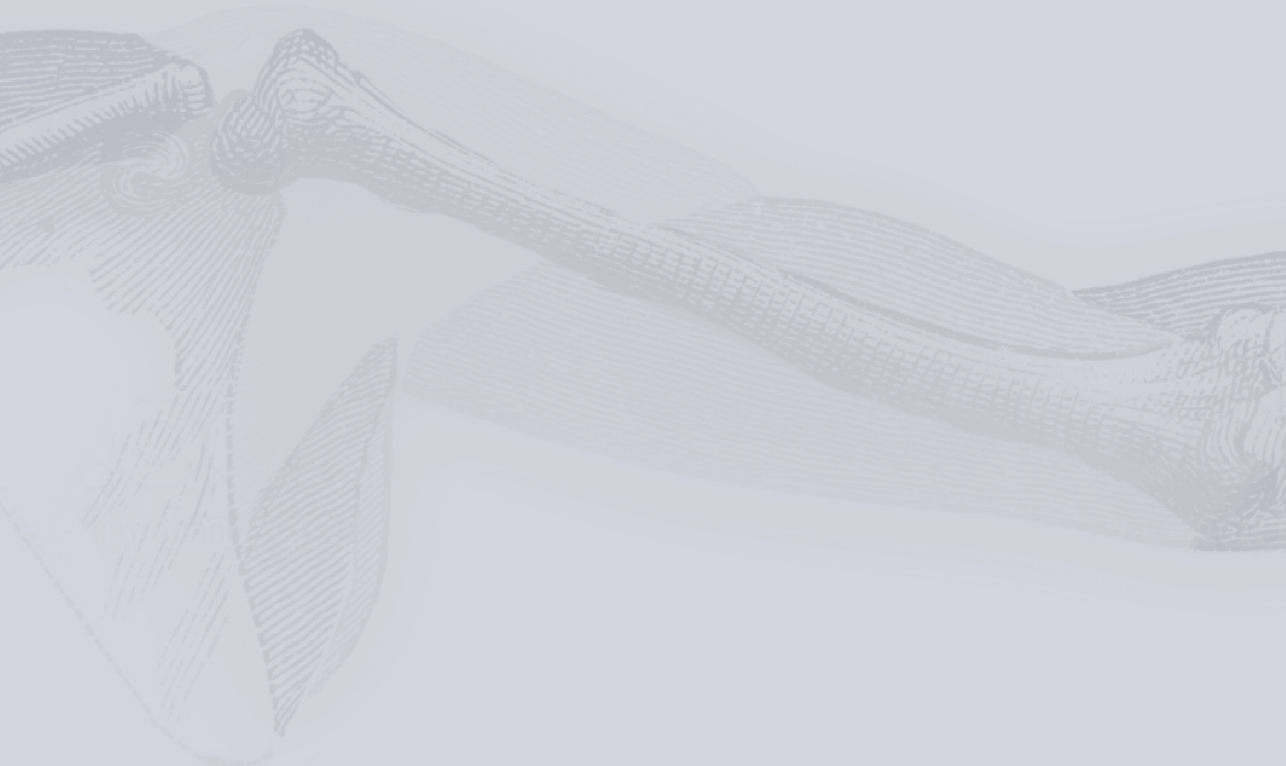
Functional implications of structural “anomalies” in shoulder pain

Kolk, A.



1 General introduction

SUBACROMIAL PAIN SYNDROME

Background

The shoulder girdle is essential to complete our daily life activities. It enables us to complete our tasks by positioning the hand into the space around us. Interestingly, we are usually unaware of the great mobility it requires to eat and wash, until we experience shoulder pain or discomfort. The shoulder movements are created by a complex synergy of motions of the thorax, clavicle, scapula and humerus. The bones are connected at the sterno-clavicular joint, the acromioclavicular joint, the scapulothoracic gliding area and the glenohumeral joint. The glenohumeral joint is a ball-in-socket joint that contributes to the majority of shoulder motion when elevating the arm.[8] Forces generated by scapulothoracic, humerothoracic and scapulohumeral muscles like the latissimus dorsi, teres major, pectoral major muscle, serratus anterior, deltoid muscle and the rotator cuff (i.e. teres minor, infraspinatus, supraspinatus and subscapularis muscle) all facilitate arm movements.

The shoulder joint is after the low-back the second most reported anatomic site of musculoskeletal pain in Dutch adults.[100] The prevalence of shoulder complaints is approximately 48 per 1000 person-years.[43, 94] Incidence rates are about 11 to 29 per 1000 person-years, with the highest incidence between 40 to 65 years.[7, 43, 122] The most likely origin of shoulder complaints largely depends on age. At younger age (under 35 years), shoulder complaints are frequently caused by glenohumeral instability or a shoulder sprain.[72] In patients over 35 years of age, complaints are more commonly attributed to a supposedly painful subacromial inflammation of the bursa or rotator cuff.[72, 122, 123] Interestingly, the age-dependent cause of shoulder disorders is also reflected by the prevalence of rotator cuff tears, with a prevalence of 3 percent at the 4th decade, 25 percent at the 6th decade, to over 50 percent at the 8th decade of life.[90, 116, 127]

Historical Perspective

At the beginning of the 20th century, the clinical entity and aetiology of shoulder pain was studied by several authors.[16-18, 39] According to these authors, it was evident that inflammation of subacromial structures resulted in pain with arm abduction at the anterior edge of the acromion.[16, 33, 39] As early as 1909, anatomic considerations led to the assumption that repeated mechanical impingement under the acromion could cause painful irritation of the bursa.[12, 39] In these years, Codman extensively published his personal views on shoulder pain. He reported on patient characteristics, the physical examination and symptoms which characterised the clinical entity of a supraspinatus rupture.[17] In an attempt to understand the aetiology of the painful shoulder, Codman further discussed several hypotheses explaining subacromial inflammation, while discussing attrition of subacromial tissues under the acromion as one possible mechanism for pain and rotator cuff tears.[18] Codman was

not convinced that a traumatic event caused a supraspinatus rupture. He argued that an "underlying degenerative process" could make the tendon more prone to rupture.[18]

