The study of loading in the muscle is essential to better understanding the adaptation and plasticity of the muscle under pathologic or surgically-altered conditions. Muscle recruitment and muscle force are determined by the muscle’s mechanical function as a joint mover and a joint stabilizer. The coordination of muscle contraction affects joint stability. However, the conditions of the joint passive constraints influence the muscle recruitment. Furthermore, muscle force is regulated based on muscle size, such as the physiologic cross-sectional area, and its physiology, namely, the length-tension and the tension-velocity relationship. Alterations of these physiologic relationships also will influence the overall mechanical function of the muscle.

Biomechanically, muscle is considered to be an actuator, which provides force and power for the movement and balance of the musculoskeletal structures. Muscle physiology regulates the function of the muscle under static and dynamic conditions. The anatomic arrangement of muscle relative to the skeletal structure determines the mechanical behavior and efficiency of the function. In general, a muscle can cross several joints, and there can be numerous muscles spanning one given joint. The recruitment of the muscle and the magnitude of the muscle force exerted for a given task therefore are dependent on muscle physiology and the mechanical arrangement of the musculoskeletal system.

Mechanical loading of connective tissue has been found to be significant to the plasticity and biologic remodeling of the tissue. The same influence of mechanical loading on tissue remodeling has been recognized for muscle. To understand better the plasticity of muscle under various physiologic and pathologic conditions, additional study of muscle force is important. The current author will focus on the discussion of the factors that regulate muscle recruitment and muscle force. In addition, the contribution of the muscle to joint dynamic stability will be considered.

**Muscle Function**

Based on rigid body mechanics, when force and moment applied to an object are balanced the object will maintain its equilibrium position. However, if the force and moment are unbalanced, there will be an associated acceleration in translation and rotation. Mathematically, such interaction can be described by the equilibrium equations when doing free-body analysis. From this mechanical point of view, the musculoskeletal system can be thought of as a collection of rigid segments interconnected at the
joints. The muscles serve as actuators providing forces to move the segments and balance the joint. Therefore, biomechanically the function of muscle has been regarded as a segment mover and also a joint stabilizer. The function of mover and stabilizer can be described respectively based on the moment arms and line of action considered in the equilibrium equations.

Physiologically, muscle anatomy and physiology also regulate the tension generated by the muscle. Therefore, in determining muscle function and muscle force, muscle physiology, such as length-tension and tension-velocity relationships, need to be considered.\(^3\)

**Muscle as Segment Mover**

To achieve equilibrium of rotation, the resultant moment generated by external loading has to be balanced with the moment generated by muscle contraction. The moment generated by the muscle is equal to the muscle force multiplied by the moment arm of the muscle force to the joint axis of rotation. The larger the moment arm the greater the mechanical advantages of that muscle, and therefore, less force is required to resist a fixed amount of external loading.

It is helpful to recall that muscle crosses a joint in a three-dimensional fashion. In general, muscle contraction will generate moments about all three axes of rotation of a given joint. However, when the constraints of other periarticular soft tissues are not available, the muscle will have the primary responsibility for maintaining balance of joint rotation. For example, the flexors and extensors of the elbow are the primary elements responsible for resisting any flexion and extension joint moment attributable to external loading. The contractions of elbow flexors and extensors also will generate valgus and varus moment about the elbow. However, within normal anatomic conditions when the varus and valgus rotation of the elbow is restricted by the collateral ligaments and the joint articulating surfaces, the contribution of muscle moments are not manifested.

For joints with additional degrees of freedom where the capsuloligamentous constraints are not important, the contribution of muscle moment in multiple planes is greater. For example, the wrist has two-degrees-of-freedom, namely flexion and extension and radial and ulnar deviation (Fig 1A). Cross-sectional anatomy clearly shows the tendon of wrist muscle crossing the joint with both moment-arms about the axes of flexion and extension and radial and ulnar deviation. Contraction of the flexor carpi ulnaris causes flexion and ulnar deviation, and contraction of the extensor carpi radialis causes extension and radial deviation. The recruitment of muscle activities, as measured by electromyography, thus depends on the resultant joint moment generated by the external loading (Fig 1B).

