J Shoulder Elbow Surg (2009) 18, 661-667

ELSEVIER

Journal of Shoulder and Elbow Surgery

www.elsevier.com/locate/ymse

Genetic and biomechanical determinants of glenoid version: Implications for glenoid implant placement in shoulder arthroplasty

Joshua P. Landau, MD, Heinz R. Hoenecke, MD*

Shiley Center for Orthopaedic Research and Education at Scripps Clinic, La Jolla, CA

Summary: The universally accepted method of measuring glenoid version to determine proper alignment of the glenoid component during total shoulder arthroplasty does not account for the complex and variable relationship of the glenoid vault with the scapular body. Existing evidence indicates that the glenoid and the scapular body development are controlled by independent genetic and biomechanical factors. This raises the question: How relevant is the relationship of the glenoid face to the scapular body? This review paper integrates our present understanding of the genetics of scapular development and congenital and neuromuscular conditions to generate insights into scapular morphology and biomechanics. Glenoid version as traditionally defined may have limited relevance when positioning the glenoid component during total shoulder arthroplasty. Further studies of soft-tissue and muscular balance are needed to fully understand the consequences of variations in glenoid version.

Level of evidence: Review.

Glenoid version (defined as the angle between the glenoid face and the scapular body) changes significantly with arthritis. In shoulder arthroplasty, restoration of glenoid version to normal values is recommended; however, the relationship of the glenoid cavity to the scapular body is extremely variable. This raises the question of the relevance of the relationship of the glenoid face to the scapular body.

The current understanding of the relationship between scapular osseous anatomy and function is limited. There are some currently accepted definitions of ''normal'' relationships that theoretically carry some implications on biomechanics, function, and the development of pathologic states.

Clinicians have made assumptions about the relationships between pathologic conditions of the glenohumeral joint and abnormalities in glenoid version. The mature adult glenoid neck and face may be considered the final target or end result of scapular development. From a simplified point of view, the ultimate goal in the development of the scapula is to create a stable articular platform to allow force transmission across the glenohumeral joint. Keeping this target in mind, an analysis of the embryologic and genetic determinants of osseous anatomy will help to understand the anatomic and biomechanical pathologic changes seen in glenohumeral disease states.

The goal of this paper is to advance our conceptual understanding of scapular morphology in health and diseased states through an exploration of the existing literature regarding scapular anatomy, genetics, and embryology. The relationship between osseous and soft-tissue developmental factors will be

*Reprint requests: Heinz R. Hoenecke, MD, 11025 N. Torrey Pines Road, Suite 240, La Jolla, CA 92037.

E-mail address: bhoeneck@san.rr.com (H.R. Hoenecke).

1058-2746/2009/$36.00 - see front matter © 2009 Journal of Shoulder and Elbow Surgery Board of Trustees.
doi:10.1016/j.jse.2008.11.012

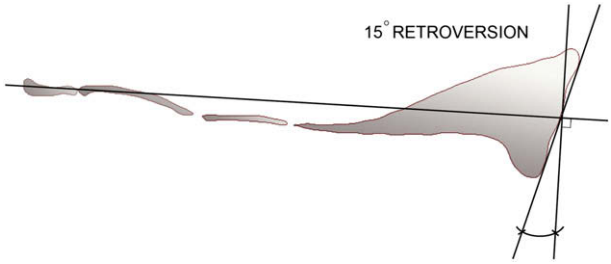

Figure 1 Measurement of glenoid version.

analyzed by evaluating specific disease states such as brachial plexus birth palsy, glenoid retroversion with posterior glenohumeral subluxation, glenoid hypoplasia, and Sprengel's Deformity. Through analysis of these disease states, we hope to elucidate the genetic and biomechanical determinants of glenoid version. We also aim to propose a basic science rationale as to why it may not be important to restore glenoid version to a predefined anatomic average value during arthroplasty; rather, the operative goals should be to achieve muscular balance and to create a stable articluar surface based on the available bone stock found within the glenoid vault.