The theory of attrition of structures under the acromion was the reason for Charles S. Neer to introduce the anterior acromioplasty in 1972.[92] Neer concluded that such an impingement occurs at the anterior edge of the acromion rather than the lateral aspect of the acromion.[92, 93] Adjacent to bony morphology, the coracoacromial ligament was assumed to contribute to extrinsic compression.[49, 92] Neer distinguished three stages of "shoulder impingement syndrome": stage I associated with subacromial edema, stage II associated with a partial tear or tendinitis, and stage III associated with a rotator cuff tear.[93] The cause-effect relation of acromion morphology and rotator cuff disease was further propagated by Bigliani.[4, 5] Bigliani argued that more acromial slope was correlated to a higher prevalence of rotator cuff tears.[4] Interestingly, neither physical exam nor radiographic evaluations were able to distinguish between bursitis or a partial thickness rotator cuff tear from the presence of a rotator cuff tear according to Neer's classification.[92, 98] Authors also noticed that radiographs frequently did not show pathology which could be associated with shoulder pain.[38] Nevertheless, the subacromial impingement syndrome was now considered as one clinical entity and Neer's classification was widely accepted among orthopaedic surgeons worldwide. As a consequence, biomechanical and intervention studies studied patients with shoulder impingement syndrome from stage I to III as one entity without additional imaging of the rotator cuff to separate a tendinitis from a torn rotator cuff.[9, 10, 37, 41, 42, 44, 45, 47, 70, 75, 78, 82]

Consistent with the propagation of the attrition theory, the number of anterior acromioplasty (i.e. subacromial decompression) dramatically increased in the nineties and beginning of the twenty-first century.[60, 97, 125] During this procedure the anterolateral undersurface of the acromion was removed to flatten the anterior process of the acromion.[92] Although successful results after acromioplasty have been reported in cohort studies[6, 11, 30, 106], randomised controlled trials were unable to demonstrate the beneficial treatment effect of acromioplasty compared to physiotherapy.[9, 10, 32, 44, 45, 64-66] At the beginning of this century, the first trials were designed to detect the treatment effect of acromioplasty itself by introducing a surgical "placebo" treatment arm as control group.[36, 52] These trials did also not confirm the success of acromioplasty 2.5 years after surgery, which put the effectiveness of anterior acromioplasty into question. The findings led to alternative hypotheses regarding the aetiology of shoulder complaints and alternative diagnostic definitions of "subacromial impingement syndrome".[22, 24] Since impingement syndrome as such suggested a specific anatomic cause (i.e. subacromial attrition) for pain, the Dutch Orthopaedic Association changed the entity "subacromial impingement syndrome" to a more general term: the "subacromial pain syndrome".[29, 91]

Many intrinsic and extrinsic mechanisms have been proposed to cause subacromial pain.[3, 22, 24, 89] Long before the impingement theory was popularised, Codman already hypothesised in his classic paper of 1931, on both tendon degeneration (i.e. intrinsic mechanism)

as well as anatomic variants (i.e. extrinsic mechanism) causing shoulder pain and ultimately a rotator cuff tear.[18] Later, more intrinsic mechanisms have been suggested to cause subacromial pain syndrome including: a subacromial inflammatory reaction with tendon thickening and overuse causing repetitive microtrauma.[3, 22, 24, 89] Many researchers have focused on extrinsic mechanisms causing friction of the tendon under the acromion by a reduction of the subacromial space.[3, 22, 24, 89] This reduction of subacromial volume might be caused by the os acromiale, coracoid, the coracoacromial ligament, acromioclavicular osteophytes and a hooked acromial shape.[3, 22, 24, 89] Lastly, a dynamic reduction of the subacromial space as a result of muscle weakness, causing glenohumeral instability with subsequent dynamic cranialization of the humerus under the acromion, or disturbed scapulothoracic motion (i.e. scapular dyskinesis) have been suggested to cause secondary impingement.[3, 22, 24, 89]

Pathophysiology of the subacromial pain syndrome was studied in the SISTIM project, which started in 2009. The SISTIM project aimed to identify causal mechanisms and to classify patients based on distinct pathophysiological subgroups.[24] This SISTIM project was conducted at the department of Orthopaedics and Rehabilitation from the Leiden University Medical Centre which harbours the laboratory for Kinematics and Neuromechanics. This laboratory has a long-standing track-record in studying the biomechanics and kinematics of the shoulder in a network with the Delft University of Technology and associated hospitals (Medical Centre Haaglanden, the Hague; Alrijne Hospital, Leiderdorp).[1, 2, 19, 20, 23, 25, 26, 53, 54, 80, 81, 85, 86, 112-115]

BIOMECHANICS AND KINEMATICS OF THE SHOULDER

Shoulder Biomechanics

Observations from anatomic dissection resulted in papers describing the assumed mechanics of the shoulder function.[13-15, 39] Movements of the shoulder-girdle were explained by close observations of the anatomic orientation and attachments of shoulder muscles relative to the joint.[13-15, 39] The findings in these anatomic specimens were linked to the observations in-vivo .[13, 15] The application of electromyography and radiographs in patients enabled a better understanding of the complex in-vivo interplay of the shoulder girdle structures. The introduction of radiographs illustrated that abduction was not solely initiated via glenohumeral motion when raising the arm from vertical to the horizontal, but involved movement of the scapulothoracic joint at the beginning of abduction.[35, 58, 74] Electromyographic studies revealed the activity of muscles during shoulder movement and was described in detail by Inman.[58] In these electromyographic studies, it was concluded that the middle deltoid and supraspinatus were main contributors of the abduction moment, while the infraspinatus, teres minor and subscapular muscles were identified as essential stabilizers to allow elevation and rotation of the arm.[21, 58]

Cadaveric and in-silico shoulder models gave us more insight in the requirements for shoulder motion and biomechanical adaptations that occur in case of a rotator cuff tear.[48, 57, 68, 99, 113, 117, 119-121, 124] Cadaveric models illustrated the stabilizing role of the teres minor, infraspinatus and subscapularis.[46, 48, 73, 110, 117] A supraspinatus tear caused significantly higher forces in the remaining intact rotator cuff[48, 117] and may introduce glenohumeral translations.[28, 96] A decrease in joint reaction force with excessive superior humeral head translations occurred when the tear extended in the subscapularis or infraspinatus muscle in these cadaveric models.[48, 99, 117] In line with these results, inverse dynamic simulations demonstrated comparable findings with an increase in force generated by the infraspinatus and subscapularis in case of a supraspinatus tear.[113]