For muscles crossing multiple joints, recruitment of muscle activities depends on the moments of all the joints spanned by the muscle. The concept of multiple joint muscle is extremely important in the clinical setting. For example, the tendons of extrinsic flexors and extensors of the hand span not only the wrist, but also the metacarpophalangeal and interphalangeal joints. Contraction of the muscle coordinates the movement of all these joints. The dynamic tenodesis effect has been adopted for controlling hand prosthetics and consideration in mobilization after tendon repair.\(^5\) Synergistic wrist motion allows for full finger joint extension with the wrist in flexion, and alternatively allows full passive finger flexion with the wrist in extension so that the full excursion of repair tendon could be expected and the formation of tendon adhesion could be reduced.\(^5\)

As another example, consider rehabilitation after reconstructive surgery of the anterior cruciate ligament. Various types of exercise have been developed. The goal of these rehabilitation protocols is to have adequate muscle strengthening but have moderate or no tension placed on the ligament. Quadriceps loading, especially with the knee in a near extended position, results in anterior joint shear force and displacement of the tibia. Such shear force induces tension in the anterior cruciate ligament. The concept of kinetic chain has been used extensively to address this.\(^7,9\) In fact, this principle simply is based on the concept of two-joint muscles. During closed kinetic chain exercises
such as squat and leg press, the foot is fixed and motion at the knee is accompanied by motion at the hip and ankle. The ground reaction force applied along the tibial axis causes flexion moments at the knee and hip (Fig 2). The antagonistic muscle of the hamstrings at the knee is recruited to balance the hip flexion moment. Cocontraction of the quadriceps and hamstrings at the knee result in reduced anterior joint shear force, thereby reducing tension in the anterior cruciate ligament.7,10

From the perspective of the muscle as segment mover, the recruitment of muscle activities depends very much on the contribution of the muscle in resisting the joint moments resulting from the external loading. The primary constraint on the specific rotation associated with the degrees of freedom of the joint, where the periarticular constraint is negligible, is muscle. It is highly possible to have multiple functions in rotation at one joint or a single function at multiple joints of a given muscle, or both. The magnitude of the muscle force also depends on the relative mechanical efficiency, namely the moment arm of the muscle in resisting the particular moment.

Muscle as a Joint Stabilizer
To achieve equilibrium of translation, the resultant joint forces caused by external loading must be balanced by the summation of forces generated by individual muscles across the joint. In a three-dimensional situation, such force equilibrium equations have to be satisfied along each of the three directions or axes. A given muscle force at a given joint can be decomposed into three components that commonly are used to represent the lines of action of the muscle. If the muscle force component is in the direction to contribute to the balance of the resultant joint force, then the muscle is a joint stabilizer. However, if the muscle force component is not in favor of balancing the resultant joint force, but rather in the same direction as the resultant joint force, then this muscle even may facilitate joint subluxation and dislocation.

The glenohumeral joint in the shoulder is a unique articulation that, under normal circum-

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**Fig 1A–B.** (A) The moment arms of the five wrist motor tendons (ECRL = extensor carpi radialis longus; ECRB = extensor carpi radialis brevis; ECU = extensor carpi ulnaris; FCR = flexor carpi radialis; FCU = flexor carpi ulnaris), were expressed as dots on the cross section view of the wrist. The potential moment contribution to the wrist was estimated by multiplying the moment arm of the muscle by its physiologic cross-sectional area,² and is expressed by arrows. (B) The activities of the flexor carpi ulnaris when the wrist was loaded in the specific directions, flexion (FL), extension (EX), radial deviation (RD), and ulnar deviation (UD) were expressed in the normalized electromyographic signals. Muscle action usually provided resistance or movement in more than one direction or plane.
Fig 2. Anterior tibial translation could be expected as a consequence of isolated quadriceps contraction. Stabilization of the tibia would be accomplished through hamstring contraction. The induction of muscular cocontraction at the knee is attributable to the multiple joint function of the hamstring to balance the hip flexion moment caused by the applied force. $A = \text{applied force; } r_h = \text{hip moment arm; } r_k = \text{knee moment arm.}$ (Used with permission of the Mayo Foundation.)

instances, maintains a balance between its high degree of mobility and its lack of intrinsic stability. Static and dynamic factors are responsible for glenohumeral stability. The line of action of each rotator cuff muscle, representing the direction of its force vector, can be resolved into compressive and shear components. The magnitude of these components changes as the humerus rotates from neutral (midrange) to 90° external rotation (end range). The rotator cuff muscles contribute primarily in compression in the midrange and end range of motion of the glenohumeral joint in that the magnitudes of the compressive force components accounted for in more than 85% of the force generated by each muscle in these ranges. The shear force components in the anteroposterior (AP) direction generated by each rotator cuff muscle changes significantly with rotation of the humerus. The direction and magnitude of the shear force components in the superoinferior direction also vary significantly with humeral rotation. In neutral rotation, the shear force components generated by the four muscles are directed inferiorly. As the humerus is rotated externally more than 67.5°, the infraspinatus and supraspinatus generate superior shear force components.