Glenoid version

Our current conceptual model of scapular biomechanics and function is based on a range of accepted ''normal'' relationships between the glenoid and the scapular body. Before CT scans, the technique for measuring glenoid version was based on axillary radiographs. The technique described by Saha in 1971 is to draw a line from the center point of the glenoid to the junction between the medial border of the scapula and the scapular spine.[14] The glenoid version is defined as the angle between this line and the line between the most anterior and the most posterior margin of bone of the glenoid. Friedman et al[5] adapted this technique to provide a measurement technique for glenoid version based on CT scans (Figure 1). They found a mean of $2^{\circ} \pm 5^{\circ}$ of glenoid anteversion in 63 normal control subjects. They found $11^{\circ} \pm 8^{\circ}$ of retroversion in patients with osteoarthritis or inflammatory arthritis. The conclusion based on these data was that reconstructive surgical techniques should aim to restore glenoid version to approximately 2° of anteversion utilizing eccentric reaming or posterior bone grafting.

We have used 3-dimensional (3-D) CT technology to study the variability in the relationship between the glenoid and the scapular body (Figure 2). The axial images can be processed to produce a slice outline of the bony anatomy of the scapular body, neck, and glenoid at the level of the glenoid center (Figure 3). The osseous relationship appears to be extremely variable. This broad range of variability is not characteristic of most other bones. The variability seems to be organized into 3 categories: body shape (curved versus flat), glenoid translation (anterior, centered, posterior), and glenoid version

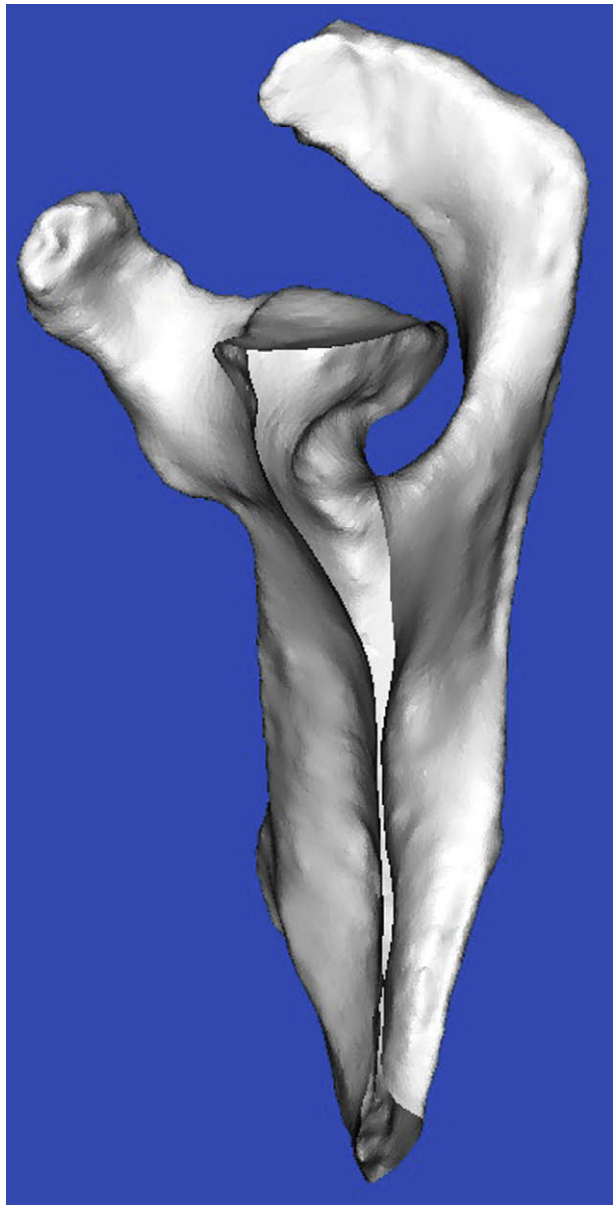

Figure 2 Example of a 3-D CT reconstruction used to identify the center of the glenoid and to create a slice outline to analyze the relationship between the scapular body, neck, and glenoid in normal subjects.