A better understanding of the glenohumeral centre of rotation resulted in more complex studies on in-vivo biomechanics.[21, 102] Although the centre of rotation was considered to be slightly variable, some authors concluded that the glenohumeral joint functioned as a ball-in socket joint with approximately a fixed centre of rotation in healthy volunteers.[102] Based on this conclusion, a calculation of lever arms and force vectors around the glenohumeral joint was made.[103] Accuracy of these first estimations remained questionable, because analyses of shoulder kinematics were conducted in static biplanar test settings, while motion of the shoulder girdle occurs around three axes. Moreover, three-dimensional motion analysis advanced after defining the glenohumeral centre of rotation. Radiostereometric analysis (RSA) provided a methodology to measure three-dimensional shoulder motion. However, the in-vivo RSA research, although very accurate, has not been taken up widely for the evaluation of non-implant related shoulder research, since tantalum beads have to be inserted in the patient.[56] For that matter, other methods were developed to study shoulder motion, like the electromagnetic tracking device as the Flock-of Birds.[59, 62, 63, 77, 85, 88, 104]

Biomechanics in Subacromial Pain Syndrome

A main focus of biomechanical research in "subacromial impingement syndrome" has been the spatial shape of the subacromial space. Elevating the arm between 30 to 120 degrees of abduction brings the humerus in closer proximity to the acromion reducing subacromial space, which could explain the painful arc sign that is found in patients with subacromial impingement syndrome.[27, 40, 41, 50, 55, 61, 87, 109] However, inconsistent outcomes have been found when comparing the subacromial space in patient with subacromial impingement syndrome with asymptomatic controls. Whether the subacromial space width is reduced[28, 37, 50], not different [61, 109], or increased[23, 27] remains unclear. The latter shows the intricate interplay between dynamic cranial translation, posture, scapular rotations, elevation angle and muscle contractions on subacromial space width.[27, 28, 47, 55, 61, 76, 96, 107, 109, 111]

Important to note is that subacromial impingement syndrome evolved to subacromial pain syndrome in the Netherlands recent years, parting the attrition theory as dominant pathologic mechanism.[29, 91] In the past, patients with bursitis, tendinopathy and a rotator

cuff tear have been considered as one clinical entity according to the stages of Neer's impingement syndrome for many years.[28, 41, 42, 61] The latter caused huge heterogeneity when outcomes were compared among studies, since it is very likely that patients with subacromial pain syndrome demonstrate different biomechanics and kinematics than patients with a full-thickness rotator cuff tear. Consequently, many prior studies are currently not applicable for the patient with subacromial pain syndrome (i.e. thus a patient with an intact rotator cuff).

Shoulder Kinematics

The physical examination is still an important part of diagnosing a patient. A simple observation of active shoulder motion gives us more information about the functional deficits of the patient. Next to range of motion, the clinician generally observes the scapula-humeral rhythm to determine the presence of scapular dyskinesis. The latter will have inter- and intra-observer variability, but is considered to give clinical information on the type of shoulder pathology. The importance of the scapula in shoulder movement has been acknowledged by Codman in 1911, who described a disturbed scapula-humeral rhythm, as a *"sine qua non"* for the diagnosis of a supraspinatus tear.[17]

Scapular dyskinesis is now defined as "any alteration of normal scapular kinematics"[67], but more frequently "asymmetry in scapulothoracic motion" is used in clinical practice and in literature.[118] Scapular dyskinesis, with an increase in internal rotation, a decrease in lateral rotation (i.e. also known as upward rotation) and posterior tilt are postulated to reduce the subacromial volume by bringing the humeral head in closer contact with the acromion.[34, 75, 111] Whether these observed kinematic alterations are a result of the pathophysiology of disease or a compensatory mechanism, is still part of debate.[67] Interestingly, a comparable prevalence of scapular dyskinesis in healthy volunteers and in patients with subacromial pain was found using clinicians' visual inspection.[101] This indicates a need for more robust quantitative methods to measure the direction and amplitude of small deviations of normal kinematics, like three-dimensional motion analyses. Therefore, glenohumeral and scapulothoracic kinematics have been evaluated by applying radiography, magnetic resonance imaging, opto-electronic systems or electromagnetic tracking systems.[28, 41, 79, 84, 95, 96, 99, 105, 108, 117, 126]

Patients with a rotator cuff tear were found to have reduced glenohumeral elevation and increased scapulothoracic lateral rotation to reach positions above shoulder level, thus confirming Codman's observation in 1911.[28, 84, 96, 105] Most studies had the limitation that kinematics of the shoulder had been calculated at a static elevation angle hampering the validity of these data by allowing a setting phase for the scapula.[28, 42, 95, 96] Pain was an important confounder contributing to a disturbed scapula-humeral rhythm in these patients if comparing them with healthy volunteers. The use of a suprascapular nerve block has been proposed to evaluate the effect of the supraspinatus and infraspinatus muscle on shoulder mobility in healthy volunteers by eliminating the effect of pain. Interestingly, a comparable

reduction in glenohumeral elevation and increase in scapulothoracic lateral rotation was found in these simulated posterosuperior rotator cuff tears.[83]

Kinematics in Subacromial Pain Syndrome

Three-dimensional kinematic analyses in "subacromial impingement syndrome" gave contradictory outcomes between studies. Some studies found a decrease in scapular lateral rotation[31, 70, 75], while others did not find a difference[51, 69, 71, 78, 84] or even showed an increased lateral rotation.[82] A reduction in posterior tilt was found by several investigators[31, 70, 71, 75, 78] while others did not[51, 84] or even found more posterior tilt.[69, 82] These inconsistent findings are most probably related to the large heterogeneity in study populations caused by a different interpretation of physical tests among clinicians[22], treatment of patients with a different anatomic substrate of pain as one clinical entity (i.e. impingement syndrome)[70, 75, 78, 82] and investigations in highly selected subgroups based on occupation or sport activities.[69, 71, 75] For that matter, available outcomes are not translatable to the patient in the daily orthopaedic clinical practice. Shoulder kinematics in subacromial pain syndrome has to be evaluated in a group of patients with a more similar phenotype with respect to at least age and anatomy (i.e. intact rotator cuff).

In conclusion, extrinsic compression of the acromion is no longer assumed the dominant pathophysiological pathway contributing to subacromial pain. Despite attrition of the rotator cuff under the acromion may be a long-lasting process, the long-term effect of acromioplasty after 10 to 20 years is not investigated in literature. Alternative pathophysiological pathways contributing to the development of subacromial pain syndrome include a dynamic reduction of subacromial structures due to destabilizing muscle forces within the glenohumeral joint or disturbed shoulder kinematics. Therefore, there is a clear need to use biomechanical and kinematical analyses in a well-defined study population with subacromial pain syndrome.

