JHT READ FOR CREDIT ARTICLE #139.

Anatomy and Mechanics of the Shoulder: Review of Current Concepts

Jack Hurov, PhD, MSPT, CHT
Hand & Upper Extremity at UF Orthopaedic Institute, Gainesville, Florida

ABSTRACT: This narrative review is intended to provide hand and upper extremity therapists, who occasionally treat patients with shoulder diagnoses, with several current concepts related to normal shoulder anatomy and function. It is hoped that this review will be useful for 1) appreciating patho-anatomy and pathophysiology, 2) planning treatment approaches, and 3) stimulating research aimed at improved understanding of the shoulder.

J HAND THER. 2009;22:328–43.

It has recently been estimated that lifetime prevalence of shoulder pain is as high as 67%, while up to 46% of patients reported persistent pain 26 weeks after first consultation for a new episode of shoulder complaint.[1,2] Kuijpers et al. estimated that up to 47% of incurred cost among patients with shoulder pain was due to lost productivity while away from work.[2]

Clinical guidelines for conservative management of shoulder complaints may include a trial of physiotherapy in up to 46% of patients.[3] Yet, studies on prevalence and incidence of shoulder pain in the general population potentially underestimated the true frequency of physiotherapy because neurovascular conditions, such as thoracic outlet syndrome and glenohumeral (GH) joint instability, also managed conservatively, were specifically excluded.[2,3]

It seems reasonable to assume that a large number of patients, presenting a variety of shoulder conditions, would be available for treatment in a therapy setting providing conservative and postoperative management, when seen in conjunction with an orthopedic practice specializing in upper extremity disorders. Accordingly, the primary purpose of this paper is to provide a review of several current concepts related to normal shoulder anatomy and function for hand and upper extremity therapists who might occasionally treat the shoulder. It is hoped this review will permit improved understanding of shoulder patho-anatomy and pathophysiology, and possibly serve as a guide for therapeutic treatment and research opportunities.

For the purpose of this review, the terms "anatomy" and "structure" are used interchangeably, as are, "function" and "physiology" and these are distinguished as follows. Shoulder studies that rely on cadaveric materials are categorized as anatomic or structural investigations while studies of living materials represent functional or physiologic investigations, regardless of whether these studies are conducted at the cellular, tissue, or organismal level. Terms such as "mechanics" and "biomechanics" are used to describe, or make inferences about, shoulder function.

This review is necessarily selective; basic anatomy of the shoulder skeleton[4,5] definitions of axes of joint rotation,[6] directions and amplitudes of joint motion,[7–16] muscle attachments and innervations,[5] and ligament attachments and orientations of principle fibers,[5] are well covered. The interested therapist is also encouraged to read an excellent paper by Clark and Harryman[17] reviewing gross and microscopic anatomy of tendons, ligaments, and capsule of the rotator cuff.

Because of their regional interdependence, postural and movement faults, motion restrictions, shape changes such as kyphosis, and/or nerve entrapment, engendered in the cervical and thoracic spine and ribs, may profoundly influence shoulder structure and function.[18–21] Thus, the upper extremity therapist must know how to perform an upper quarter screen, and, in certain instances, clinical findings may be an invitation to refer a patient to a spine expert.

A review of clinical diagnoses and therapeutic treatment planning for selected shoulder conditions and a review of cervical and thoracic spine and rib

A version of this paper was first presented at the Fourth Annual Teton Hand Conference, Jackson, Wyoming, January 4, 2007.

Correspondence and reprint requests to Jack Hurov, PhD, MSPT, CHT, Hand & Upper Extremity at UF Orthopaedic Institute, 3450 Hull Road, Gainesville, Florida 32607; e-mail: <hurovj@shands.ufl.edu>.

doi:10.1016/j.jht.2009.05.002

anatomy and functions are likewise beyond the scope of this paper. Detailed treatments may be found in Magee[22] and McClure[23] who describe upper quarter orthopedic physical assessments.

OVERALL KEY CONCEPTS

1. The shoulder enjoys remarkable mobility, yet, is exceptionally stable over an individual's lifespan.
2. GH joint stability depends upon precise centering of the humeral head within the glenoid fossa.[24] When hands are used in overhead positions, compressive forces required to stabilize the GH joint are approximately 90% of body weight and are attained at 90° abduction.[25]
3. An ensemble of static structures, defined as nonmuscular, and dynamic, or muscular structures, contribute to mobility and stability of the GH joint.[7,26–28] Although distinction between static and dynamic structures is based on properties of active muscle, tendons and aponeuroses also serve important roles. Not only do they provide physical couplings between bones and muscles, they are also capable of modulating muscle output. For example, when tendons and aponeuroses are stretched, they store energy; as these structures return to their prestretched lengths, this stored energy is recovered and added to that of active skeletal muscle.[29]

WHAT FACTORS CONTRIBUTE TO SHOULDER MOBILITY?

Three key anatomical features have been identified that contribute to remarkable mobility of the shoulder. The role played by each of these features is reviewed below:

1. The upper extremity has limited connection to the axial skeleton with articulations at the sternoclavicular (SC) and, to a lesser extent, the costoclavicular joints.
2. The scapulothoracic (ST) ''joint'' consists of a broad soft-tissue interface.
3. The humeral head and glenoid fossa have similar shapes, but differ in size.

The Upper Extremity has Limited Connection to the Axial Skeleton

The sternal end of the clavicle has a diameter of 2.5 cm and cross-sectional area of approximately 5 cm^2.[30] Less than one-half the total available surface of the medial clavicle contacts the sternal facet on the manubrium and adjacent first costal cartilage, and is limited to the inferior aspect.[5]

The SC joint is characterized by an intra-articular fibrocartilage disc dividing the joint into two parts[5] (Figure 1). The interposed disc may serve to enhance joint congruity, increase joint surface area, and transmit forces engendered in the upper extremity to the axial skeleton.[11] Despite its limited articular contact, the SC joint was rarely dislocated; the joint capsule was amply reinforced by periarticular ligaments.[11]

The ST "Joint" Consists of a Broad Soft-Tissue Interface

The position of the scapula on the thorax is determined, in part, by thorax shape[21,31] and resting tone and net vectors of the axioscapular (AS) muscles, levator scapulae, pectoralis minor, rhomboids, serratus anterior, and trapezius.[18,19] Motion between the ventral scapula and thorax is facilitated by an interface of loose connective tissue between serratus anterior and subscapularis, and between costal structures and serratus anterior.[32]

The Humeral Head and Glenoid Fossa have Similar Shapes but Differ in Size

GH joint mobility is attributable to the 1) small surface area of the humeral head in contact with the glenoid fossa and 2) ''shallowness'' of the glenoid fossa. The maximum depths of the cartilage-clad glenoid fossa, exclusive of the labrum, were approximately 2–4 mm transversely and 7–9 mm horizontally. The glenoid fossa was therefore characterized as a rather shallow receptive surface for the humeral head[7] (Figure 2A).

In a study examining in situ contact areas of normal human cadaver GH joints, Warner[8] established that the spherical humeral head had an articular surface area of approximately 21–22 cm^2, whereas that of the glenoid fossa was approximately 8–9 cm^2. The maximum contact area between the humeral head and glenoid fossa measured approximately 4–5 cm^2.[33] Thus, articular surface area of the proximal humerus was approximately 2.5 times greater than that of the glenoid fossa while a mere 22% of that area was engaged by the fossa.

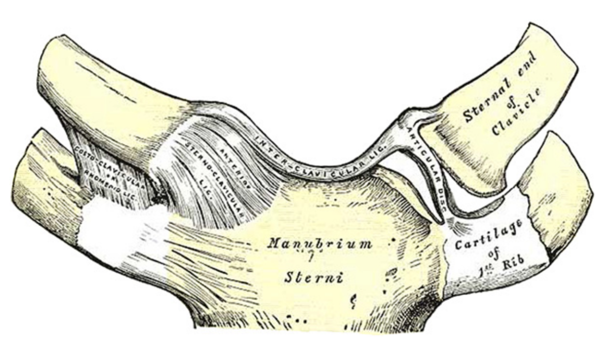

FIGURE 1. Anterior view, sternoclavicular joint; intra-articular fibrocartilage disc divides joint into two parts.