The compressive force component of the muscle stabilizes the glenohumeral joint by a mechanism referred to as concavity-compression. The stability is related to the depth of concavity and the magnitude of the compressive force. Specifically, the anterior subluxation of the humeral head can be stabilized by the compressive force component of the muscle through the concavity-compression mechanism, and the shear force component of the muscle in the AP direction that can decrease or increase the stability in the anterior direction. The stability ratio is a concept describing the maximum dislocating force in a given direction that can be stabilized by the compressive muscle load on the glenoid fossa. For accounting muscle stabilizing function of compressive and shear force components, the dynamic stability index has been defined to represent the combined stabilizing effects of the rotator cuff muscle force vectors and the concavity-compression mechanism of the glenohumeral joint. The unit of the dynamic stability index is a percent magnitude of the transversely stabilizing force of the magnitude of the rotator cuff muscle force. The dynamic stability index in the anterior direction for example, can be derived as follows:

$$\text{Dynamic stability index (DSI) = \% compressive force \times stability ratio in anterior direction} - \% \text{ anterior shear force}$$

The dynamic glenohumeral stability in the anterior direction provided by an individual rotator cuff muscle with the humerus in midrange differs significantly from that with the humerus in end range in terms of the dynamic stability index values. In the midrange
of motion, the dynamic stability indices for the supraspinatus and subscapularis are greater than those of the infraspinatus and teres minor. In end range, the dynamic stability indices in the anterior direction provided by the teres minor and infraspinatus increases significantly, whereas those by the supraspinatus and subscapularis decreases significantly.

To also show the importance of the coordinative efforts of muscle action, the elevation of the shoulder is considered. First, assume that the deltoid muscle acts alone; second, that the supraspinatus muscle acts alone; and third, that the deltoid and supraspinatus muscles act together and the relative force generated by each muscle is proportional to its physiologic cross-sectional area. The results of the joint reaction force and the direction in relation to the glenoid surface have been obtained (Fig 3). In general, the joint reaction force is highest at approximately 90° arm elevation. This is because the largest moment generated by the weight of the upper arm must be balanced by the muscle force that induces the largest joint reaction force. At lower positions of arm elevation, the supraspinatus muscle has a larger moment arm and a greater mechanical advantage than the deltoid muscle. Using the supraspinatus to counterbalance the moment at this position requires less muscle force and less joint reaction force. When the arm is elevated at a higher position, the deltoid muscle has a greater mechanical advantage; therefore, the modes that use the deltoid muscle show a lower joint force. Because the shoulder is not inherently stable, the orientation and location of the joint reaction force with respect to the glenoid surface is another important parameter for consideration. More centrally located joint reaction forces will not only favor the joint pressure distribution, but more importantly, be associated with more stable joint condition. Off-center joint force has more potential for subluxation and dislocation. Joint force associated with supraspinatus contraction is more centrally located because the relative orienta-

**Fig 3A–C.** Direction and magnitude of the resultant joint force vector for different glenohumeral joint positions (0° to 150° arm elevation) as a function of different muscle activity are shown. Because of the direction of the line of action of the muscles, (A) the associated resultant joint force by the deltoid muscle alone tends toward the superior rim of the glenoid, and (B) that by the supraspinatus muscle along tends to the center of the glenoid. The muscle located at the rim would encounter potential subluxation and the muscle located at the center of the joint surface would be more stable. However, because the deltoid has larger moment arms for shoulder abduction than does the supraspinatus, the magnitude of the muscle force and the joint force are relatively smaller. (C) Ideally, synergistic function of a powerful deltoid and a stabilized supraspinatus would accomplish forceful and stable shoulder elevation activity. (Reprinted with permission from Morrey BF, Itoi E, An KN: Biomechanics of the Shoulder. In Rockwood CA, Matsen III FA, Wirth MA, Harryman DT (eds). The Shoulder. Philadelphia, WB Saunders Company 233–276, 1998.)
tion of the line of action of the supraspinatus muscle is almost perpendicular to the surface of the glenoid joint throughout the range of arm motion. However, the line of action of the deltoid muscles deviates from the surface of the glenoid joint with elevation of the arm. With the arm at less than 40° abduction, the line of action is oriented superiorly and approximately parallel to the glenoid surface. The action of the deltoid muscle therefore will result in a more off-center joint reaction force at the glenoid surface. Ideally, the best strategy in elevation would be the combination of a powerful deltoid muscle to reduce the muscle and joint force, and also the rotator cuff muscle to stabilize the joint by directing the joint force toward the stable location at the center of the joint surface.

From the perspective of the muscle as joint stabilizer, the recruitment of muscle activities will determine the magnitude and direction of the resultant joint force. A joint will be more stable when the resultant joint force is more centrally-located. The muscle force component would contribute to such stabilization function through the direct shear component, and also the concavity-compression component.

References