AIMS OF THE THESIS

1) Evaluation of the long-term effects of subacromial decompression surgery on pain, shoulder function and rotator cuff integrity.
2) Evaluation of shoulder muscle activity and kinematics in patients with subacromial pain syndrome.
3) Evaluating the association of rotator cuff tear size and shoulder kinematics.

OUTLINE OF THIS THESIS

The concept of tendon attrition suggests that subacromial decompression will have an effect after many years. In **Chapter 2**, we present a long-term follow-up study of a randomised controlled trial examining the effects of arthroscopic subacromial decompression on pain, shoulder function and rotator cuff integrity 10 years after the operation. In an observational study, the kinematics and coordination of shoulder muscles in patients with subacromial pain syndrome were compared to asymptomatic volunteers **(Chapter 3)**. In **Chapter 4**, the effect of subacromial anaesthetics on scapular dyskinesis is evaluated and we elaborated on the influence of pain. The association between rotator cuff tear size and glenohumeral/scapulothoracic kinematics is investigated in **Chapter 5**. Changed mechanical loads of intact muscles not being part of the rotator cuff tear (i.e. the deltoid and teres minor muscle) were hypothesised to influence muscle atrophy with age. The alterations in mechanical loads in the shoulder in the presence of a rotator cuff tear were indirectly measured by observing changes in muscle volume **(Chapter 6)**. From here we started to investigate the effects of rotator cuff repair on shoulder kinematics (**Chapter 7**). The mid- to long-term clinical outcomes of a teres major or lattisimus dorsi tendon transfer, a salvage procedure in a chronic massive posterosuperior rotator cuff tear, are evaluated in **Chapter 8**. The study outcomes, their clinical implications and the future perspective are discussed (**Chapter 9**). Finally, a summary of findings is provided (**Chapter 10**).

REFERENCES

1 Aaronson NK, Muller M, Cohen PD, Essink-Bot ML, Fekkes M, Sanderman R et al. Translation, validation, and norming of the Dutch language version of the SF-36 Health Survey in community and chronic disease populations. J Clin Epidemiol 1998;51:1055-1068. DOI: 10.1016/s0895-4356(98)00097-3

2 Arwert HJ, de Groot JH, Van Woensel WW, Rozing PM. Electromyography of shoulder muscles in relation to force direction. J Shoulder Elbow Surg 1997;6:360-370. DOI: 10.1016/S1058-2746(97)90004-5

3 Bigliani LU, Levine WN. Subacromial impingement syndrome. J Bone Joint Surg Am 1997;79:1854-1868. DOI: 10.2106/00004623-199712000-00012

4 Bigliani LU, Morrison DS, April EW. The morphology of the acromion and its relationship to rotator cuff tears. Orthop Trans 1986;10:228.

5 Bigliani LU, Ticker JB, Flatow EL, Soslowsky LJ, Mow VC. The relationship of acromial architecture to rotator cuff disease. Clin Sports Med 1991;10:823-838.

6 Bjornsson H, Norlin R, Knutsson A, Adolfsson L. Fewer rotator cuff tears fifteen years after arthroscopic subacromial decompression. J Shoulder Elbow Surg 2010;19:111-115. DOI: 10.1016/j.jse.2009.04.014

7 Bot SD, van der Waal JM, Terwee CB, van der Windt DA, Schellevis FG, Bouter LM et al. Incidence and prevalence of complaints of the neck and upper extremity in general practice. Ann Rheum Dis 2005;64:118-123. DOI: 10.1136/ard.2003.019349

8 Braman JP, Engel SC, LaPrade RF, Ludewig PM. In vivo assessment of scapulohumeral rhythm during unconstrained overhead reaching in asymptomatic subjects. J Shoulder Elbow Surg 2009;18:960-967. DOI: 10.1016/j.jse.2009.02.001

9 Brox JI, Gjengedal E, Uppheim G, Bohmer AS, Brevik JI, Ljunggren AE et al. Arthroscopic surgery versus supervised exercises in patients with rotator cuff disease (stage II impingement syndrome): a prospective, randomized, controlled study in 125 patients with a 2 1/2-year follow-up. J Shoulder Elbow Surg 1999;8:102-111. DOI: 10.1016/S1058-2746(99)90001-0

10 Brox JI, Staff PH, Ljunggren AE, Brevik JI. Arthroscopic surgery compared with supervised exercises in patients with rotator cuff disease (stage II impingement syndrome). BMJ 1993;307:899-903. DOI: 10.1136/bmj.307.6909.899

11 Budoff JE, Rodin D, Ochiai D, Nirschl RP. Arthroscopic rotator cuff debridement without decompression for the treatment of tendinosis. Arthroscopy 2005;21:1081-1089. DOI: 10.1016/j.arthro.2005.05.019

12 Burkhead WZ, Jr. A history of the rotator cuff before Codman. J Shoulder Elbow Surg 2011;20:358-362. DOI: 10.1016/j.jse.2011.01.002

13 Cathcart CW. Movements of the Shoulder Girdle involved in those of the Arm on the Trunk. J Anat Physiol 1884;18:211-218.

14 Cleland J. Shoulder-girdle and its movements. Lancet 1881;117:283-284.

15 Cleland J. Notes on Raising the Arm. J Anat Physiol 1884;18:275-278.

16 Codman EA. On stiff and painful shoulders, as ecplained by subacromial bursitis and partial rupture of the tendon of the supraspinatus. Boston Medical and Surgical Journal 1911;165:115-120. DOI: 10.1056/NEJM191107271650401

17 Codman EA. Rupture of the supraspinatus tendon. 1911. Clin Orthop Relat Res 1990:3-26. DOI: 10.1097/00003086-199005000-00002

18 Codman EA, Akerson IB. The Pathology Associated with Rupture of the Supraspinatus Tendon. Ann Surg 1931;93:348-359. DOI: 10.1097/00000658-193101000-00043

19 de Groot JH. The scapulo-humeral rhythm: effects of 2-D roentgen projection. Clin Biomech (Bristol , Avon) 1999;14:63-68. DOI: 10.1016/s0268-033(98)00027-8

20 de Groot JH, van de Sande MA, Meskers CG, Rozing PM. Pathological Teres Major activation in patients with massive rotator cuff tears alters with pain relief and/or salvage surgery transfer. Clin Biomech (Bristol , Avon) 2006;21 Suppl 1:S27-S32. DOI: 10.1016/j.clinbiomech.2005.09.011

