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# Determination of Muscle Orientations and Moment Arms

*In muscle force analysis, orientations and moment arms of the muscles about a joint provide essential coefficients in the equilibrium equations. For the determination of these parameters, several experimental techniques, including geometric measurement, tendon-joint displacement measurement and direct load measurement, are available. Advantages and disadvantages associated with each of the techniques are reviewed and compared based on our extensive experience.*

## Introduction

Analytic calculation of internal forces in the joints and muscles of the musculoskeletal system has been one of the challenging topics in the field of biomechanics. In general, accurate data concerning the muscle orientations and moment arms are required to define the coefficients in the equilibrium equations of the muscles. The relative accuracies of the resultant muscle and joint forces are proportional to the accuracies of specifying the moment arms and orientations of muscle lines of action.

In the past, simplified analytic studies with a straight line or lines joining the points of origin and insertion of muscles were used to define the directions of muscle forces [4, 9]. The locations of origins and insertions have been measured by planar [8] or biplanar radiography [1]. These data have also been measured directly from specimens [10] or through the serial sectioning method [5, 6].

Besides the geometric measurement, the techniques of applying the principle of moment equilibrium about a joint, namely, the ratio of forces is equal to the ratio of the shortest distance from the fulcrum to the line of action of these forces, were used in measuring the moment arms [7]. In addition, based on the relationship among the moment arm, tendon excursion and joint angle, the moment arms of muscles could also be obtained [2, 3].

The purpose of this report is to compare currently available techniques based on our experience. Theoretical background, specific experimental techniques and associated advantages, disadvantages and limitations of each technique will be discussed.

## Theoretical Background

In general, equilibrium equations for force analysis of the musculoskeletal system are formulated by free-body force analysis in which the musculoskeletal system is considered as a linkage system of intercalated bony segments balanced by two groups of forces. The first group consists of the resultant passive constraint forces and moments exerted by the joint articulating surfaces and ligaments. The other group consists of the active tensions of tendons and muscles.

In the force equilibrium equations, the "coefficients" of the muscles represent the components of the unit force vector of the muscles in the respective coordinate axes. In moment equilibrium equations, the coefficients of the muscles represent the three components of the moment arm of the muscle force vector about the joint center with respect to the three axes.

An alternate approach to formulate the equilibrium equations is based on the principle of virtual work [11]. In this formulation, it is assumed that in the direction or plane of the degree of freedom of motion the ligaments are inextensible, and the frictionless bony contacts are treated as workless constraints. If external moment, $Q$, is applied to the distal segments of the joint resulting in forces, $T_i$, in the tendons and muscles, the principle of virtual work gives

$$\sum_{i=1}^{n} T_i \left( \frac{dX_i}{d\theta} \right) + Q = 0 \qquad (1)$$

in which the displacements of the tendons ($X_i$) are assumed to be a function of the joint displacement ($\theta$).

The above equation implies that the instantaneous moment arm in the plane of motion at a specific joint configuration would be obtained from the slope of the plot of the tendon excursion versus joint angle. In fact, this relationship among tendon excursions, moment arms, and joint angles can also be derived through analytic modeling of the tendons across the joint [2].

## Experimental Methods

The experimental techniques to determine orientations and moment arms of muscles can be divided into three broad categories.

**Geometric Measurement.** The geometric measurement method, in principle, is to locate the tendon and muscle paths

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at the joint in terms of the joint coordinate system and then calculate the orientations and moment arms of the lines of action of muscles based on the coordinates of points on the paths. To determine the tendon and muscle paths, three methods are available.

(*a*) *Biplanar X-ray Method.* In this technique, specimens with metal markers inserted in the tendons and muscles are subjected to biplanar X-ray exposure. From true AP and lateral views, with known distances between the X-ray source and the films, the three-dimensional locations of these markers are reconstructed.

Proper selection of locations for the metal markers along the tendon paths is very important. Usually, this requires knowledge of how these tendons and muscles are constrained when crossing the joint.

(*b*) *Direct Digitization Method.* Basically, this method is similar to that of the biplanar X-ray method except for the use of a three-dimensional digitizer instead. However, in order to achieve direct measurement of the muscles and tendons, more extensive dissection and exposure of the specimens are usually required.

