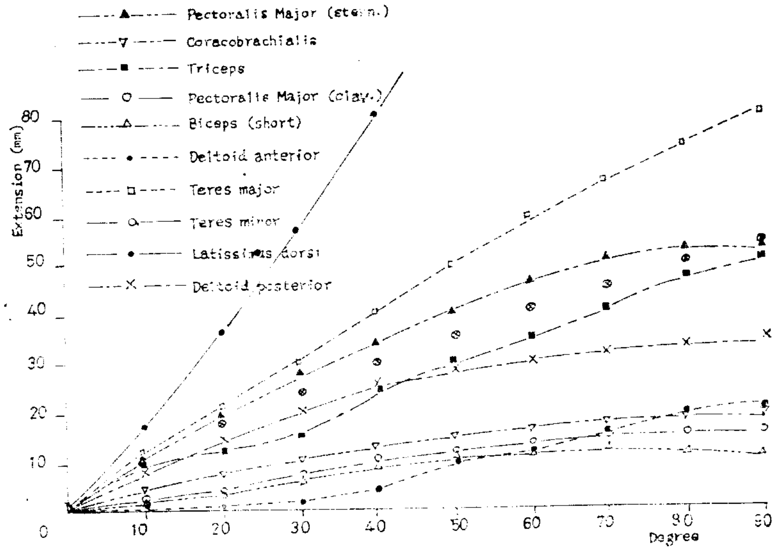


Fig. 5. Length-Degree diagram of extending muscles.

$\Sigma M_{Zi}+M_{Rz}=0 \qquad i=1,2,\cdots,15$

Where F_{Xi}, F_{yi} and F_{Zi} are the x,y, and z components of the force probuced by the ith muscle, M_{Xi}, M_{yi} and M_{Zi} are the x,y, and z components of the moment produced by the ith muscle, R_X, R_y and R_Z are the x,y, and z components of the reaction force at the joint, F_W is the total weight of the upper arm, lower arm, hand and external load held in the hand (F_W is taken to be 10kg) and M_W is the moment produced at the joint. M_{Rx}, M_{Ry} and M_{RZ} are moments due to the reaction force components R_x,R_y and R_Z. Due to the assumption that the resultant reaction

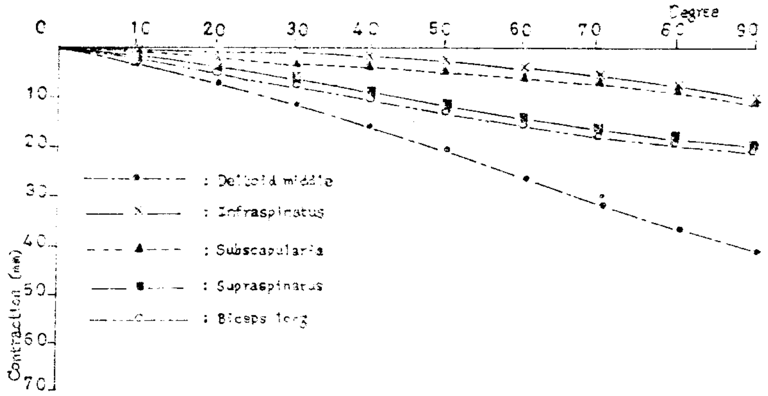


Fig. 6. Length-Degree diagram of contracting muscles.

forces would go through the center of rotation, M_{Rx}, M_{Ry} and M_{Rz} become zeros.

From these equilibrium equations of the system it is clear that there are six equations in eighteen unknowns (15 muscle forces and 3 reaction forces). Since there are more unknowns than equations, the system is said to be statically indeterminate and additional information is necessary in order to solve for the muscle forces.

The additional information used in this snalysis came from the minimal principle of Nubar and Contini.[11] They assumed that the human system adjusts itself in such a manner so as to minimize the total muscular effort. They define muscular effort as:

$$E = A_0 + (\Sigma c_i M_i^2 \triangle t) \quad i = 1, 2, \cdots, 15 \quad (3)$$

where E is the muscular effort, A_0 is an initial constant, M_i is the magnitude of the moment produced by the ith muscle, c_i is a constant and t is time.