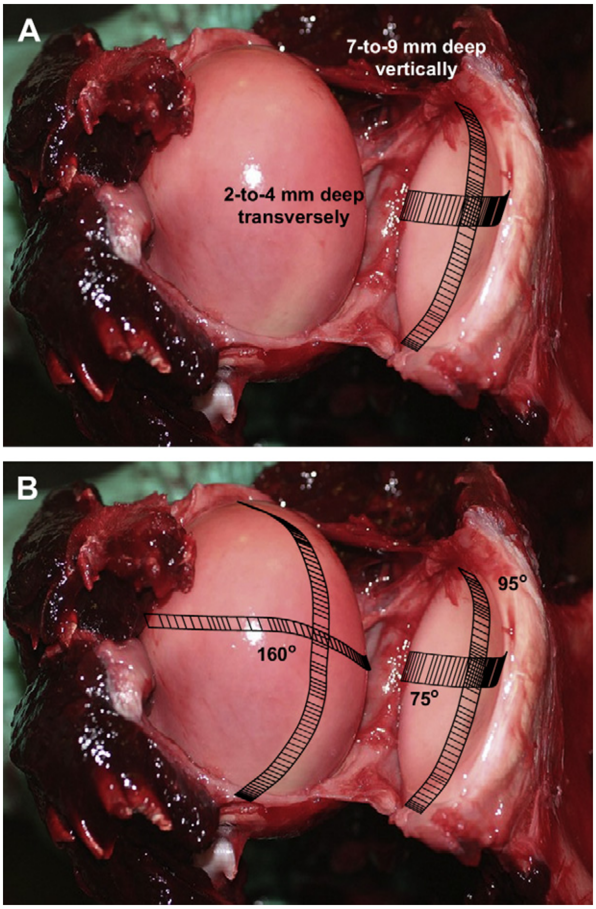

FIGURE 2. Anterior view, right glenohumeral joint. ***(A).*** *Glenoid fossa is approximately 2–4 mm deep transversely and 7–9 mm deep vertically.* ***(B).*** *Humeral head presents 160 degrees of articular cartilage in transverse and coronal planes apposed by 75 and 95 degrees of glenoid articular cartilage, respectively, leaving 85 and 65 degrees of humeral articular cartilage unconstrained by glenoid, respectively.*

Jobe and Iannotti[34] demonstrated that the humeral head presented up to 160 degrees of articular cartilage in both transverse and coronal planes, apposed by 75 and 95 degrees of glenoid articular cartilage, respectively (Figure 2B). Therefore, up to 85 and 65 degrees of humeral articular cartilage was unconstrained by glenoid, respectively. Despite this mismatch in cartilage coverage between the humeral head and glenoid fossa, Soslowsky et al.[35] determined their articular surfaces were of nearly identical shape and highly congruent with curvatures within 2–3 mm over their entire surfaces.

WHAT FACTORS CONTRIBUTE TO SHOULDER STABILITY?

The GH joint is stable at rest, in mid ranges, and extremes of motion. A central concept that has emerged is that stability depends upon interactions among static and dynamic restraints that precisely center the humeral head within the glenoid fossa.[24,28]

Static Restraints

Joint surfaces wet with synovial fluid are held together by 1) *adhesion*, the molecular attraction of synovial fluid to a joint surface and 2) *cohesion*, the molecular attraction of synovial fluid to itself. These properties can be easily demonstrated. A thin film of soapy water may be applied to a glass slide and *adheres* to the glass. When a second glass slide is similarly prepared, and the two gently pressed together, the soap films *cohere* to one another yielding a construct with high tensile strength and pulled apart with difficulty.[28]

Negative pressure within the GH joint capsule helps stabilize the humeral head within the glenoid fossa much like a suction cup adhering to a smooth surface, and three inter-related mechanisms have been described.[7]

First, negative pressure within the joint is a mechanical consequence of a closed compartment in which two apposing joint surfaces have different compliances. The glenoid fossa exhibits graduated flexibility from its rather rigid center, where hyaline cartilage is relatively thin, to its compliant periphery, where hyaline cartilage is relatively thick and the glenoid labrum is composed of fibrocartilage and dense fibrous connective tissue. This suction cup property of the GH joint is retained even in a cadaver specimen providing the joint capsule is intact, and is lost when the joint capsule is vented. Experimental venting of the GH joint capsule resulted in up to 10 mm of inferior displacement of the humeral head.[36]

Second, negative pressure within the GH joint is maintained in vivo as free fluid diffuses along its concentration gradient out of the synovial cavity and into synovial vasculature.[7]

Third, synovial fluid, composed of the mucoprotein hyaluronic acid[37] and secreted by synovial cells, is distributed within the synovium and GH joint space. Because osmotic pressure of the synovium slightly exceeds that of synovial fluid within the joint space, there exists a negative pressure gradient that adds additional intra-articular stability to the GH joint.[7,38]

The stabilizing property of negative pressure can be easily demonstrated in the following manner. Capping an unarmed syringe and attempting to withdraw the plunger from the barrel is difficult due to negative pressure within the barrel. Removing the cap from the tip of the syringe permits air pressure inside and outside the syringe to equilibrate, and the plunger is readily moved within the barrel.

In addition to serving as a load-bearing structure,[8] the glenoid labrum also stabilized the GH joint by increasing the depth of the glenoid fossa, and its meniscoid shape increased glenoid surface area in contact with the humeral head by as much as 50%.[39] Experimental removal of the labrum decreased GH joint stability up to 20%.[40]

Cooper et al.[41] demonstrated that the labrum was composed of densely woven collagen and, in the 12 o'clock position of the glenoid fossa, inserted distal to the long head of biceps tendon. Moreover, the superior labrum was normally found to be loosely attached to the glenoid rim between the 10 o'clock to 2 o'clock positions. In contrast, the labrum was firmly attached to the glenoid rim between the 2 o'clock to 10 o'clock positions, and possessed a transitional layer of fibrocartilage between the osseous rim and superficial layers of densely woven collagen.[41]

There have been a number of elegant in vitro studies that demonstrated the manner in which ligaments, tendons, and indeed, skeletal muscles provided static restraints stabilizing the shoulder.[36,42,43] These studies involved measuring motion of intact, fresh GH joints as a predetermined load was applied in a specific direction, and re-measuring joint motion after cutting a particular structure. Based on the *difference* in motion between intact and cut conditions, inferences were made about the relative importance of that structure for stabilizing the GH joint. The primary static restraints responsible for limiting humeral head motion, as a function of shoulder position, are shown in Table 1, and, in general, capsulohumeral ligaments form motion barriers stabilizing the GH joint at *extremes* of motion. Experimental sectioning of GH ligaments interfered with normal motion restraints, resulting in significantly increased humeral head motion, subluxation, and/or dislocation.

With the arm at rest by the side of the body, the intact GH joint permitted approximately 2 cm of anteroposterior and less than 1 cm of supero-inferior motion, in response to loads of 30 N (Figure 3).[28] Translational laxity of the intact GH joint increased to maximum values at approximately 30° elevation and attained minimum values at approximately 90° elevation.

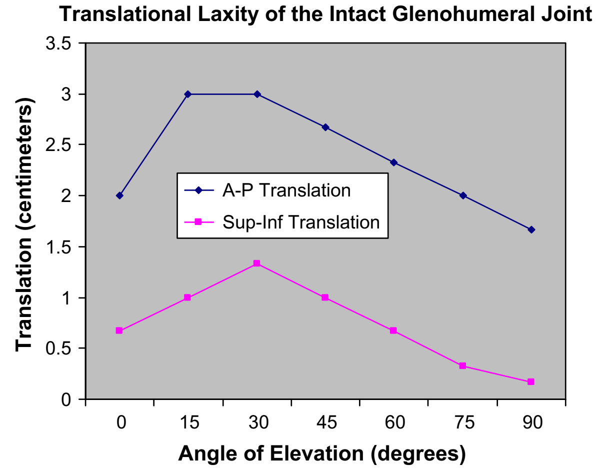

FIGURE 3. Graph showing relationship between humeral head translation and angle of arm elevation. When subjected to experimental load of 30 N, intact glenohumeral joint allows only 3 cm anteroposterior and 1.5 cm supero-inferior translation.

With the unloaded arm at rest, GH joint stability depended, in part, upon glenoid fossa orientation.[44] Inferior displacement of the humeral head upon the upward sloping glenoid fossa resulted in a component of lateral displacement resisted by tensioning the superior part of the GH joint capsule and coracohumeral ligament and by supraspinatus activity (Figure 4).[44] As the humerus was abducted, this ''locking'' mechanism became less efficient for preventing inferior translation of the humeral head because tension in the superior part of the GH joint capsule and coracohumeral ligament was reduced.[45] However, middle and inferior parts of the capsule became tensioned because their orientations changed, relative to the center of rotation of the GH joint.[36] This ''reciprocal effect'' among the ensemble of

TABLE 1. **Selective Ligament Cutting—Directions of Humeral Head Motion and Motion Restraints[36,42,43]**

Shoulder Position	*Superior*	*Inferior*	*Anterior*	*Posterior*	*External Rotation*
0–45° Abd	Biceps LH (+3 mm)	Sup GH lig	Sup GH lig	Infraspinatus/teres minor	Supscapularis (+18°)
	Coraco-acromial arch	Coracohumeral lig	Mid GH lig		Sup GH lig (+5°)
	Rotator cuff	Biceps LH (+3 mm)	Coracohumeral lig		Mid GH lig (+8°)
			Subscapularis		Inf GH lig (ant band, +6°)
			Biceps LH (+6 mm)		
45–90° Abd		Inf GH lig	Inf GH lig (ant band)	Inf GH lig (post band)	Supscapularis
					Inf GH lig (ant band)

Abd = abduction; ant = anterior; deg = degrees; GH = glenohumeral; Inf = inferior; LH = long head; lig = ligament; Mid = middle; post = posterior; Sup = superior.
Note: Numbers in parentheses indicate average amounts of humeral head displacement after transection of structure.