21 De Luca CJ, Forrest WJ. Force analysis of individual muscles acting simultaneously on the shoulder joint during isometric abduction. J Biomech 1973;6:385-393. DOI: 10.1016/0021-9290(73)90098-5

22 de Witte PB, de Groot JH, van Zwet EW, Ludewig PM, Nagels J, Nelissen RG et al. Communication breakdown: clinicians disagree on subacromial impingement. Med Biol Eng Comput 2013;52:221-231. DOI: 10.1007/s11517-013-1075-0

23 de Witte PB, Henseler JF, van Zwet EW, Nagels J, Nelissen RG, de Groot JH. Cranial humerus translation, deltoid activation, adductor co-activation and rotator cuff disease - Different patterns in rotator cuff tears, subacromial impingement and controls. Clin Biomech (Bristol , Avon) 2014;29:26-32. DOI: 10.1016/j.clinbiomech.2013.10.014

24 de Witte PB, Nagels J, van Arkel ER, Visser CP, Nelissen RG, de Groot JH. Study protocol subacromial impingement syndrome: the identification of pathophysiologic mechanisms (SISTIM). BMC Musculoskelet Disord 2011;12:282. DOI: 10.1186/1471-2474-12-282

25 de Witte PB, van der Zwaal P, van Arkel ER, Nelissen RG, de Groot JH. Pathologic deltoid activation in rotator cuff tear patients: normalization after cuff repair? Med Biol Eng Comput 2013. DOI: 10.1007/s11517-013-1095-9

26 de Witte PB, Werner S, Ter Braak LM, Veeger HE, Nelissen RG, de Groot JH. The Supraspinatus and the Deltoid - Not just two arm elevators. Hum Mov Sci 2014;33:273-283. DOI: 10.1016/j.humov.2013.08.010

27 Desmeules F, Minville L, Riederer B, Cote CH, Fremont P. Acromio-humeral distance variation measured by ultrasonography and its association with the outcome of rehabilitation for shoulder impingement syndrome. Clin J Sport Med 2004;14:197-205. DOI: 10.1097/00042752-200407000-00002

28 Deutsch A, Altchek DW, Schwartz E, Otis JC, Warren RF. Radiologic measurement of superior displacement of the humeral head in the impingement syndrome. J Shoulder Elbow Surg 1996;5:186-193. DOI: 10.1016/S1058-2746(05)80004-7

29 Diercks R, Bron C, Dorrestijn O, Meskers C, Naber R, de RT et al. Guideline for diagnosis and treatment of subacromial pain syndrome: a multidisciplinary review by the Dutch Orthopaedic Association. Acta Orthop 2014;85:314-322. DOI: 10.3109/17453674.2014.920991

30 Ellman H, Kay SP. Arthroscopic subacromial decompression for chronic impingement. Two- to five-year results. J Bone Joint Surg Br 1991;73:395-398. DOI: 10.1302/0301-620x.73b3.1670435

31 Endo K, Ikata T, Katoh S, Takeda Y. Radiographic assessment of scapular rotational tilt in chronic shoulder impingement syndrome. J Orthop Sci 2001;6:3-10. DOI: 10-1007/s007760170017

32 Farfaras S, Sernert N, Hallstrom E, Kartus J. Comparison of open acromioplasty, arthroscopic acromioplasty and physiotherapy in patients with subacromial impingement syndrome: a prospective randomised study. Knee Surg Sports Traumatol Arthrosc 2014. DOI: 10.1007/s00167-014-3416-4

33 Ferguson LK. Painful Shoulder: Arising from Lesions of the Subacromial Bursa and Supraspinatus Tendon. Ann Surg 1937;105:243-256.

34 Flatow EL, Soslowsky LJ, Ticker JB, Pawluk RJ, Hepler M, Ark J et al. Excursion of the rotator cuff under the acromion. Patterns of subacromial contact. Am J Sports Med 1994;22:779-788. DOI: 10.1177/036354659402200609

35 Freedman L, Munro RR. Abduction of the arm in the scapular plane: scapular and glenohumeral movements. A roentgenographic study. J Bone Joint Surg Am 1966;48:1503-1510. DOI: 10.2106/00004623-196648080-00004

36 Gartsman GM, O'Connor D P. Arthroscopic rotator cuff repair with and without arthroscopic subacromial decompression: a prospective, randomized study of one-year outcomes. J Shoulder Elbow Surg 2004;13:424-426. DOI: 10.1016/S1058274604000527

37 Girometti R, De Candia A, Sbuelz M, Toso F, Zuiani C, Bazzocchi M. Supraspinatus tendon US morphology in basketball players: correlation with main pathologic models of secondary impingement syndrome in young overhead athletes. Preliminary report. Radiol Med 2006;111:42-52. DOI: 10.1007/s11547-006-0005-8

38 Golding FC. The shoulder--the forgotten joint. Br J Radiol 1962;35:149-158. DOI: 10.1259/0007-1285-35-411-149

39 Goldthwait JE. An anatomic and mechanical study of the shoulder-joint, explaining many of the cases of painful shoulder, many of the recurrent dislocation, and many of the cases of brachial neuralgias or neuritis. Am J Orthop Surg 1909;6:579-606.

40 Graichen H, Bonel H, Stammberger T, Englmeier KH, Reiser M, Eckstein F. Subacromial space width changes during abduction and rotation--a 3-D MR imaging study. Surg Radiol Anat 1999;21:59-64. DOI: 10.1007/s00276-999-0059-0

41 Graichen H, Bonel H, Stammberger T, Haubner M, Rohrer H, Englmeier KH et al. Three-dimensional analysis of the width of the subacromial space in healthy subjects and patients with impingement syndrome. AJR Am J Roentgenol 1999;172:1081-1086. DOI: 10.2214/ajr.172.4.10587151

42 Graichen H, Stammberger T, Bonel H, Wiedemann E, Englmeier KH, Reiser M et al. Three-dimensional analysis of shoulder girdle and supraspinatus motion patterns in patients with impingement syndrome. J Orthop Res 2001;19:1192-1198. DOI: 10.1016/s0736-0266(01)00035-3

43 Greving K, Dorrestijn O, Winters JC, Groenhof F, van der Meer K, Stevens M et al. Incidence, prevalence, and consultation rates of shoulder complaints in general practice. Scand J Rheumatol 2012;41:150-155. DOI: 10.3109/03009742.2011.605390