(anteversion, neutral, retroversion). Figure 4 depicts these categories conceptually. The scapular morphology appears to be somewhat modular, with the body being 1 component and the glenoid being a 2nd component. These 2 components are situated separately in space and then joined by a bridge of tissue forming the glenoid vault.

Scapular embryology and genetics

Why is there so much variability in scapular morphology? How is the scapula formed and are malformations the result

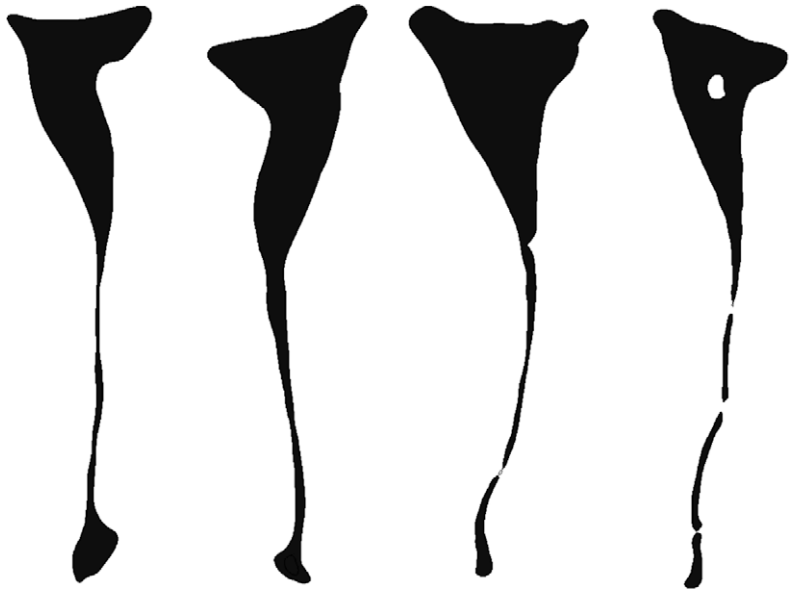

Figure 3 CT scan slice outlines of the right scapulae from 4 different normal cadaveric subjects.

of intrinsic genetic developmental mishaps or the result of pathological influences from extrinsic sources?

The osseous development of the scapula is mostly formed by intramembranous ossification by at least 8 ossification centers (Figure 5).[6] There are multiple growth centers that ossify to form the acromion: 1 for the body of the scapula, 1 for the medial border, 1 for the inferior angle, 2 for the coracoid, and 2 for the glenoid. The glenoid has 1 superior growth center that is at the base of the coracoid and 1 horseshoe shaped growth center inferiorly. The inferior center is thin at its center and thicker peripherally to form the concavity and shape of the glenoid.

The scapula differentiates at fetal week 5 and is located at the level of the 4th, 5th, and 6th cervical vertebrae.[7] By 8 weeks of development all limb structures are present. Early on the scapula is wider than it is tall, as is the case in quadrupeds. As the human fetus develops, the scapular body elongates until the length is greater than the width. This allows for increased motion of the upper extremity for a bipedal human. Additionally, there is a caudal migration of the scapula, as there is differential growth within the spine resulting in the final position of the scapula to be at the level of the 2nd through 7th thoracic ribs.

In Sprengel's Deformity, the scapula remains undescended and develops in a different muscular and bony milieu. The normal elongation does not occur, and the surrounding musculature becomes infiltrated with fibrofatty tissue.[2] Additionally, the scapular body is curved over the superior aspect of the chest wall, as if accommodating to the shape of the thoracic cage. This will interfere with normal scapulothoracic motion if this deformity is not addressed at the time of corrective surgery. Although the position of the scapula can be surgically lowered with respect to the thorax, the shape of the scapular body still matches the curvature of the upper part of the thorax, thereby resulting in scapulothroacic incongruency. Even in patients without Sprengel's Deformity, it appears that the bodies of some scapulae are curved and some are flat; this appears to be dependent upon the shape of the adjacent rib cage (Figure 4). From the undescended scapula, it appears as if the shape of the body is at least heavily influenced if not determined by the surrounding muscular and bony envelope, rather than a predetermined genetic design.