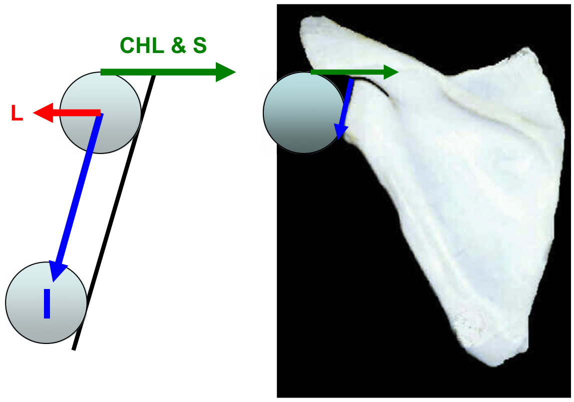

FIGURE 4. Posterior view, left scapula, and model of humeral head. Humeral head glides inferiorly (I) undergoing lateral translation (L) upon upwardly tilted glenoid fossa. Further motion is resisted by coracohumeral ligament (CHL) and activity in horizontally oriented fibers of supraspinatus muscle (S). These restraints prevent inferior dislocation of humerus with arm by side.

capsular ligaments permitted each to play a role in stabilizing the GH joint through a particular range of motion.[8,36]

Although anatomic studies have demonstrated individual variation in morphologic details and attachments of shoulder ligaments, significant structural and functional identity existed that clarified the stabilizing roles of these structures.[8,17,36,42,45] A number of basic concepts and clinical correlates have emerged, which are reviewed below.

1. As a ligament was stretched, it generated counterforce acting in the direction *opposite* humeral motion thereby resisting further motion[28] (Figures 5A–5C). Clinically, we appreciate that motion restrictions can be quite dramatic, for example, in patients with adhesive capsulitis—joint mobilization and static-progressive splints are used to increase ligament length and enhance joint mobility.
2. As shoulder abduction and external rotation increased, the primary static stabilizers of the GH joint shifted from superior to inferior capsular structures (Table 1). In particular, the anterior band of the inferior GH ligament was tensioned.[8,42,46] Reciprocal interdependence between superior and inferior and anterior and posterior structures was termed the "circle concept of capsuloligamentous stability of the shoulder."[36]
3. The long head of the biceps was important for stabilizing the GH joint in multiple directions.[43]
4. Coraco-acromial arch release and acromioplasty may be performed to manage subacromial compression and grade 1, bursal-side partial rotator cuff tears (<3 mm deep).[47] The remaining superior restraints, coracohumeral ligament and supraspinatus, are theoretically subjected to increased loading. Similarly, acromial release of the deltoid, associated with acromioplasty, may shift significant loads to intact adjacent muscle fibers.[24,47]
5. Collagen fiber interweaving and crimping, characteristic of the histologic anatomy of the inferior GH ligament complex, offer a distinct mechanical advantage because they permit energy absorption, in the direction of loading, through fiber reorientation and elongation, before collagen fibers becoming fully tensioned.[46,48,49] Thus, GH ligaments are capable of absorbing considerable energy over a wider range of terminal joint positions than would otherwise be permitted in the absence of fiber interweaving and crimping.[50]
6. GH capsular ligaments were approximately 35% stiffer when loaded at "fast" (4 mm/sec) versus "slow" rates (0.004 mm/sec), which is consistent with the tensile properties of visco-elastic structures.[50] When tested at "fast" strain rates, failure was predominantly within ligament substance, whereas at "slow" strain rates, failure occurred primarily at the ligament–bone interface, and tended to occur at the humeral insertion.[50] Glenoid insertion failures occurred with approximately equal frequency at fast and slow strain rates, and GH ligaments failed at approximately 10% elongation beyond their "resting" lengths[50] (Figure 5D). One limitation of in vitro tensile tests is that loading rates may not accurately reflect physiologic loads.[36] For example, the GH joint capsule may be subjected to intrasubstance strains of up to 100% per second during overhead throwing.[50]
7. Ligament attenuation has been postulated to be an important factor contributing to GH joint instability and thus, a proximate cause of cartilage and bone remodeling associated with altered joint mechanics[50] (Figure 5E). Moreover, according to the circle concept of capsuloligamentous stability of the shoulder, a substantial ligamentous lesion on one side of the joint capsule may result in shifting loads to, and eventually overwhelming, the *opposite* side of the capsule permitting the humeral head to subluxate or dislocate.[36]
8. There appears to be morphologic identity between mechanoreceptors in the inferior GH ligament and Ruffini receptors.[51] Ruffini receptors provide afference reflecting joint position, motion amplitude, and velocity; such mechanoreceptors may participate in regulating GH joint stability by adjusting shoulder muscle forces in response to external loads.[51] Problematic, though, is the fact that such a neural pathway has not been demonstrated in the human shoulder. Neither is it clear that a reflex pathway would be sufficiently rapid to protect the GH joint from injury.[51,52]
9. Angulation of the proximal humerus, relative to coronal and transverse planes, and glenoid orientation influence shoulder stability through a subtle

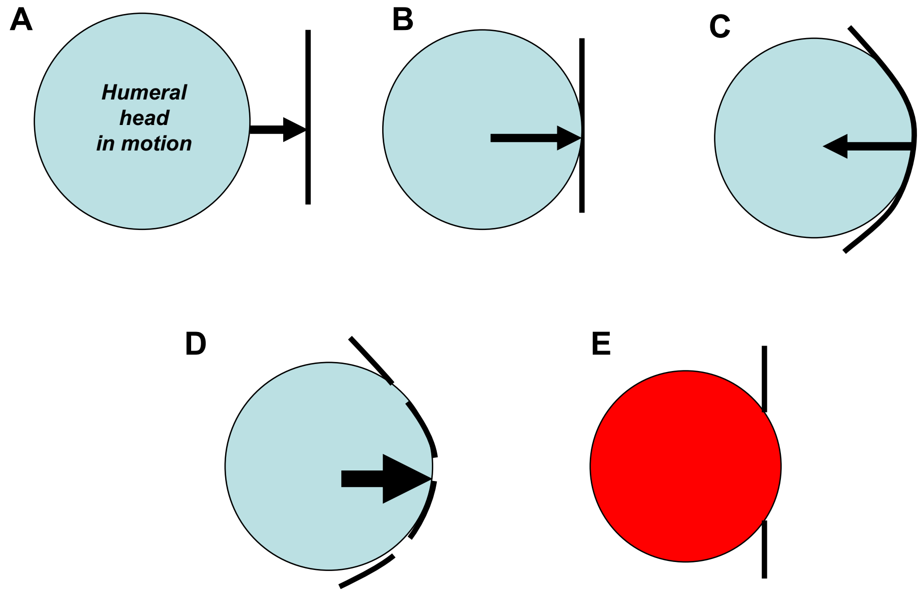

FIGURE 5. Model describing ligamentous stability of shoulder. ***(A).*** *Humeral head in motion approaches ligament.* ***(B).*** *Capsulohumeral ligament forms barrier stabilizing humeral head at motion extreme.* ***(C).*** *Stretched ligament generates counterforce acting in opposite direction, tending to resist further humeral head motion.* ***(D).*** *Overwhelmed glenohumeral ligament fails at approximately 10% elongation beyond "resting" length.* ***(E).*** *Ligament failure leads to joint instability.*

interplay between osseous and pericapsular ligamentous constraints.[8,27,45] Misalignment of the humeral head and glenoid fossa, which may occur during fracture healing, results in decreased overhead motion and GH joint instability. For example, with the arm by the side, an inferiorly facing glenoid fossa predisposes the humeral head to being "dumped." Similarly, Weiser et al.[53] showed, under experimental conditions, that as little as 20 degrees of compensatory ST joint motion may result in a tenfold increase in strain experienced by GH ligaments. Therefore, from a clinical perspective, it is important to appreciate that significant trade-offs may exist between a patient's functional goal of reaching overhead, or, behind their back, and the potential for readily exceeding safety factors of optimal GH joint loading.

Dynamic Restraints

The aforementioned static restraints ensure GH joint stability when the arm is by the side and at end ranges of motion. Under normal circumstances, static restraints function well with minimal participation of shoulder muscles.[44] However, static structures are insufficient to ensure GH stability in the mid ranges of the joint, which are often characterized by high velocity motion and large external loads.[24,40,54] For example, overhead throwing of sports implements, support of body weight on narrow, unstable surfaces, characterizing many gymnastic activities, and using the arms for hoisting and propulsion, as in rock climbing and kayaking, require a combination of static stabilizers *and* active shoulder muscles to dynamically center the humeral head within the glenoid fossa.

Three important concepts have emerged, related to dynamic stability of the GH joint in mid ranges of motion: 1) *concavity compression*, 2) *muscle stiffness*, and 3) *tendon compliance*.

Concavity compression specifies that translational stability of the GH joint depends upon active compression of the convex humeral head into the concave glenoid fossa. Experimental studies modeling compressive forces produced by muscles whose action lines crossed the GH joint revealed that stability 1) increased as a function of the magnitude of simulated compressive force and 2) varied depending upon depth of the glenoid fossa.[40,54–58] For example, once the humeral head was actively compressed into the glenoid, the joint resisted peak transverse forces applied in a supero-inferior direction, in accord with greater depth of the fossa in this plane.[40,54–58] Moreover, resection of the glenoid labrum resulted in up to 20% less resistance to transverse forces.[40,54–58]

The ensemble of shoulder muscles has classically been divided into four groups, based on muscle attachments 1) AS, 2) axiohumeral (AH), 3) scapulohumeral (SH), and 4) extrinsic (E; biceps and triceps). Of these, the SH group comprising the rotator cuff, supraspinatus, infraspinatus, teres minor, and subscapularis was regarded as playing a pre-eminent stabilizing role, along with contributions by deltoid and long head of biceps for centering the humeral head within the glenoid fossa through the mechanism of concavity compression[7,55] (Figure 6).