For a specific position of humerus, the equilibrium ondition can be considered to be constraint conditions for this system. Equation (2), the constraint equations, can be rewritten in the form:

$$f_1(M_i) = M_w$$
$$f_2(M_i) = 0 \qquad (4)$$
$$f_3(M_i) = 0 \qquad i = 1, 2, \cdots, 15$$

where f_1, f_2 and f_3 are equilibrium conditions in the x,y, and z directions.

By differentiations of E in equation (3), using equation (4) and applying the method of Lagrange's undetermined multipliers, the following differetial element equation can be obtained,

$$\left(M_i + \lambda_1 \frac{\partial f_1}{\partial M_i} + \lambda_2 \frac{\partial f_2}{\partial M_i} + \lambda_3 \frac{\partial f_3}{\partial M_i}\right) dM_i = 0 \qquad (5)$$

where λ_1, λ_2 and λ_3 are Lagrange's undetermined multipliers. Since the variations dM_i are independent and arbitrary, their coefficient must be zero. In above differentiation of E, for normal individual, operating in normal condition, c values were taken as equal and dropped out. Therefore,

$$\left(M_i + \lambda_1 \frac{\partial f_1}{\partial M_i} + \lambda_2 \frac{\partial f_2}{\partial M_i} + \lambda_3 \frac{\partial f_3}{\partial M_i}\right) = 0 \qquad (6)$$

Equation (6) is really 15 equations, one for each muscle. With the equations of mathematical equatilibrium, there are 21 equations in the 21 unknowns (15 muscle forces, 3 reaction forces and 3 Lagrange's multipliers). These equations were solved to obtain the 15 muscle tensile forces $F_1, F_2, .., F_{15}$. Details of this solution can be found in the work of Park.(24)

Results

The results of the solutions to this set of simultaneous equations at the various angular positions are presented as degree-force graphs in Figures 7 to 9. These graphs constitute the results of this work and show the force distribution in the muscles crossing the glenohumeral joint in abduction of the arm from 0 to 90 degrees.

As mentioned previously, a sensitivity analysis was conducted to determine the sensitivity of the resulting forces to changes in the location of the center of rotation of the humerus. This was accomplished by repeating the entire analysis with different locations for the center of rotation displaced 5mm in each of the following directions: upward, downward, medially and laterally.

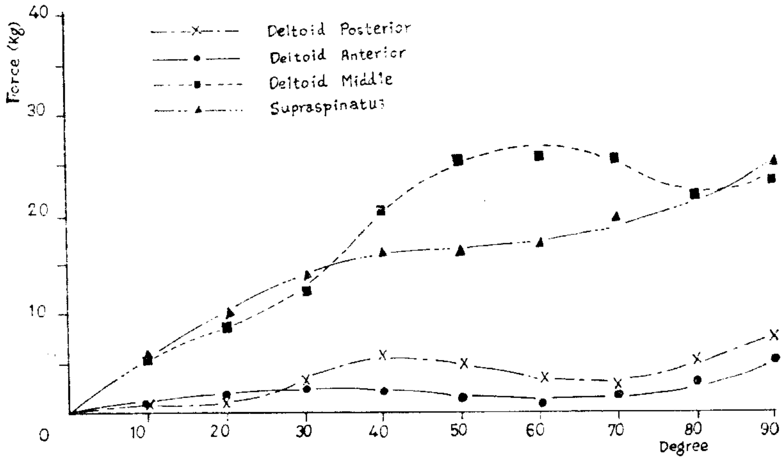


Fig. 7. Force-Degree diagram abduction muscles.