44 Haahr JP, Andersen JH. Exercises may be as efficient as subacromial decompression in patients with subacromial stage II impingement: 4-8-years' follow-up in a prospective, randomized study. Scand J Rheumatol 2006;35:224-228. DOI: 10.1080/03009740600556167

45 Haahr JP, Ostergaard S, Dalsgaard J, Norup K, Frost P, Lausen S et al. Exercises versus arthroscopic decompression in patients with subacromial impingement: a randomised, controlled study in 90 cases with a one year follow up. Ann Rheum Dis 2005;64:760-764. DOI: 10.1136/ard.2004.021188

46 Halder AM, Zhao KD, Odriscoll SW, Morrey BF, An KN. Dynamic contributions to superior shoulder stability. J Orthop Res 2001;19:206-212. DOI: 10.1016/S0736-0266(00)00028-0

47 Hallstrom E, Karrholm J. Shoulder kinematics in 25 patients with impingement and 12 controls. Clin Orthop Relat Res 2006;448:22-27. DOI: 10.1097/01.blo.0000224019.65540.d5

48 Hansen ML, Otis JC, Johnson JS, Cordasco FA, Craig EV, Warren RF. Biomechanics of massive rotator cuff tears: implications for treatment. J Bone Joint Surg Am 2008;90:316-325. DOI: 10.2106/JBJS.F.00880

49 Hawkins RJ, Kennedy JC. Impingement syndrome in athletes. Am J Sports Med 1980;8:151-158. DOI: 10.1177/036354658000800302

50 Hebert LJ, Moffet H, Dufour M, Moisan C. Acromiohumeral distance in a seated position in persons with impingement syndrome. J Magn Reson Imaging 2003;18:72-79. DOI: 10.1002/jmri.10327

51 Hebert LJ, Moffet H, McFadyen BJ, Dionne CE. Scapular behavior in shoulder impingement syndrome. Arch Phys Med Rehabil 2002;83:60-69. DOI: 10.1053/apmr.2002.27471

52 Henkus HE, de Witte PB, Nelissen RG, Brand R, van Arkel ER. Bursectomy compared with acromioplasty in the management of subacromial impingement syndrome: a prospective randomised study. J Bone Joint Surg Br 2009;91:504-510. DOI: 10.1302/0301-620X.91B4.21442

53 Henseler JF, de Witte PB, de Groot JH, van Zwet EW, Nelissen RG, Nagels J. Cranial translation of the humeral head on radiographs in rotator cuff tear patients: the modified active abduction view. Med Biol Eng Comput 2013. DOI: 10.1007/s11517-013-1057-2

54 Henseler JF, Nagels J, Nelissen RG, de Groot JH. Does the latissimus dorsi tendon transfer for massive rotator cuff tears remain active postoperatively and restore active external rotation? J Shoulder Elbow Surg 2013. DOI: 10.1016/j.jse.2013.07.055

55 Hinterwimmer S, Von Eisenhart-Rothe R, Siebert M, Putz R, Eckstein F, Vogl T et al. Influence of adducting and abducting muscle forces on the subacromial space width. Med Sci Sports Exerc 2003;35:2055-2059. DOI: 10.1249/01.MSS.0000099089.49700.53

56 Hogfors C, Peterson B, Sigholm G, Herberts P. Biomechanical model of the human shoulder joint--II. The shoulder rhythm. J Biomech 1991;24:699-709. DOI: 10.1016/0021-9290(91)90334-j

57 Hogfors C, Sigholm G, Herberts P. Biomechanical model of the human shoulder--I. Elements. J Biomech 1987;20:157-166. DOI: 10.1016/0021-9290(87)90307-1

58 Inman VT, Saunders JB, Abbott LC. Observations of the function of the shoulder joint. 1944. Clin Orthop Relat Res 1996:3-12. DOI: 10.1097/00003086-199609000-00002

59 Johnson GR, Stuart PR, Mitchell S. A method for the measurement of three-dimensional scapular movement. Clin Biomech (Bristol, Avon) 1993;8:269-273. DOI: 10.1016/0268-0033(93)90037-I

60 Judge A, Murphy RJ, Maxwell R, Arden NK, Carr AJ. Temporal trends and geographical variation in the use of subacromial decompression and rotator cuff repair of the shoulder in England. Bone Joint J 2014;96-B:70-74. DOI: 10.1302/0301-620x.96b1.32556

61 Kalra N, Seitz AL, Boardman ND, III, Michener LA. Effect of posture on acromiohumeral distance with arm elevation in subjects with and without rotator cuff disease using ultrasonography. J Orthop Sports Phys Ther 2010;40:633-640. DOI: 10.2519/jospt.2010.3155

62 Karduna AR, McClure PW, Michener LA, Sennett B. Dynamic measurements of three-dimensional scapular kinematics: a validation study. J Biomech Eng 2001;123:184-190. DOI: 10.1115/1.1351892

63 Karduna AR, Williams GR, Williams JL, Iannotti JP. Kinematics of the glenohumeral joint: influences of muscle forces, ligamentous constraints, and articular geometry. J Orthop Res 1996;14:986-993. DOI: 10.1002/jor.1100140620

64 Ketola S, Lehtinen J, Arnala I, Nissinen M, Westenius H, Sintonen H et al. Does arthroscopic acromioplasty provide any additional value in the treatment of shoulder impingement syndrome?: a two-year randomised controlled trial. J Bone Joint Surg Br 2009;91:1326-1334. DOI: 10.1302/0301-620X.91B10.22094

65 Ketola S, Lehtinen J, Rousi T, Nissinen M, Huhtala H, Konttinen YT et al. No evidence of long-term benefits of arthroscopicacromioplasty in the treatment of shoulder impingement syndrome: Five-year results of a randomised controlled trial. Bone Joint Res 2013;2:132-139. DOI: 10.1302/2046-3758.27.2000163

66 Ketola S, Lehtinen JT, Arnala I. Arthroscopic decompression not recommended in the treatment of rotator cuff tendinopathy: a final review of a randomised controlled trial at a minimum follow-up of ten years. Bone Joint J 2017;99-B:799-805. DOI: 10.1302/0301-620X.99B6.BJJ-2016-0569.R1

67 Kibler WB, Ludewig PM, McClure PW, Michener LA, Bak K, Sciascia AD. Clinical implications of scapular dyskinesis in shoulder injury: the 2013 consensus statement from the 'Scapular Summit'. Br J Sports Med 2013;47:877-885. DOI: 10.1136/bjsports-2013-092425