When considered as a group, rotator cuff muscles have a large cross-sectional area.[59–62] Because muscle cross-section is related to potential force (P), rotator cuff muscles are capable of generating high forces required to compress the humeral head into the glenoid.[63] Moreover, lengths of individual fibers comprising rotator cuff muscles are relatively short.[59,62] Because muscle fiber length is related to potential excursion (L), rotator cuff muscles are well suited for constraining humeral head translation within the glenoid.[63]

Dynamic stability of the GH joint will be determined by that fraction of force, generated by each shoulder muscle, acting *along* the humerus toward the center of the glenoid; this *transarticular force* represents the net joint reaction force compressing the humeral head into the glenoid.[55] The rotator cuff in particular, as well as deltoid and AH muscles, generate forces sufficient to produce GH joint motion and necessary to stabilize the humeral head within the glenoid fossa.[25,63,64]

When skeletal muscle is activated, it generates tension and exhibits a mechanical property termed *stiffness*, defined as resistance to change in length in response to an external load.[65,66] Muscle stiffness is measurable and may be described as change in muscle tension per unit change in muscle length ($\Delta T/\Delta L$); it is the ability of active skeletal muscle to resist length changes that contributes to dynamic stability of the GH joint.[65,66] For example, when subjects were required to maintain a constant position of shoulder internal rotation against randomly applied external rotation perturbations, shoulder muscle stiffness, measured as change in torque divided by change in joint angle ($\Delta\Gamma/\Delta\theta$), increased 77%, due primarily to subscapularis activity.[65] In the ranges of shoulder motion studied, GH joint stability appeared to depend on an interplay between anticipatory and reflex muscle recruitment in which stiffness was a regulated parameter.[65,66]

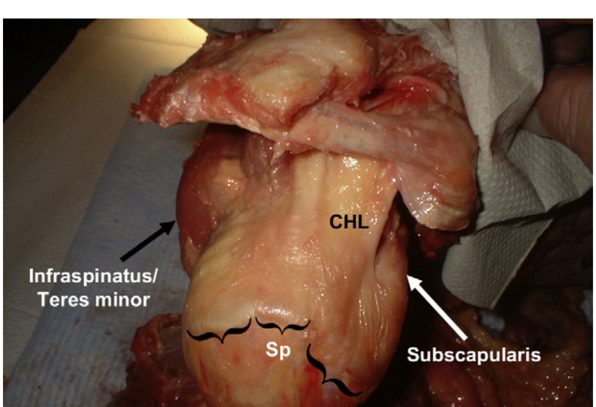

FIGURE 6. Superolateral view, right shoulder. {} indicate approximate insertions of infraspinatus, supraspinatus (Sp), and coracohumeral ligament (CHL) into glenohumeral joint capsule.

Tendons are integral to the structure of shoulder muscles and demonstrate a mechanical property termed *compliance*, that is, they can be stretched in response to muscle force or an external load. Tendon elongation, beyond its resting length, is termed *strain* and as tendon is stretched, it has the capacity to store *strain energy*. When applied force is removed, tendon will return to its original, prestretched length releasing strain energy; this stored energy may be added to those dynamic forces generated by active skeletal muscle to stabilize the GH joint.[29] One functional objective of the nervous system may therefore be to "tune" skeletal muscle stiffness such that tendons are permitted from 3% to 10% elongation. This strain range appears to correspond to optimal energy storage and return by "long" and "very long" tendons, which may account for as much as 10–25% of the total tension contributed by skeletal muscle.[29]

In their detailed examination of gross and microscopic anatomy of rotator cuff tendons, ligaments, and capsule, Clark and Harryman[17] demonstrated that the GH joint capsule "forms a continuous fibrous cylinder extending from the glenoid labrum to the neck of the humerus" into which tendons of rotator cuff muscles inserted to form a multilayered network of interwoven collagen fibers. Firmly adherent to the underlying joint capsule, humeral insertions of rotator cuff tendons also fused with one another.[17] When activated, rotator cuff muscles therefore become functionally linked and dynamically stabilize the GH joint through the mechanical properties of muscle stiffness and tendon compliance; the rotator cuff has been aptly described as a "musculotendinous glenoid" acting as an extension of the osseous glenoid to control humeral head position.[7]

SHOULDER KINEMATICS DURING OVERHEAD REACHING

Studies examining shoulder kinematics during voluntary overhead reaching in normal subjects have used two- and three-dimensional measurement systems, including real-time tracking of metallic markers or motion sensors inserted directly into the clavicle, humerus, and scapula.[25,67–72] A kinematic model emphasizing motion of the clavicle and scapula will be reviewed, and is based on the work of Dvir and Berme.[69] Accordingly, overhead reaching was divided into four "phases" permitting movements of and linkages between various components to be emphasized and readily appreciated. It should be understood however, that once initiated, overhead motion is normally continuous, and the clavicle, humerus, and scapula move in a coupled fashion.

The first phase of overhead reaching involved 5–15 degrees of upward rotation of the scapula,

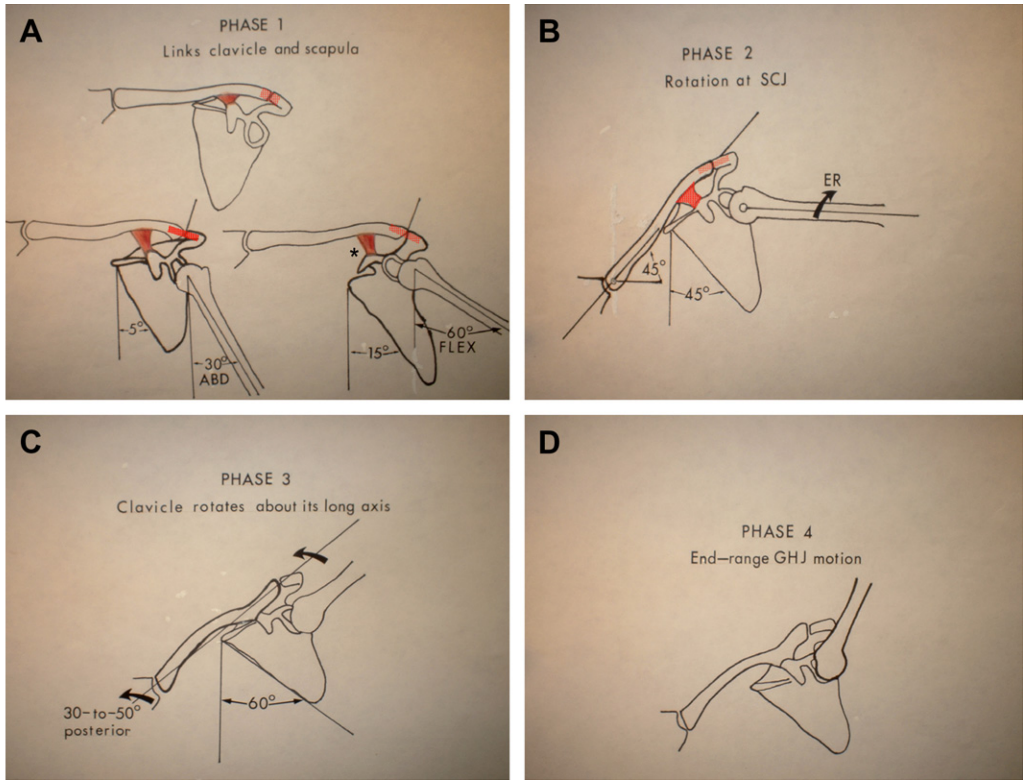

FIGURE 7. Kinematic model describing shoulder motion during overhead reaching. ***(A).*** *Phase 1 links clavicle and scapula as acromioclavicular and coracoclavicular ligaments are tensioned (asterisk), ADB = abduction, FLEX = flexion.* ***(B).*** *Phase 2 involves rotation at sternoclavicular joint (SCJ) resulting in elevation of linked clavicle and scapula. Obligate external rotation (ER) of humerus clears greater tuberosity from beneath acromion.* ***(C).*** *Phase 3 entails 30—50 degrees of posterior axial rotation of clavicle.* ***(D).*** *Phase 4 comprises end-range glenohumeral joint (GHJ) motion.*

occurring at the acromioclavicular (AC) and ST joints (Figure 7A). This initial phase of shoulder motion, associated with up to 60 degrees of arm elevation, was described by Inman et al.[67] as a ''setting phase'' linking together the clavicle and scapula as the AC and coracoclavicular (CC) ligaments were tensioned.[69]

The second phase of overhead reaching involved rotation at the SC joint about an anteroposterior axis. Accordingly, this resulted in elevation of the lateral aspect of the clavicle, coupled with upward rotation of the scapula (Figure 7B). The absolute amount of SC joint motion, measured with respect to the thorax, ranged from <10 to 45 degrees, and was associated with approximately 100 degrees of arm elevation.[67,69,71,72] It is important to appreciate that once the clavicle and scapula are linked in phase one, motion occurring at the SC joint contributes directly to, and is permissive for, ST joint motion.[72]

The third phase of overhead reaching involved from 30 to 50 degrees of posterior axial rotation of the clavicle occurring at the SC joint[67] (Figure 7C). The majority of clavicular axial rotation occurred between 70 and 90 degrees of arm elevation and end-range overhead motion, and presumably accounted for observed posterior tilt of the scapula that accompanied overhead reaching.[67,71] McClure et al.[71] suggested that posterior scapular tilt may ''clear'' the humeral head and rotator cuff tendons from beneath the anterior rim of the acromion. These researchers also reported that patients with impingement syndrome had approximately 10 degrees less posterior scapular tilt than did asymptomatic individuals.[71]

The final phase of overhead reaching involved motion occurring primarily at the GH joint (Figure 7D). Moreover, McClure et al.[71] reported that up to 70 degrees of external rotation took place at the GH joint during overhead reaching. External rotation was hypothesized to be an additional prerequisite for clearing the greater tuberosity from beneath the acromion thus minimizing subacromial impingement[67,68] (Figure 7B).