Where does the tissue that forms the scapula come from? Shoulder girdle development is commonly grouped together with the limb formation; however, this is probably not an accurate conceptual grouping. There are 3 embryologic structures that appear to play a significant role in limb development: the apical ectodermal ridge (AER), the wingless-type (Wnt) pathway, and the zone of polarizing activity (ZPA). Multiple studies have shown, however, that interfering with these pathways interferes with limb development but does not affect the scapula or shoulder girdle.[15,16] There are, however, a number of genes that have been found to govern specific portions of scapular development; these include the Pax1 gene, Emx2 gene, and Hoxc6 gene. Figure 6 summarizes these genes and their location of primary influence.

The Pax1 gene controls development of the acromion and scapular spine. Genetic knockout analysis has found that if the Pax1 gene is lacking, then the acromion and part of the scapular spine is missing.[19]

The Emx2 gene controls development of the scapular body, as well as the ilium. Knockout mice lacking Emx2 results in a complete absence of the body of the scapula, while the distal end of the acromion is present and articulates with the clavicle. The coracoid and the glenoid cavity develop normally, and glenoid articulates with the humeral head normally.[13] Interestingly, these mice also lacked the majority of the ilium. This implies that the iliac wing may

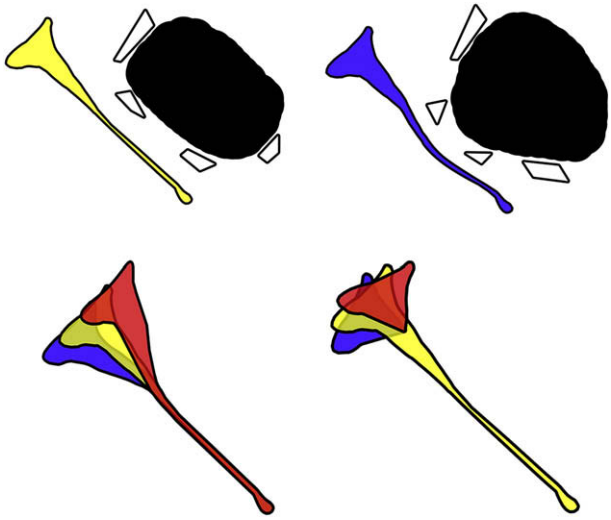

Figure 4 The modular scapula: variations in normal scapular morphology can be expressed in terms of the shape of the scapular body, glenoid translation, and glenoid version.

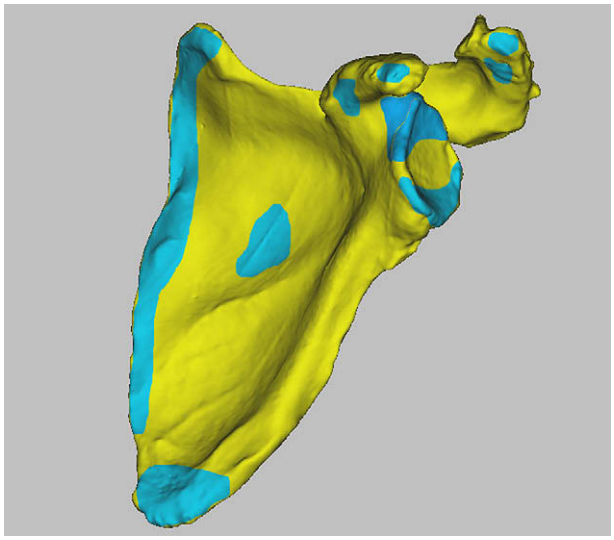

Figure 5 Ossification centers of the scapula.

be a homolog to the scapular body. This pattern of pathology has been noted clinically in humans by Cousin et al[4] who described pelviscapular dysplasia with bilateral agenesis of the wing of the scapula and hypoplasia of the ilium. It appears that scapular body development is not governed by the same genetic mechanism that governs the development of the acromion, coracoid, and glenoid.