68 Klein Breteler MD, Spoor CW, Van der Helm FC. Measuring muscle and joint geometry parameters of a shoulder for modeling purposes. J Biomech 1999;32:1191-1197. DOI: 10.1016/S0021-9290(99)00122-0

69 Laudner KG, Myers JB, Pasquale MR, Bradley JP, Lephart SM. Scapular dysfunction in throwers with pathologic internal impingement. J Orthop Sports Phys Ther 2006;36:485-494. DOI: 10.2519/jospt.2006.2146

70 Lawrence RL, Braman JP, LaPrade RF, Ludewig PM. Comparison of 3-dimensional shoulder complex kinematics in individuals with and without shoulder pain, part 1: sternoclavicular, acromioclavicular, and scapulothoracic joints. J Orthop Sports Phys Ther 2014;44:636-638. DOI: 10.2519/jospt.2014.5339

71 Lin JJ, Hsieh SC, Cheng WC, Chen WC, Lai Y. Adaptive patterns of movement during arm elevation test in patients with shoulder impingement syndrome. J Orthop Res 2011;29:653-657. DOI: 10.1002/jor.21300

72 Linsell L, Dawson J, Zondervan K, Rose P, Randall T, Fitzpatrick R et al. Prevalence and incidence of adults consulting for shoulder conditions in UK primary care; patterns of diagnosis and referral. Rheumatology (Oxford) 2006;45:215-221. DOI: 10.1093/rheumatology/kei139

73 Lippitt S, Matsen F. Mechanisms of glenohumeral joint stability. Clin Orthop Relat Res 1993:20-28. DOI: 10.1097/00003086-199306000-00004

74 Lockhart RD. Movements of the Normal Shoulder Joint and of a case with Trapezius Paralysis studied by Radiogram and Experiment in the Living. J Anat 1930;64:288-302.

75 Ludewig PM, Cook TM. Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. Phys Ther 2000;80:276-291. DOI: 10.1093/ptj/80.3.276

76 Ludewig PM, Cook TM. Translations of the humerus in persons with shoulder impingement symptoms. J Orthop Sports Phys Ther 2002;32:248-259. DOI: 10.2519/jospt.2002.32.6.248

77 Ludewig PM, Cook TM, Nawoczenski DA. Three-dimensional scapular orientation and muscle activity at selected positions of humeral elevation. J Orthop Sports Phys Ther 1996;24:57-65. DOI: 10.2519/jospt.1996.24.2.57

78 Lukasiewicz AC, McClure P, Michener L, Pratt N, Sennett B. Comparison of 3-dimensional scapular position and orientation between subjects with and without shoulder impingement. J Orthop Sports Phys Ther 1999;29:574-583. DOI: 10.2519/jospt.1999.29.10.574

79 Magermans DJ, Chadwick EK, Veeger HE, Rozing PM, van der Helm FC. Effectiveness of tendon transfers for massive rotator cuff tears: a simulation study. Clin Biomech 2004;19:116-122. DOI: 10.1016/j.clinbiomech.2003.09.008

80 Magermans DJ, Chadwick EK, Veeger HE, van der Helm FC. Requirements for upper extremity motions during activities of daily living. Clin Biomech 2005;20:591-599. DOI: 10.1016/j.clinbiomech.2005.02.006

81 Magermans DJ, Chadwick EK, Veeger HE, van der Helm FC, Rozing PM. Biomechanical analysis of tendon transfers for massive rotator cuff tears. Clin Biomech 2004;19:350-357. DOI: 10.1016/j.clinbiomech.2003.11.013

82 McClure PW, Michener LA, Karduna AR. Shoulder function and 3-dimensional scapular kinematics in people with and without shoulder impingement syndrome. Phys Ther 2006;86:1075-1090. DOI: 10.1093/ptj/86.8.1075

83 McCully SP, Suprak DN, Kosek P, Karduna AR. Suprascapular nerve block disrupts the normal pattern of scapular kinematics. Clin Biomech 2006;21:545-553. DOI: 10.1016/j.clinbiomech.2006.02.001

84 Mell AG, LaScalza S, Guffey P, Ray J, Maciejewski M, Carpenter JE et al. Effect of rotator cuff pathology on shoulder rhythm. J Shoulder Elbow Surg 2005;14:58S-64S. DOI: 10.1016/j.jse.2004.09.018

85 Meskers CG, Fraterman H, van der Helm FC, Vermeulen HM, Rozing PM. Calibration of the "Flock of Birds" electromagnetic tracking device and its application in shoulder motion studies. J Biomech 1999;32:629-633. DOI: 10-1016/s0021-9290(99)00011-1

86 Meskers CG, van der Helm FC, Rozendaal LA, Rozing PM. In vivo estimation of the glenohumeral joint rotation center from scapular bony landmarks by linear regression. J Biomech 1998;31:93-96. DOI: 10-1016/s0021-9290(97)00101-2

87 Meskers CG, van der Helm FC, Rozing PM. The size of the supraspinatus outlet during elevation of the arm in the frontal and sagittal plane: a 3-D model study. Clin Biomech (Bristol, Avon) 2002;17:257-266. DOI: 10.1016/s0268-0033(02)00021-9

88 Meskers CG, Vermeulen HM, de Groot JH, van der Helm FC, Rozing PM. 3D shoulder position measurements using a six-degree-of-freedom electromagnetic tracking device. Clin Biomech 1998;13:280-292. DOI: 10-1016/s0268-0033(98)00095-3

89 Michener LA, McClure PW, Karduna AR. Anatomical and biomechanical mechanisms of subacromial impingement syndrome. Clin Biomech 2003;18:369-379. DOI: 10.1016/s0268-0033(03)00047-0

90 Minagawa H, Yamamoto N, Abe H, Fukuda M, Seki N, Kikuchi K et al. Prevalence of symptomatic and asymptomatic rotator cuff tears in the general population: From mass-screening in one village. J Orthop 2013;10:8-12. DOI: 10.1016/j.jor.2013.01.008

91 Nederlandse Orthopaedische Vereniging. Diagnostiek en behandeling van het subacromiaal pijnsyndroom. 2012.

92 Neer CS. Anterior acromioplasty for the chronic impingement syndrome in the shoulder: a preliminary report. J Bone Joint Surg Am 1972;54:41-50. DOI: 10.2106/00004623-197254010-00003

93 Neer CS, 2nd. Impingement lesions. Clin Orthop Relat Res 1983:70-77. DOI: 10.1097/00003086-198303000-00010

94 NIVEL. Zorgregistraties eerste lijn: incidenties en prevalenties (2017). https://www.nivel.nl/nl/zorgregistraties-eerste-lijn/incidenties-en-prevalenties. In.