When reviewing shoulder kinematics during overhead motion, several key concepts emerged:

1. The clavicle, humerus, and scapula move concurrently.
2. Amplitudes of joint motion reported in the literature[7] are variable and depend upon:
   i. Subject age and gender,
   ii. Condition in which the upper extremity was loaded, for example, rate of motion and whether a weight was held in the hand,

iii. Measurement technique and instrumentation,
iv. Whether measurements were made on living individuals or cadaver specimens, and manner in which cadaver specimens were prepared, and
v. Specific task(s) performed.

3. Motor control of multiple bones and joints can be simplified by tensioning specific ligaments effectively welding together skeletal elements, for example, clavicle and scapula. In this manner, four (or, five) joints and three (or, four) bones, comprising the shoulder, are reduced to two bones, the ''claviscapula'' and humerus, and three joints, GH, SC, and ST. This reduction of moveable parts may be one way the motor system has evolved to simplify orchestration and neural control of motion.[69]
4. Once the clavicle and scapula are linked, through tensioning the AC and CC ligaments, ST joint motion is coupled to that occurring at the SC joint. Therefore, motion faults observed at the ST joint must be associated with motion faults occurring at the SC joint.[72]
5. GH and ST joints contribute to patterned upper extremity elevation historically described as ''scapulohumeral rhythm.'' In a recent review of shoulder kinematics in adult subjects, average angular changes occurring at the GH joint, relative to the ST joint, ranged from 1:2 to greater than 2:1 when examined at 90 and 180 degrees of arm elevation.[7] Moreover, the GH:ST ratio appeared to vary from 7:1, favoring the ST joint, to 4:1, favoring the GH joint, during the initial 30 degrees of arm elevation.[25,73] Accordingly, ''instantaneous'' GH and ST joint motion, recorded during overhead reaching demonstrated considerable variation when compared among studies. Nonetheless, when averaged over the *total arc* of elevation, the relative contributions of GH and ST joint motion were essentially and consistently 2:1 across studies.[7]
6. In contrast to adults, children appear to rely on a coordinative strategy during overhead reaching in a scapular plane, in which the GH:ST ratio was approximately 1:1.[74] Using an electromagnetic system to track adhesive markers attached to the thoracic spine, scapula, and humerus, the average contribution of ST joint motion to overhead reaching was approximately 50% greater in children than their adult counterparts, and approximately 33% less variable.[74]
7. McClure et al.[71] were impressed by significant between-subject variation in amplitudes of scapular translations, relative to the thorax. If one functional objective of shoulder muscles is to provide a dynamical tracking system maintaining humeral head position within the center of the glenoid fossa, observed variation in scapular excursion may reflect subtle between-subject differences in skeletal and joint geometries, as well as in muscle recruitment.

SHOULDER MUSCLE ACTIVITY

Electromyography (EMG) has been used to study in vivo patterns of muscle activity in normal volunteers as they engaged in physiologic shoulder motion. When EMG is precisely time coupled with cine or video images of shoulder motion, inferences can be made regarding the roles of muscles for producing the observed motions. Normal patterns of shoulder muscle activity, as revealed by EMG, are reviewed below during 1) eight kinematically distinct shoulder motions and 2) overhead throwing.

The Couples Concept

A *couple* is a term used to describe rotatory motion brought about by forces that are generally equal in magnitude and act in opposite directions at some distance D from each other.[75] The couples concept has been applied to describe scapular rotation associated with AS and AH muscle activity.[44,60,67] Accordingly, upper trapezius and lower digitations of serratus anterior form an upper, and lower trapezius a lower component, of a force couple producing upward rotation of the scapula. Similarly, rhomboids, levator scapulae, and upper digitations of serratus anterior form an upper, and pectoralis major/minor, together with latissimus dorsi, a lower component of a force couple producing downward rotation of the scapula. Deltoid forms an upper and rotator cuff a lower component of a force couple that centers the humeral head within the glenoid fossa as the distal humerus is elevated.[76] AS muscles are also recruited to control the scapula such that the humeral head has a stable glenoid platform on which to rotate.

EMG during Shoulder Motion

Table 2 shows EMG activity of shoulder muscles associated with eight kinematically distinct shoulder motions.[59,77] Numbers in parentheses represent maximum amplitudes of motion, measured with a goniometer, and beneath each muscle are shown motion ranges during which a minimum of 10% reference EMG activity was recorded, while subjects held up to 35 N. Aside from confirmed agonist activity, predicted on the basis of muscle attachments and fiber orientation, there are four important conclusions to be drawn from EMG data.

First, deltoid was recruited during each identified shoulder motion; indeed, it is the true ''work-horse'' among shoulder muscles and possesses the largest cross-sectional area.[59–62] Second, rotator cuff muscles were recruited during six of eight kinematically distinct shoulder motions. Activity in anterior and posterior cuff muscles was inferred to center the humeral head within the glenoid fossa during shoulder abduction, flexion, and extension.[59,77] Third, in marked

TABLE 2. **Electromyography of Shoulder Muscles during Active Motion**[59,77]

Shoulder Motion	*Active Muscles*									
	Deltoid	*Suprasp*	*Infrasp/T. Minor*	*Subscap*	*LD*	*P. Major*	*T. Major*	*Tri (LH)*	*Biceps*	*Coracobrach*
Abduction (180°)	60–150° (all parts)	30–180°	*30–180°	*30–150°	√				*LH & SH	
Adduction	Post	E	√	√	√	√	√	√		√
Flexion (180°)	30–180° (all parts)	*30–180°	*30–180°	*30–150°	E	30–150°				
Extension (60°)	10–50° (mid & post)	*10–50°	*10–50°	*10–50°	25–50°					
External rotation (50°)	All parts	*0–50°	0–50°	*10–40°	E				LH	√
Internal rotation (50°)	10–50° (mid & post)	*0–50°		20–50°	20–40°	20–50°	√	√		
Horizontal flexion	Ant			√	√	√	√	√	SH	√
Horizontal extension	Post	√	√						LH	

Ant = anterior; Coracobrach = Coracobrachialis; E = eccentric; Infrasp = Infraspinatus; LD = Latissimus Dorsi; LH = Long Head; mid = middle; P = Pectoralis; Post = posterior; SH = Short Head; Subscap = Subscapularis; Suprasp = Supraspinatus; T = Teres; Tri = Triceps; √ = agonist.
Notes: * = muscle activity associated with humeral head centering within glenoid.
Numbers in parentheses represent maximum amplitudes of active motion measured with a goniometer.
Beneath each muscle is shown active ranges of shoulder motion during which a minimum 10% reference electromyography activity was recorded while subjects held up to 35 N.

contrast to that activity predicted on the basis of muscle attachments, subscapularis was recruited during external rotation of the shoulder, thus serving as an anterior stabilizer of the GH joint.[59,77] Fourth was noteworthy activity in long head of biceps, recorded during shoulder abduction, external rotation, and horizontal extension. These recruitment patterns accorded with experimental data implicating biceps as a key multidirectional stabilizer of the GH joint[43] (Table 1).

EMG during Overhead Throwing

Overhead throwing arguably places peak demands on the shoulder. For example, the elite overhead athlete is capable of throwing a baseball in excess of 90 miles per hour, associated with angular velocities measured at the GH joint that approached 7,000 degrees/sec.[78] Table 3 shows EMG activity of shoulder muscles associated with overhead throwing.[79–83] For the purpose of this review, the overhead throw is divided into three phases, in accord with standard descriptions.[84]

The first phase of the overhead throw, from 1.5 to 2 seconds in duration, is termed preparatory/cocking, and is initiated as the center of gravity of the body is raised above the support leg. Preparatory/cocking ends when the throwing arm achieves maximum external rotation. The shoulder is abducted approximately 90 degrees and horizontally extended.[84] Deltoid, rotator cuff, and ST muscles accelerate the humerus and rotate the scapula. As the GH joint achieves maximum external rotation, anterior deltoid and rotator cuff, in particular subscapularis, are lengthened while producing tension. These muscles decelerate and center the humeral head within the glenoid fossa, respectively. Pectoralis major, latissimus dorsi, and triceps are also lengthened while producing tension and decelerate shoulder external rotation and elbow flexion, respectively.

Approximately 93–95% of the time the overhead athlete spends in the preparatory/cocking phase is devoted to imparting energy to a sport implement. The athlete then decelerates their shoulder in approximately 100 milliseconds as active shoulder muscles and their tendons are rapidly lengthened and absorb energy. Moreover, as the athlete's arm attains maximum external rotation, shear force, measured at the anterior aspect of the GH joint, reaches 400–600 N, equal to approximately 50% of body weight. This anterior shear force must be resisted by static and dynamic forces that stabilize the shoulder (Figure 8).[78,84]

The second phase of the overhead throw, from 40 to 100 milliseconds in duration, is termed acceleration/ball release, and is initiated as the thrower's arm begins to rotate internally. Acceleration/ball release ends when the sport implement is released.