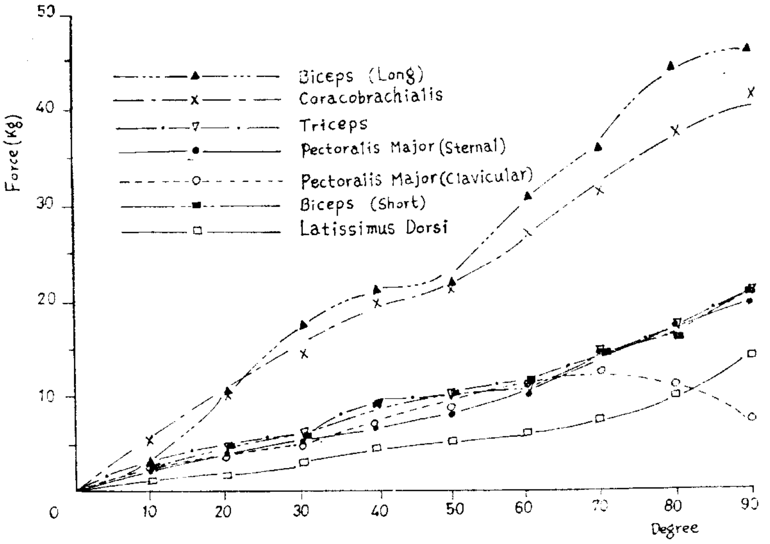


Fig. 8. Force-Degree diagram adduction muscles.

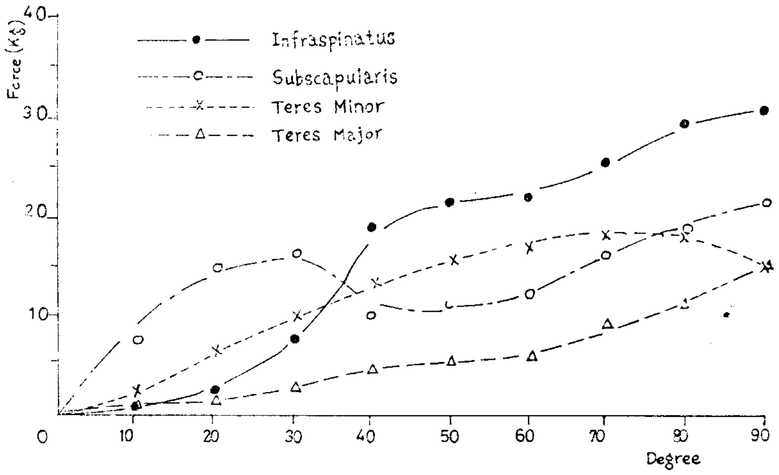


Fig. 9. Force-Degree diagram cuff muscle.

The variations in force were small with the largest single variation being for the infraspinatus muscle at 90 degree of rotation for the case where the center of rotation of the humerus was moved down 5mm. For this case the force determined was 1.5kg (or 4.8%) larger than the force with rotation about the measured rotation center.

Discussion and Conclusions

Based on this work, several conclusions can be reached concerning both the methodology employed and the physiological results.

With regard to the methodology, it is concluded that any statically indeterminate muscle force determination problem in the human boey can be approached by this technique of application of vector methods and the minimal prinimal principle, no matter how complicated the problem might be. Also if the center of rotation of a joint is chosen with care, small errors in its location are of minor importance.

With regard to the physiological results of this analysis, it is concluded that the role of the cuff muscles is important to stabilizigng the gleno-humeral joint as these muscles exert large forces compared to the adducuction muscles. However, the role of the abduction and adduction muscles is very important because they have very large moment arms adn produce the large moments required for abduction and adduction.

As a result of this research several questions have become evident and should be clarified by further research. The question as to the accuracy of the physiological modeling is important. The locations of origin and insertion points were determined by dissection of a cadaver. It was, therefore, difficult to maintain the proper flexibility characteristics of the body in its movements. Also the approximation of the origin and insertion areas by one, two, or at best three points may be questioned. The effects of subdividing more muscles into parts should be investigated.

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