(*c*) *Serial Cross-Sectioning Method.* Conventionally, this technique involves steps of specimen embedding, sectioning, photographing and digitizing. Coordinates of the centroids based on the digitized perimeters of the muscle and tendon cross sections are then calculated for each slice and used to represent muscle paths. The muscle orientations are calculated based on the unit vectors tangential to the centroid lines. From these tangential vectors and corresponding position vectors, the moment arms are calculated. Recent advances in computerized tomography provide a noninvasive technique for performing serial cross sectioning. Unfortunately, the resolution is not yet satisfactory for separating individual soft tissues.

**Tendon and Joint Displacement Method.** This particular method is mainly for determining moment arms using the relationship as described in equation (1). The basic equipment consists of an electrogoniometer and an electropotentiometer to monitor joint angles and tendon excursions during joint rotation. While performing the test, a constant weight is usually applied to the tendon, and rotation of the joint is performed slowly in order to eliminate any possible error due to the viscoelastic characteristics of soft tissue.

From the tendon and joint displacement curve, the slope at various joint angles throughout the range of joint motion can further be derived, which represents the moment arm about the center of rotation of that particular muscle in the plane of motion.

**Direct Load Measurement Method.** The rationale for direct load measurement is very simple. Muscles and tendons create forces which are transmitted through the joint and applied to the distal segment. If the forces and moments created on the distal segment can be monitored when loads are applied to these muscles, then the coefficients in the force and moment equilibrium equations can be obtained.

(*a*) *Two-Dimensional Approach.* This approach is usually utilized to determine the moment arm about a hinge joint, such as the finger interphalangeal joint, elbow joint or knee joint. A single-load transducer is utilized to monitor the forces preventing rotation of the distal segment when a load is applied on the muscle proximally. Muscle moment arms are calculated based on simple fulcrum equations.

(*b*) *Three-Dimensional Approach.* The foregoing concept can easily be generalized for three-dimensional analysis in which the distal and proximal segments of the specimens are rigidly mounted, each on a separate fixture with a three-dimensional (six-component) load transducer placed between the distal fixture and the table. Before loading the muscles, the joint is manipulated so that minimal joint constraints due to articular contact force and ligament tension are imposed upon the bony segments. A known weight is then applied on one single muscle. The force and moment created at the distal segment are registered by the load transducer and normalized to the weight for the coefficients in the force and moment equations.

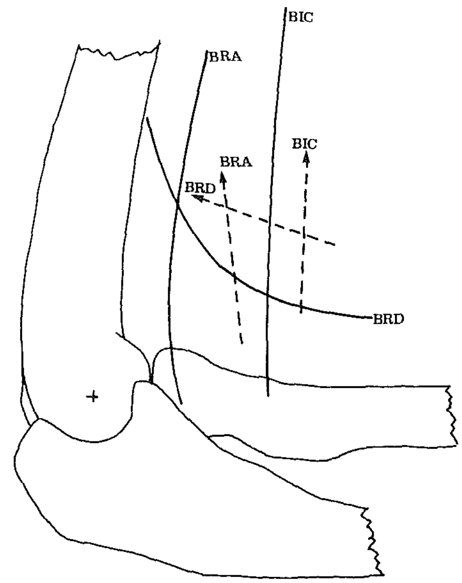

**Fig. 1 Comparison of the elbow muscle paths obtained by serial cross sections (solid line) and those of straight lines joining the origins and intersections (dotted line) – BIC = Biceps, BRA = Brachialis, BRD = Brachioradialis**

## Results

For illustration and comparison of various methods, two examples are presented. First, the moment arms of both intrinsic and extrinsic muscles during abduction-adduction motion of the metacarpophalangeal (MCP) joint of the index finger have been determined [2]. In general, the determination of these moment arms using geometric measurements was difficult due to a less well-defined center of rotation and constraint of the tendon path at the MCP joint. In addition, for the extrinsic muscles, the lines of action lie almost on top of the center of rotation. Slight misplacement of the markers for the geometric measurements causes great error in the results. However, by using the method of tendon-joint displacement, the individual moment arms were clearly defined. The specific functions of the extrinsics in abduction-adduction of the index finger MCP joint were, for the first time, verified experimentally. Although the magnitude of the abduction moment arm of the extensor digitorum is small, its contribution to strong key pinch force along with the radial interosseous and lumbrical is significant.