With the exception of subscapularis, activity persists in those muscles identified during the

TABLE 3. **Muscle Activity during Overhead Throw**[79–83]

	Phases (Duration)			
	Preparatory/Cocking (1.5–2 sec)		*Acceleration/Ball Release (40–100 msec)*	*Follow-Through (350 msec)*
Active Muscle	*Accelerative*	*Decelerative (100 msec)*	*Accelerative*	*Decelerative*
Deltoid	All parts	Anterior	Anterior	Posterior
Suprasp	Active	Centers humeral head		Active
Infrasp/T. Minor	Active	Centers humeral head		Centers humeral head
Subscap		Active	Active	
Serratus anterior	Rotates scapula	Stabilizes scapula	Stabilizes scapula	Decelerates scapula
Trapezius	Rotates scapula	Stabilizes scapula	Stabilizes scapula	Decelerates scapula
Rhomboids				Decelerates scapula
P. Major		Active	Active	
LD		Active	Active	
Tri		Active late	Active	Active early
Biceps				Active
Brachialis				Active

Infrasp = Infraspinatus; LD = Latissimus Dorsi; P = Pectoralis; Subscap = Subscapularis; Suprasp = Supraspinatus; Tri = Triceps.

decelerative phase of preparatory/cocking. These muscles and their tendons now shorten and accelerate the upper extremity (Table 3). Note that serratus anterior and trapezius stabilize the scapula, permitting energy transfer from the lower extremities and trunk to the humerus and forearm. Amplitudes of EMG activity actually *decrease* uniformly in the shoulder during acceleration/ball release, in accord with energy transfer from the lower extremities and trunk to the throwing arm.[84]

As the athlete's shoulder achieves maximum internal rotation, a distraction force of approximately 750 N, or 75% of body weight, is engendered in the GH joint.[78]

When considered as a free body, this distraction force and associated angular velocity must be resisted by a combination of static and dynamic forces that stabilize the shoulder; otherwise, the upper extremity would ''fly off'' the trunk at 90 miles per hour (Figure 9).

The third phase of the overhead throw, approximately 350 milliseconds in duration, is termed follow-through, and is initiated once the ball leaves the thrower's hand and ends when motion of the throwing arm ceases. During this phase, static and dynamic forces continue to stabilize the shoulder (Table 3).

Posterior deltoid and AS muscles are recruited to decelerate the humerus and stabilize the scapula on the thorax, respectively. Infraspinatus and teres minor are also recruited during follow-through and decelerate internal rotation of the GH joint. The posterior cuff also provides a motion barrier limiting posterior translation of the humeral head. Note that elbow flexors are also recruited to decelerate elbow extension. Therefore, follow-through is characterized by deceleration of the upper extremity, brought about as active muscles and tendons of the shoulder are lengthened absorbing considerable energy.

Several key concepts, related to shoulder muscle function, have been revealed by EMG:

1. Although any shoulder muscle is *theoretically* capable of contributing to stability of the GH joint, the rotator cuff plays a pre-eminent role in centering the humeral head within the glenoid fossa. Thus, there exists a limit beyond which shoulder muscles will not substitute for an injured rotator cuff.[55,85]
2. Despite kinematic distinctions among identified shoulder motions, there exists functional equivalence among rotator cuff muscles. In other words, the rotator cuff is consistently recruited to stabilize the GH joint regardless of shoulder kinematics. From a clinical perspective, EMG data suggest

FIGURE 8. *Shoulder attains maximum external rotation during preparatory/cocking phase of overhead throw. Anterior shear force at glenohumeral joint reaches 400–600 N = 50% body weight (0.5 M_b).*

FIGURE 9. Acceleration/ball release associated with shoulder internal rotation >7,000 degrees/second (°/sec) and 750 N distraction force at glenohumeral joint (=75% body weight, 0.75 M_b).

there are multiple shoulder exercises that could be equally effective for rotator cuff strengthening provided that workloads are sufficient to challenge the cuff muscles.[55]

3. Muscles and tendons of the shoulder *add* energy during the preparatory/cocking phase of the overhead throw, *stabilize* the shoulder, permitting energy transfer from the lower extremities and trunk during acceleration/ball release, and *absorb* energy that decelerates the shoulder during follow-through.
4. During overhead throwing, anterior shear force reaches a peak as the GH joint attains maximum external rotation; distraction force and angular velocity attain maximum values as a sport implement is released from the hand. Static and dynamic restraints provide barriers and counterforces resisting anterior shear and distraction such that resultant forces compress the humeral head into the concave glenoid fossa stabilizing the GH joint.[55]
5. Approximately one-half the energy imparted to a sport implement during overhead throwing is developed in the upper extremity; the other half is derived from the legs and trunk. Accordingly, returning an athlete to overhead activities requires that rehabilitation address strength and flexibility of the lower extremities and trunk as well as of the upper extremities.[78]

SUGGESTIONS FOR FUTURE RESEARCH

There are several avenues of research, complimentary to the skills and training possessed by hand and upper extremity therapists, which would serve to better our understanding of the anatomy and mechanics of the shoulder:

1. To date, much of the information available about the anatomy and mechanics of the shoulder has been derived from studies of adults. During infancy however, there are fundamental shifts in the manner in which upper extremities are used. For example, upper extremities are used for body propulsion and support (closed kinetic chain activities), in addition to exploring the environment (open kinetic chain activities).[86] Thus, important new information about the development of concavity compression and the relative roles played by muscles and ligaments for stabilizing the GH joint could be obtained from infants learning to creep, cruise, and walk through application of surface EMG and a force platform. Additional correlative investigations might be conducted, with the specific purposes of determining developmental changes in 1) gross and histologic anatomy of the shoulder and 2) mechanical properties of maturing skeletal connective tissues, as a function of the acquisition of, and transitions in, upper extremity motor skills in infants.
2. From a clinical perspective, justification for conservative therapeutic management and postoperative therapy must be based on reliable and valid test instruments for assessing shoulder impairment and function, and such questionnaires should be administered before initiating treatment. Follow-up evaluations, conducted at consistent time intervals, can then be compared with pretreatment data. From the standpoint of data analysis, it would be most desirable to document change in function and impairment in *individual* patients, rather than testing the significance of *average* change scores between pre- and posttreatment groups or samples. It is important to appreciate that as variation *within* pre- and posttreatment groups increases, the likelihood of detecting significant treatment effects is diminished. Notwithstanding this caveat, for some applications, the standardized response mean may be used, which is the ratio of the average change score

between baseline and follow-up, divided by the average standard deviation of the change scores.[87,88]

3. There have been significant advances in our understanding of shoulder motion required for activities of daily living and functional activities in adults[12,89,90] and children,[91] shoulder motion faults associated with impingement syndrome[92] and full thickness rotator cuff tears,[93] patterns of muscle activity distinguishing normal subjects from those with rotator cuff tears,[94] and exercise that optimizes recruitment of GH and ST muscles.[95] Gaps that remain to be addressed relate to 1) determining the manner in which normal age-related changes in shoulder muscle strength[96,97] influence shoulder motion, 2) documenting shoulder motion and muscle activity in occupations requiring extensive overhead use of hands, and establishing the relative role of muscle fatigue and injury as determinants of motion faults or compensatory motion patterns, and 3) demonstrating whether therapeutic exercise prescriptions[94,98,99] actually ''correct'' identified shoulder motion faults, perhaps through combinations of improvement in muscle performance and learning novel motor patterns.

Acknowledgments

The author gratefully acknowledges those photographers whose images were downloaded from the Internet to create Figures 2A, 2B, 4, 8, and 9. Figure 4.36 from Williams and Warwick[5] and Figure 14 from Inman et al.[67] were used by the author to create Figures 1 and 7A−7D, respectively, herein. Thomas Wright, MD, Department of Orthopedics, University of Florida, Gainesville, read an early draft of this manuscript and provided friendly criticism that helped improve the paper. The author thanks an editor-in-chief and two anonymous reviewers for their very helpful comments and suggestions. In particular, valuable references on the anatomy and mechanics of the shoulder were made available to the author that substantially improved the quality of this paper's content and exposition.