The Hoxc6 gene controls the development of the coracoid and glenoid. Isolated abnormalities of the coracoid and glenoid have been seen with Hoxc6 defects. Expanding expression of Hoxc6 genes results in duplicate shoulder coracoid and acromion formation in chick embryos.[11] This has been seen clinically in humans (Figure 7), as reported by McClure et al.[10]

Additional information on the origin of the scapular tissue has been further elucidated through an avian model. Huang et al [8] found that the scapula has a dual origin. The glenoid and acromion are formed from the somatopleura. In contrast, the body of the scapula is derived from a compartment called the dermomyotome, which also serves as the precursor for all the musculature of the trunk. Why does the scapular body have so many different muscular attachments? Huang et al found that the scapular body was divided into segments, formed by the coalescence of tissue derived from multiple embryologic somites. Interestingly, each somite is responsible for creating a portion of the bone, as well as the respective muscle and connective tissue that are attached to that specific segment (Figure 6). This implies that the scapular body is not a skeletal element proper, but rather an ossifying muscle attachment.[3]

Kieny et al[9] found that transplanted cervical presomites into the thorax did not form ribs, but did form normal scapula. This implies that the scapula is formed based on local environmental cues. Alternatively, transplanting thoracic somites into the cervical region causes cervical ribs to form, but does not form scapula, thereby further supporting that the scapula only forms according to the correct environmental cues. From this information combined with the information we learned by analyzing the scapular deformity seen with Sprengel's Deformity, it appears that the scapular body and the surrounding ligaments and musculature are formed within a soft-tissue sleeve that depends on signals and structure from the local environment. This development is governed by separate genes and is from distinctly separate tissue than those controlling the acromion, coracoid, and glenoid development.

By analyzing the embryology and genetics governing scapular development, it appears that the scapular body and the glenoid develop from 2 completely separate tissues and are governed by independent forces. The body seems to be more of an ossified muscular attachment whose development depends on the surrounding muscular sleeve, while the glenoid has separate ossification centers and develops according to genetic composition.

Posterior glenohumeral subluxation

How do these embryological findings help us understand glenoid retroversion and posterior subluxation? Are these manifestations of an isolated developmental bony deformity? How much does soft-tissue balance play a role?

Historically, orthopaedic surgeons have approached understanding the glenohumeral relationship from primarily a bony standpoint. In the case of glenoid retroversion and posterior subluxation, the solution intuitively would be to fix the retroversion, which should theoretically center the humeral head, resulting in less pain and less progression of arthritis. Brewer et al[1] reported a small series of 5 patients who underwent corrective glenoid osteotomy with posterior capsular imbrication for the treatment of nontraumatic

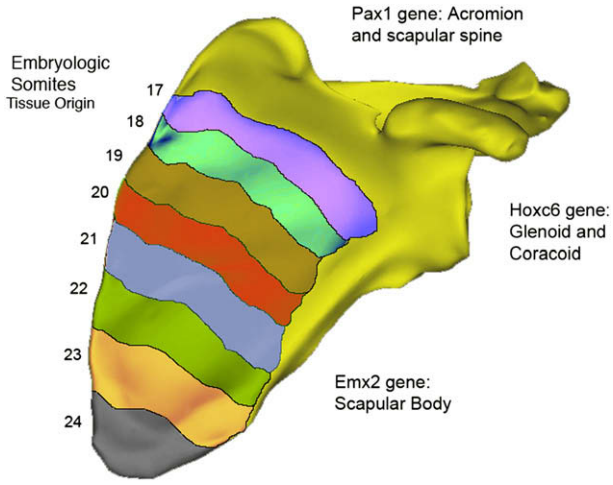

Figure 6 Regions of genetic influence governing scapular development.