Second, the lines of action of the three major elbow flexors were examined. Geometric measurements based on biplanar X-ray and cross-sectional methods, as well as the three-dimensional load measurement technique, were used. The paths of the flexors across the elbow joint were obtained by using the centroid of the muscle and tendon cross sections (Fig. 1). The curved nature of these muscle paths, especially the brachialis and brachioradialis, makes representation of the line of action by straight lines between origins and insertions inappropriate. Not only will the orientation be different, the flexion moment arm can also be increased by almost 50 percent in the flexed position.

The orientation and moment arms, as determined by using three-dimensional load measurement, are relatively similar to those when using biplanar X-ray measurement with this particular arrangement of the metal markers (Fig. 2).

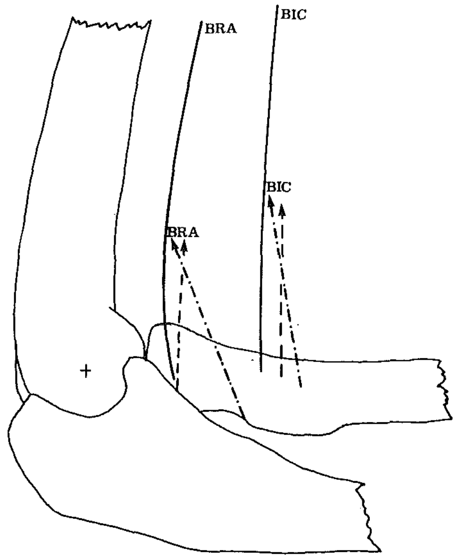


Fig. 2 Comparison of the elbow flexor lines of action as obtained by using the load cell (----), as well as biplanar X-ray digitization (·······). The solid curve represents the muscle path obtained by using serial cross sections.

However, due to the nature of the curved paths of these muscles, the orientation and moment arms, when using geometrical assessment, can possibly be different when different points are selected to represent the line of action.

## Discussion

Each of the experimental techniques has its own merits, as well as disadvantages. The method of geometric measurement provides not only the moment arms, but also the orientations of the lines of muscle action. This method is best suited for those tendons crossing the joint with a well-defined pulley constraint and known joint center of rotation. Otherwise, the selection of the optimal location along the tendon path to represent the line of action of the muscles across the joint is difficult. Furthermore, the measurement procedures usually require extensive dissection, thus possibly disturbing the constraints of the muscles or tendon paths. Of course, the serial cross-sectioning technique is generally able to preserve these constraints; but the technique which uses a band saw for sectioning is a destructive method and does not allow a single specimen to be studied at multiple joint configurations. Hopefully, this difficulty can be resolved in the future by using computer tomography.

The tendon-joint excursion method is probably the least involved in terms of experimental procedures. Since each experiment requires rotating the joint through the whole range of motion, data at multiple joint configurations are available for a single experiment. However, this method allows the determination of only the moment arms in the plane of rotation. The major advantage of this method, of course, is that the moment arm can be accurately measured without knowledge of the axis or center of joint rotation. In fact, accurate moment arms obtained by this method can be utilized in the geometric measurement technique to optimally select locations along the path of the tendon or muscle for the determination of the line of action.

The direct load measurement method, theoretically, should provide the most accurate force and moment coefficients, simply because this method deals with the load directly. This is unlike the geometric measurement method in which the orientation and moment arms are indirectly derived. However, from an experimental viewpoint, the direct load method is more demanding. It requires rigid fixtures and sensitive load transducers, since the method is based on the premise that the load observed on the distal end of the joint is due totally to the force applied to the tested muscle. In other words, the friction loss through the pulley or along the sheath and joint contact and surrounding soft tissue constraint forces are either assumed to be negligible or measurable.

In summary, the best selection of an experimental method depends on the specific objective and nature of the study. If possible, various methods should be used as a cross check. Of course, anthropometric variations also have an effect on the results. Fortunately, in most cases, with appropriate normalization, the variation can be reduced and confined to less than 20 percent.

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