REFERENCES

1. Luime JJ, Hendriksen IJM, Burdorf A, et al. Prevalence and incidence of shoulder pain in the general population; a systematic review. Scan J Rheumatol. 2004;33:73–81.
2. Kuijpers T, van Tulder MW, van der Heijden GJMG, Bouter LM, van der Windt DAWM. Costs of shoulder pain in primary care consulters: A prospective cohort study in The Netherlands. BMC Musculoskeletal Disorders. 2006;7:83–90.
3. van der Windt DAWM, Koes BW, de Jong BA, Bouter LM. Shoulder disorders in general practice: Incidence, patient characteristics, and management. Ann Rheumatic Dis. 1995: 959–64.
4. Edelson G. The development of humeral head retroversion. J Shoulder Elbow Surg. 2000;9:316–8.
5. Williams PL, Warwick R. Gray's Anatomy, 36th British. Philadelphia: Saunders, 1980, pp. 453−460, 564-572.
6. Wu G, van der Helm FCT, Veeger HEJ, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion-Part II: Shoulder, elbow, wrist and hand. J Biomech. 2005;38:981–92.
7. Itoi E, Morrey BF, An K-N. Biomechanics of the shoulder. In: Rockwood CA, Rockwood CA (eds). The Shoulder. 3rd ed. Philadelphia: W.B. Saunders, 2004, pp. 223–67.
8. Warner JJP. The gross anatomy of the joint surfaces, ligaments, labrum, and capsule. In: Matsen FA (eds). The Shoulder: A Balance of Mobility and Stability. Rosemont: American Academy Orthopaedic Surgeons, 1993, pp. 7–27.
9. Steindler A. Kinesiology of the Human Body Under Normal and Pathological Conditions. Springfield: Charles C. Thomas, 1955, p 451.
10. Soderberg GL. Kinesiology. Application to Pathological Motion. Baltimore: Williams & Wilkins, 1986, p. 117.
11. Renfree KJ, Wright TW. Anatomy and biomechanics of the acromioclavicular and sternoclavicular joints. Clin Sports Med. 2003;22:219–37.
12. Doorenbosch CAM, Harlaar J, Veeger DJ. The globe system: An unambiguous description of shoulder positions in daily life movements. J Rehabil Res Develop. 2003;40:147–56.
13. Sidles JA, Pearl ML. Description and measurement of shoulder motion. In: Matsen FA (eds). The Shoulder: A Balance of Mobility and Stability. Rosemont: American Academy Orthopaedic Surgeons, 1993, pp. 129–40.
14. McCully SP, Kumar N, Lazarus MD, Karduna AR. Internal and external rotation of the shoulder: Effects of plane, end-range determination, and scapular motion. J Shoulder Elbow Surg. 2005;14:602–10.
15. Joint Motion: Method of Measuring and Recording. Chicago: American Academy of Orthopaedic Surgeons, 1965, p. 84.
16. Norkin CC, White DJ. Measurement of Joint Motion: A Guide to Goniometry. Philadelphia: Davis, 1985, p. 138.
17. Clark JM, Harryman DT. Tendons, ligaments, and capsule of the rotator cuff. Gross and microscopic anatomy. J Bone Joint Surg Am. 1992;74:713–25.
18. Endo K, Yukata K, Yasui N. Influence of age on scapulothoracic orientation. Clin Biomech. 2004;19:1009–13.
19. Lewis JS, Wright C, Green A. Subacromial impingement syndrome: The effect of changing posture on shoulder range of movement. J Orthop Sports Phys Ther. 2005;35:72–87.
20. Haddick E. Management of a patient with shoulder pain and disability: A manual physical therapy approach addressing impairments of the cervical spine and upper limb neural tissue. J Orthop Sports Phys Ther. 2007;37:342–50.
21. Gumina S, DiGiorgio G, Postacchini F, Postacchini R. Subacromial space in adult patients with thoracic hyperkyphosis and in healthy volunteers. Chir Organi Mov. 2008;91:93–6.
22. Magee DJ. Orthopedic Physical Assessment. 4th ed. Philadelphia: W.B. Saunders, 2002,
23. McClure P. Upper quarter screen. In: Mackin EJ (eds). Rehabilitation of the Hand and Upper Extremity. 5th ed. St. Louis: Mosby, 2002, pp. 111–9.
24. Matsen FA, Chebli C, Lippitt S. Principles for the evaluation and management of shoulder instability. J Bone Joint Surg Am. 2006;88:648–59.
25. Walker PS, Poppen NK. Biomechanics of the shoulder joint during abduction in the plane of the scapula. Bull Hosp Joint Dis. 1977;38:107–11.
26. Lew WD, Lewis JL, Craig EV. Stabilization by capsule, ligaments, and labrum: Stability at the extremes of motion. In: Matsen FA (eds). The Shoulder: A Balance of Mobility and Stability. Rosemont: American Academy Orthopaedic Surgeons, 1993, pp. 69–89.
27. Woo SL-Y, McMa on PJ, Debski RE, Hu FH, Blomstrom GL. Factors limiting and defining shoulder motion: What keeps it from going farther?. In: Matsen FA (eds). The Shoulder: A Balance of Mobility and Stability. Rosemont: American Academy Orthopaedic Surgeons, 1993, pp. 141–58.
28. Matsen FA, Titelman RM, Lippitt SB, Rockwood CA, Wirth MA. Glenohumeral instability. In: Rockwood CA (eds). The Shoulder. 3rd ed. Philadelphia: W.B. Saunders, 2004, pp. 655–794.
29. Zajac FE. Muscle and tendon: Properties, models, scaling, and application to biomechanics and motor control. Crit Rev Biomed Eng. 1989;17:359–411.

30. Andermahr J, Jubel A, Elsner A, et al. Anatomy of the clavicle and the intramedullary nailing of midclavicular fractures. Clin Anat. 2007;20:48–56.
31. Lowrey GH. Growth and Development of Children. 8th ed. Chicago: Year Book Medical Publishers, 1986, p. 89.
32. Williams GR, Shakil M, Klimkiewicz J, Iannotti JP. Anatomy of the scapulothoracic articulation. Clin Orth Rel Res. 1999: 237–46.
33. Soslowsky LJ, Flatow EL, Bigliani LU, Pawluk RJ, Ateshian GA, Mow VC. Quantitation of in situ contact areas at the glenohumeral joint: A biomechanical study. J Orthop Res. 1992;10: 524–34.
34. Jobe CM, Iannotti JP. Limits imposed on glenohumeral motion by joint geometry. J Shoulder Elbow Surg. 1995;4:281–5.
35. Soslowsky LJ, Flatow EL, Bigliani LU, Mow VC. Articular geometry of the glenohumeral joint. Clin Orthop Relat Res. 1992;285:181–90.
36. Curl LA, Warren RF. Glenohumeral joint stability. Selective cutting studies on the static capsular restraints. Clin Orthop Rel Res. 1996;330:54–65, 26.
37. Lehninger AL. Biochemistry. New York: Worth, 1975, pp 272-3.
38. Guyton AC. Textbook of Medical Physiology. Philadelphia: Saunders, 1976, pp. 408-9.
39. Howell SM, Galinat BJ. The glenoid-labral socket: A constrained articular surface. Clin Orthop Rel Res. 1989;243: 122–5.
40. Lippitt SB, Vanderhooft JE, Harris SL, Sidles JA, Harryman DT, Matsen FA. Glenohumeral stability from concavity-compression: A quantitative analysis. J Shoulder Elbow Surg. 1993;2:27–35.
41. Cooper DE, Arnoczky SP, O'Brien SJ, Warren RF, DiCarlo E, Allen AA. Anatomy, histology, and vascularity of the glenoid labrum. J Bone Jt Surg Am. 1992;74:46–52.
42. Turkel SJ, Panio MW, Marshall JL, Girgis FG. Stabilizing mechanisms preventing anterior dislocation of the glenohumeral joint. J Bone Jt Surg Am. 1981;63:1208–17.
43. Kumar VP, Satku K, Balasubramaniam P. The role of the long head of biceps brachii in the stabilization of the head of the humerus. Clin Orthop. 1989;244:172–5.
44. Basmajian JV. Muscles Alive. Their Functions Revealed by Electromyography. 4th ed. Baltimore: Williams & Wilkins, 1978, pp. 196-200.
45. Itoi E, Motzkin NE, Morrey BF, An K-N. Scapular inclination and inferior stability of the shoulder. J Shoulder Elbow Surg. 1992;1:131–9.
46. O'Brien SJ, Neves MC, Arnoczky SP, et al. The anatomy and histology of the inferior glenohumeral ligament complex of the shoulder. Am J Sports Med. 1990;18:449–56.
47. Wolff AB, Sethi P, Sutton KM, Covey AS, Magit DP, Medvecky M. Partial- thickness rotator cuff tears. J Am Acad Orthop Surg. 2006;14:715–25.
48. Ticker JB, Flatow EL, Pawluk RJ, et al. The inferior glenohumeral ligament: A correlative investigation. J Shoulder Elbow Surg. 2006;15:665–74.
49. Mow VC, Bigliani LU, Flatow EL, Ticker JB, Ratcliffe A, Soslowsky LJ. Material properties of the inferior glenohumeral ligament and the glenohumeral articular cartilage. In: Matsen FA (eds). The Shoulder: A Balance of Mobility and Stability. Rosemont: American Academy Orthopaedic Surgeons, 1993, pp. 29–67.
50. Bigliani LU, Kelkar R, Flatow EL, Pollock RG, Mow VC. Glenohumeral stability. Clin Orthop Rel Res. 1996;330:13–30.
51. Steinbeck J, Brüntrup J, Greshake O, Pötzl W, Filler T, Liljenqvist U. Neurohistological examination of the inferior glenohumeral ligament of the shoulder. J Orthop Res. 2003;21:250–5.
52. Vangsness CT, Ennis M, Taylor JG, Atkinson R. Neural anatomy of the glenohumeral ligaments, labrum, and subacromial bursa. Arthroscopy: J Arthroscopic Rel Surg. 1995;11:180–4.
53. Weiser WM, Lee TQ, McMaster WC, McMahon PJ. Effects of simulated scapular protraction on anterior glenohumeral stability. Am J Sports Med. 1999;27:801–5.
54. Lazarus MD, Sidles JA, Harryman DT, Matsen FA. Effect of a chondral-labral defect on glenoid concavity and glenohumeral stability. J Bone Jt Surg. 1996;78A:94–102.
55. Lippitt S, Matsen S. Mechanisms of glenohumeral joint stability. Clin Orth Rel Res. 1993;291:20–8.
56. Kedgley AE, Mackenzie GA, Ferreira LM, et al. Humeral head translation decreases with muscle loading. J Shoulder Elbow Surg. 2008;17:132–8.
57. Wuelker N, Schmotzer M, Thren K, Korell M. Translation of the glenohumeral joint with simulated active elevation. Clin Orth Rel Res. 1994;309:193–200.
58. Kelkar R, Wang VM, Flatow EL, et al. Glenohumeral mechanics: A study of articular geometry, contact, and kinematics. J Shoulder Elbow Surg. 2001;10:73–84.
59. Bassett RW, Browne AO, Morrey BF, An K-N. Glenohumeral muscle force and moment mechanics in a position of shoulder instability. J Biomech. 1990;23:405–15.
60. Howell SM, Imobersteg AM, Seger DH, Marone PJ. Clarification of the role of the supraspinatus muscle in shoulder function. J Bone Jt Surg Am. 1986;68:398–404.
61. Schumacher GH, Wolff E. Trockengewicht und physiologischer Querschnitt der menschlichen Skeletmuskulatur II. Physiologische Querschnitte. Anat Anz. 1966;119:259–69.
62. Veeger HEJ, van der Helm FCT, van der Woude, Pronk GM, Rozendal RH. Inertia and muscle contraction parameters for musculoskeletal modeling of the shoulder mechanism. J Biomech. 1991;24:615–29.
63. Lieber RL, Fridén J. Neuromuscular stabilization of the shoulder girdle. In: Matsen FA (eds). The Shoulder: A Balance of Mobility and Stability. Rosemont: American Academy Orthopaedic Surgeons, 1993, pp. 91–105.
64. MacConaill MA, Basmajian JV. Muscles and Movements. A Basis for Human Kinesiology. 2nd ed Huntington: Kreiger, 1977, pp. 134—5, 253-6.
65. Huxel KC, Swanik CB, Swanik KA, et al. Stiffness regulation and muscle- recruitment strategies of the shoulder in response to external rotation perturbations. J Bone Joint Surg Am. 2008; 90:154–62.
66. Houk JC. Regulation of stiffness by skeletomotor reflexes. Ann Rev Physiol. 1979;41:99–114.
67. Inman VT, Saunders JB, deC M, Abbott LC. Observations on the function of the shoulder joint. J Bone Joint Surg Am. 1944;26:1–30.
68. An K-N, Browne AO, Korinek S, Tanaka S, Morrey BF. Three-dimensional kinematics of glenohumeral elevation. J Orthop Res. 1991;9:143–9.
69. Dvir Z, Berme N. The shoulder complex in elevation of the arm: A mechanism approach. J Biomech. 1978;11:219–25.
70. Hogfors C, Sigholm G, Herberts P. Biomechanical model of the human shoulder—I. Elements. J Biomech. 1987;20:157–66.
71. McClure PW, Michener LA, Sennett BJ, Karduna AR. Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. J Shoulder Elbow Surg. 2001; 10:269–77.
72. Ludewig PM, Behrens SA, Meyer SM, Spoden SM, Wilson LA. Three-dimensional clavicular motion during arm elevation: Reliability and descriptive data. J Orthop Sports Phys Ther. 2004;34:140–9.
73. Doody SG, Freedman L, Waterland JC. Shoulder movements during abduction in the scapular plane. Arch Phys Med Rehabil. 1970;51:595–604.
74. Dayanidhi S, Orlin M, Kozin S, Duff S, Karduna A. Scapular kinematics during humeral elevation in adults and children. Clin Biomech. 2005;20:600–6.
75. Williams M, Lissner HR. Biomechanics of Human Motion. Philadelphia: Saunders, 1962, pp. 65-8.
76. Dines DM, Moynihan DP, Dines JS, McCann P. Irreparable rotator cuff tears: What to do and when to do it; the surgeon's dilemma. J Bone Jt Surg Am. 2006;88:2294–302.
77. Kronberg M, Németh G, Broström L-A. Muscle activity and coordination in the normal shoulder. An electromyographic study. Clin Orthop Rel Res. 1990;257:76–85.
78. Zheng N, Fleisig GS, Andrews JR. Biomechanics and injuries of the shoulder during throwing. Athletic Ther Today. 1999;4:12–7.
79. Anderson M. Comparison of muscle patterning in the overarm throw and tennis serve. Res Quart. 1979;50:541–53.