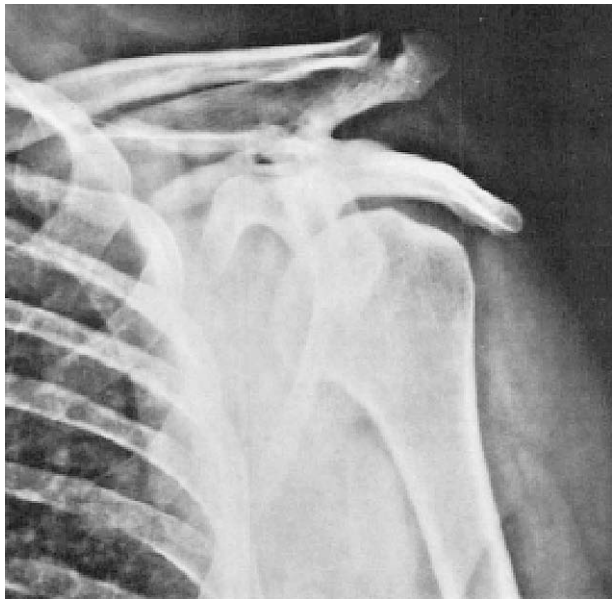

Figure 7 Double acromion and coracoid process. (Reprinted with permission from McClure et al.[10].)

adolescent patients with posterior instability. All shoulders became stable and functional (1 required revision due to loss of correction), but with only 1-2 years follow-up, and glenoid version analysis was performed with axillary radiographs rather than computed tomography.

In contrast, Walch et al[17] studied a small select population of patients under 40 years old who presented with retroversion of the glenoid and posterior subluxation and performed glenoid neck corrective osteotomies. In their first 2 patients, they performed corrective glenoid osteotomies with capsular imbrication. They abandoned this procedure because it did not successfully center the humeral head. The posterior subluxation continued despite changing the angle between the glenoid face and the scapular body. The cause-and-effect relationship between glenoid version and humeral subluxation is not as straightforward as it seems. Glenohumeral subluxation is likely governed by a complex interaction between bony architecture and soft-tissue balance.

Brewer et al[1] implicate faulty ossification centers of the glenoid as the cause for the excessive glenoid retroversion, stating that abnormalities of the ossification center at the base of the coracoid explain posterior rotation of the glenoid (Figure 5). Similarly, abnormalities of the horseshoe shaped ossification in the mid-glenoid area result in flattening of the glenoid fossa. Interestingly, these ossification centers appear at 10 and 15 years old, respectively. It may be that there is a combination of osseous developmental abnormalities and soft-tissue imbalances that both contribute to posterior subluxation and an incongruous joint.

Brachial plexus birth palsy

The relationship between osseous deformity and soft-tissue balance becomes more clearly elucidated by studying the glenoid changes seen in brachial plexus birth palsy (BPBP). Pearl and Edgerton[12] studied 25 children with internal rotation contractures from BPBP with arthrograms to define glenoid deformities due to chronic shoulder abduction and external rotation palsy. Seven had normal glenoids; there were 18 abnormal posterior glenoids. Five of these had flattening, 7 biconcave, and 6 had pseudoglenoid with a concavity separate and posterior from the original articular surface. The severity of glenoid abnormality was directly associated with the severity of the internal rotation contracture. Although all types of deformity were seen at all ages, there was a significant correlation between age and severity of glenoid deformity.