80. Hancock RE, Hawkins RJ. Applications of electromyography in the throwing shoulder. Clin Orthop Rel Res. 1996;330:84–97.
81. Jobe FW, Tibone JE, Perry J, Moynes D. An EMG analysis of the shoulder in throwing and pitching. A preliminary report. Am J Sports Med. 1983;11:3–5.
82. Jobe FW, Radovich Moynes D, Tibone JE, Perry J. An EMG analysis of the shoulder in pitching. A second report. Am J Sports Med. 1984;12:218–20.
83. DiGiovine NM, Jobe FW, Pink M, Perry J. An electromyographic analysis of the upper extremity in pitching. J Shoulder Elbow Surg. 1992;1:15–25.
84. Meister K. Injuries to the shoulder in the throwing athlete. Part one: Biomechanics/Pathophysiology/classification of injury. Am J Sports Med. 2000;28:265–75.
85. Flatow EL, Kelkar R, Raimondo RA, et al. Active and passive restraints against superior humeral translation: The constributions of the rotator cuff, the biceps tendon, and the coracoacromial arch. J Shoulder Elbow Surg. 1996;5:S111.
86. Hurov JR. Surface electromyography of superficial back muscles in human children: Functions during vertical climbing and suspension and implications for the evolution of hominid bipedalism. J Human Evol. 1982;11:117–30.
87. Beaton DE, Katz JN, Fossel AH, Wright JG, Tarasuk V, Bombardier C. Measuring the whole or parts? Validity, reliability, and responsiveness of the Disabilities of the Arm, Shoulder, and Hand outcome measure in different regions of the body. J Hand Ther. 2001;14:128–46.
88. Michener LA, Leggin BG. A review of self-report scales for the assessment of functional limitation and disability of the shoulder. J Hand Ther. 2001;14:68–76.
89. Magermans DJ, Chadwick EKJ, Veeger HEJ, van der Helm FCT. Requirements for upper extremity motions during activities of daily living. Clin Biomech. 2005;20:591–9.
90. Bourne DA, Choo AMT, Regan WD, MacIntyre DL, Oxland TR. Three- dimensional rotation of the scapula during functional movements: An *in vivo* study in healthy volunteers. J Shoulder Elbow Surg. 2007;16:150–62.
91. Petuskey K, Bagley A, Abdala E, James MA, Rab G. Upper extremity kinematics during functional activities: Three−dimensional studies in a normal pediatric population. Gait Posture. 2007;25:573–9.
92. Lukasiewicz AC, McClure P, Michener L, Pratt N, Sennett B. Comparison of three- dimensional scapular position and orientation between subjects with and without shoulder impingement syndrome. J Orthop Sports Phys Ther. 1999;29: 574–86.
93. Scibek JS, Mell AG, Downie BK, Carpenter JE, Hughes RE. Shoulder kinematics in patients with full-thickness rotator cuff tears after a subacromial injection. J Shoulder Elbow Surg. 2008;17:172–81.
94. Kelly BT, Williams RJ, Cordasco FA, et al. Differential patterns of muscle activation in patients with symptomatic and asymptomatic rotator cuff tears. J Shoulder Elbow Surg. 2005;14:165–71.
95. Reinold MM, Escamilla R, Wilk KE. Current concepts in the scientific and clinical rationale behind exercises for glenohumeral and scapulothoracic musculature. J Orthop Sports Phys Ther. 2009;39:105–17.
96. Hughes RE, Johnson ME, O'Driscoll SW, An K-N. Age-related changes in normal isometric shoulder strength. Am J Sports Med. 1999;27:651–7.
97. Kim HM, Teefey SA, Zelig A, Galatz LM, Keener JD, Yamaguchi K. Shoulder strength in asymptomatic individuals with intact compared with torn rotator cuffs. J Bone Jt Surg. 2009;91: 289–96.
98. Townsend H, Jobe FW, Pink M, Perry J. Electromyographic analysis of the glenohumeral muscles during a baseball rehabilitation program. Am J Sports Med. 1991;19:264–72.
99. Cools AM, Dewitte V, Lanszweert F, et al. Rehabilitation of scapular muscle balance: Which exercises to prescribe? Am J Sports Med. 2007;35:1744–51.

JHT Read for Credit

Quiz: Article # 139

Record your answers on the Return Answer Form found on the tear-out coupon at the back of this issue. There is only one best answer for each question.

#1. The purpose of the study was to
   a. present current treatment strategies for common shoulder pathologies
   b. make the distinction between orthopedic and neurologic shoulder conditions
   c. separate out true shoulder pathologies from cervical dysfunction
   d. review current concepts of shoulder anatomy and function

#2. Precise centering of the humeral head in the glenoid is critical to maintaining proper
   a. strength of the GH joint throughout its range
   b. balance of the anterior and posterior aspects of the rotator cuff muscles
   c. stability of the GH joint
   d. tension on the anterior inferior gleno humeral ligament (AIGHL)

#3. The articular surface of the humeral head is approximately _____ times that of the glenoid surface
   a. 2.5
   b. 1.5
   c. 3
   d. 5

#4. An additional factor contributing to the relative stability of the GH joint is
   a. the activation of the deltoid during elevation of the arm
   b. an internal negative pressure based on fluid dynamics
   c. the passive restraint of the anterior cruciate ligament (ACL)
   d. the co-contraction of the biceps and triceps during forceful internal rotation

#5. In discussing the role scapular motion to avoid impingement the authors cite the work of
   a. Harryman and Rockwell
   b. McClure
   c. LaStayo
   d. Walsh and Rineheimer

When submitting to the HTCC for re-certification, please batch your JHT RFC certificates in groups of 3 or more to get full credit.