In a similar study, Waters et al[18] prospectively followed 94 patients with BPBP to determine the relationship of age and severity of muscular weakness on glenohumeral joint deformity. Only 42 patients had persistent weakness. These patients were evaluated with CT and MRI. They found mean retroversion of 25° compared to 5° on the contralateral normal side. They also found that the more glenoid deformity, the more posterior subluxation of the humeral head. They also found an association between retroversion and age. Interestingly, the osseous anatomy of scapular body and glenoid vault was typically normal as seen on a plain x-ray with the changes in the scapula confined to the cartilage covering the glenoid face. This implies that the growth disturbance was not an intrinsic problem with the bone, but rather an impairment of the cartilaginous development of the posterior glenoid. Given that the contralateral shoulder was normal in these children, extrinsic muscle imbalance must play a significant role in the symmetric growth of the glenoid. Genetic influences do not appear to be significant. The severe glenohumeral osseous deformities were not seen

until patients were past their adolescent growth spurt. One of their conclusions was that severe muscle imbalance leads to early dislocation, rather than an osseous abnormality. It is noted that infantile shoulder dislocation leads to rapid severe osseous deformity. It appears that if bony abnormalities do not cause posterior subluxation, then correcting the bony deformity may not correct the subluxation.

From examining patients with Brachial Plexus Birth Palsy, it is clear that the development of osseous deformity of the glenoid is governed or at least strongly influenced by extrinsic muscular balance across the glenohumeral joint.

Glenoid hypoplasia

Now that we have an understanding of the different tissue sources and genetic variables involved in creating a normal scapular body and glenoid, we can look clinically at cases where this developmental process goes astray.

Wirth, Lyons, and Rockwood[20] reported on 16 patients who were found to have what they termed ''hypoplasia of the glenoid.'' Thirteen were bilateral, and the presenting complaint was pain. Severe hypoplasia was defined as having extensive hypoplasia of the inferior part of the glenoid, marked dysplasia of the humeral head, varus angulation of the humeral head, apparent joint incongruity, and associated scapular abnormalities, including an enlarged and inferiorly directed acromion, a prominent coracoid process, and hooking of the distal part of the clavicle. In this study, the patients did well with conservative physiotherapy treatment. They did not find a familial pattern. All patients had pain, 6 lost range of motion, and 5 had symptomatic instability. The severity of hypoplasia correlated with the loss of range of motion. Interestingly, 1 patient with 10 years of symptoms with moderate hypoplasia had an arthroscopic examination, which revealed a congruent joint space and normal-appearing cartilage. They noted that only 2 patients in the study developed osteoarthrosis and during the course of the study they performed more than 600 reconstructive shoulder procedures, and not one of these operations was for the treatment of problems associated with glenoid hypoplasia.

Conclusion

Understanding the embryology and genetics of scapular development can help us understand the pathomechanics and pathoanatomy found in various forms of glenohumeral disease states. The glenoid is formed from 2 ossification centers: a subcoracoid superior center, which may be implicated in the determination of physiologic glenoid version and an inferior horseshoe-shaped center that may be implicated in glenoid hypoplasia and the development of a shallow socket. The shapes of the glenoid and the scapular body are governed by separate forces. The body is dependent upon the surrounding thoracic shape and the surrounding muscular sleeve. The glenoid face and vault seem to connect to the scapular body in a modular-type fashion, with resultant normal variations in glenoid translation and version. The Emx2 gene appears to be integral to the body formation. In contrast, the Hoxc6 gene is integral for glenoid development. The Pax1 gene governs development of the acromion. Patients with brachial plexus birth palsy teach us that the glenoid development is an ongoing process through the course of childhood development and is highly dependent on the balance of muscular forces across the glenohumeral joint. In the adult patient with static posterior glenohumeral subluxation, corrective glenoid osteotomy does not necessarily correct posterior humeral subluxation, suggesting that abnormalities of glenoid version may not be the primary cause of the subluxation.

The osseous glenoid and scapular body should be considered independently. The universally accepted method of measuring glenoid version to determine proper alignment of the glenoid component during total shoulder arthroplasty does not account for the complex and variable relationship of the glenoid vault with the scapular body. Existing evidence indicates that the glenoid and the scapular body development are controlled by independent genetic and biomechanical factors. The angle formed between the glenoid face and the scapular body may be less important in understanding glenohumeral biomechanics than we previously have thought. When performing a total shoulder arthroplasty, neutral glenoid version as commonly defined may not represent the biomechanical axis of the muscles required for creating a stable glenoid articular platform. Further study is needed to better understand how soft tissues and muscular forces determine the location of biomechanical axis across the glenohumeral joint for an individual patient. This information can be used to determine the surgical options available to alter the bony and soft-tissue anatomy to achieve a successful arthroplasty.

Acknowledgments

We thank Cesar Flores and David Avi Gordon for contributions in graphic development.

References

1. Brewer BJ, Wubben RC, Carrera GF. Excessive retroversion of the glenoid cavity. A cause of non-traumatic posterior instability of the shoulder. J Bone Joint Surg Am 1986;68:724-31.
2. Cavendish ME. Congenital elevation of the scapula. J Bone Joint Surg (Br) 1972;54-B:395-408.
3. Christ B, Wilting J. From somites to vertebral column. Ann Anat 1992;174:23-32.
4. Cousin J, Walbaum R, Cegarra P, Huguet J, Louis J, Pauli A, et al. Familial pelvi-scapulary dysplasia with anomalies of the epiphyses,

dwarfism and dysmorphy: a new syndrome? Arch Fr Pediatr 1982;39: 173-5.
5. Friedman RJ, Hawthorne KB, Genez BM. The use of computerized tomography in the measurement of glenoid version. J Bone Joint Surg Am 1992;74:1032-7.
6. Gardner E, Gray DJ. Prenatal development of the human shoulder and acromioclavicular joints. Am J Anat 1953;92:219-76.
7. Grogan DP, Stanley EA, Bobechko WP. The congenital undescended scapula. J Bone Joint Surg (Br) 1983;65-B:598-605.
8. Huang R, Zhi Q, Patel K, Wilting J, Christ B. Dual origin and segmental organisation of the avian scapula. Development 2000;127:3789-94.
9. Kieny M, Mauger A, Sengel P. Early regionalization of the somite mesoderm as studied by the development of the axial skeleton of the chick embryo. Dev Biol 1972;28:142-61.
10. McClure JG, Raney RB. Double acromion and coracoid process: Case report of an anomaly of the scapula. J Bone and Joint Surg Am 1974; 56:830-2.
11. Oliver G, De Robertis EM, Wolpert L, Tickle C. Expression of a homeobox gene in the chick wing bud following application of retinoic acid and grafts of polarizing region tissue. EMBO J 1990;9:3093-9.
12. Pearl ML, Edgerton BW. Glenoid deformity secondary to brachial plexus birth palsy. J Bone Joint Surg Am 1998;80:659-67.
13. Pellegrini M, Pantoano S, Fumi MP, Lucchini F, Forabosco A. Agenesis of the scapula in Emx2 homozygous mutants. Dev Biology 2001;232:149-56.
14. Saha AK. Dynamic stability of the glenohumeral joint. Aeta Orthop. Scandinavica 1971;42:491-505.
15. Saunders JW. The proximo-distal sequence of origin of the parts of the chick wing and the role of the ectoderm. J Exp Zool 1948;108: 363-403.
16. Spater D, Hill TP, Gruber M, Hartmann C. Role of canonical wnt-signaling in joint formation. Euro Cells Mater 2006;12:71-80.
17. Walch G, Ascani C, Boulahia A, Nove-Josserand L, Edwards TB. Static posterior subluxation of the humeral head: an unrecognized entity responsible for glenohumeral osteoarthritis in the young adult. J Shoulder Elbow Surg 2002;11:309-14.
18. Waters PM, Smith GR, Jaramillo D. Glenohumeral deformity secondary to brachial plexus birth palsy. J Bone Joint Surg Am 1998; 80:668-77.
19. Wilm B, Dahl E, Peters H, Balling R, Imai K. Targeted disruption of Pax1 defines its null phenotype and proves haploinsufficiency. Proc Natl Acad Sci 1998;95:8692-7.
20. Wirth MA, Lyons FR, Rockwood CA. Hypoplasia of the glenoid. A review of sixteen patients. J Bone Joint Surg Am 1993;75:1175-84.