95 Ohl X, Hagemeister N, Zhang C, Billuart F, Gagey O, Bureau NJ et al. 3D scapular orientation on healthy and pathologic subjects using stereoradiographs during arm elevation. J Shoulder Elbow Surg 2015. DOI: 10.1016/j.jse.2015.04.007

96 Paletta GA, Jr., Warner JJ, Warren RF, Deutsch A, Altchek DW. Shoulder kinematics with two-plane x-ray evaluation in patients with anterior instability or rotator cuff tearing. J Shoulder Elbow Surg 1997;6:516-527. DOI: 10.1016/s1058-2746(97)90084-7

97 Paloneva J, Lepola V, Karppinen J, Ylinen J, Aarimaa V, Mattila VM. Declining incidence of acromioplasty in Finland. Acta Orthop 2015;86:220-224. DOI: 10.3109/17453674.2014.977703

98 Park HB, Yokota A, Gill HS, El RG, McFarland EG. Diagnostic accuracy of clinical tests for the different degrees of subacromial impingement syndrome. J Bone Joint Surg Am 2005;87:1446-1455. DOI: 10.2106/jbjs.d.02335

99 Parsons IM, Apreleva M, Fu FH, Woo SL. The effect of rotator cuff tears on reaction forces at the glenohumeral joint. J Orthop Res 2002;20:439-446. DOI: 10.1016/S0736-0266(01)00137-1

100 Picavet HS, Schouten JS. Musculoskeletal pain in the Netherlands: prevalences, consequences and risk groups, the DMC(3)-study. Pain 2003;102:167-178. DOI: 10.1016/s0304-3959(02)00372-x

101 Plummer HA, Sum JC, Pozzi F, Varghese R, Michener LA. Observational Scapular Dyskinesis: Known-Groups Validity in Patients With and Without Shoulder Pain. J Orthop Sports Phys Ther 2017;47:530-537. DOI: 10.2519/jospt.2017.7268

102 Poppen NK, Walker PS. Normal and abnormal motion of the shoulder. J Bone Joint Surg Am 1976;58:195-201. DOI: 10.2106/00004623-197658020-00006

103 Poppen NK, Walker PS. Forces at the glenohumeral joint in abduction. Clin Orthop Relat Res 1978:165-170. DOI: 10.1097/00003086-197809000-00035

104 Pronk GM, van der Helm FC. The palpator: an instrument for measuring the positions of bones in three dimensions. J Med Eng Technol 1991;15:15-20. DOI: 10.3109/03091909109015443

105 Robert-Lachaine X, Allard P, Godbout V, Tetreault P, Begon M. Scapulohumeral rhythm relative to active range of motion in patients with symptomatic rotator cuff tears. J Shoulder Elbow Surg 2016;25:1616-1622. DOI: 10.1016/j.jse.2016.02.031

106 Roye RP, Grana WA, Yates CK. Arthroscopic subacromial decompression: two- to seven-year follow-up. Arthroscopy 1995;11:301-306. DOI: 10.1016/0749-8063(95)90007-1

107 Royer PJ, Kane EJ, Parks KE, Morrow JC, Moravec RR, Christie DS et al. Fluoroscopic assessment of rotator cuff fatigue on glenohumeral arthrokinematics in shoulder impingement syndrome. J Shoulder Elbow Surg 2009;18:968-975. DOI: 10.1016/j.jse.2009.03.002

108 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;17:172-181. DOI: 10.1016/j.jse.2007.05.010

109 Seitz AL, McClure PW, Finucane S, Ketchum JM, Walsworth MK, Boardman ND et al. The scapular assistance test results in changes in scapular position and subacromial space but not rotator cuff strength in subacromial impingement. J Orthop Sports Phys Ther 2012;42:400-412. DOI: 10.2519/jospt.2012.3579

110 Sharkey NA, Marder RA. The rotator cuff opposes superior translation of the humeral head. Am J Sports Med 1995;23:270-275. DOI: 10.1177/036354659502300303

111 Solem-Bertoft E, Thuomas KA, Westerberg CE. The influence of scapular retraction and protraction on the width of the subacromial space. An MRI study. Clin Orthop Relat Res 1993:99-103. DOI: 10.1097/00003086-199311000-00018

112 Steenbrink F, de Groot JH, Veeger HE, Meskers CG, van de Sande MA, Rozing PM. Pathological muscle activation patterns in patients with massive rotator cuff tears, with and without subacromial anaesthetics. Man Ther 2006;11:231-237. DOI: 10.1016/j.math.2006.07.004

113 Steenbrink F, de Groot JH, Veeger HE, van der Helm FC, Rozing PM. Glenohumeral stability in simulated rotator cuff tears. J Biomech 2009;42:1740-1745. DOI: 10.1016/j.jbiomech.2009.04.011

114 Steenbrink F, Meskers CG, Nelissen RG, de Groot JH. The relation between increased deltoid activation and adductor muscle activation due to glenohumeral cuff tears. J Biomech 2010;43:2049-2054. DOI: 10.1016/j.jbiomech.2010.04.012

115 Steenbrink F, Nelissen RG, Meskers CG, van de Sande MA, Rozing PM, de Groot JH. Teres major muscle activation relates to clinical outcome in tendon transfer surgery. Clin Biomech 2010;25:187-193. DOI: 10.1016/j.clinbiomech.2009.11.001

116 Tempelhof S, Rupp S, Seil R. Age-related prevalence of rotator cuff tears in asymptomatic shoulders. J Shoulder Elbow Surg 1999;8:296-299. DOI: 10.1016/S1058-2746(99)90148-9

117 Thompson WO, Debski RE, Boardman ND, III, Taskiran E, Warner JJ, Fu FH et al. A biomechanical analysis of rotator cuff deficiency in a cadaveric model. Am J Sports Med 1996;24:286-292. DOI: 10.1177/036354659602400307

118 Uhl TL, Kibler WB, Gecewich B, Tripp BL. Evaluation of clinical assessment methods for scapular dyskinesis. Arthroscopy 2009;25:1240-1248. 10.1016/j.arthro.2009.06.007

119 van der Helm FC. Analysis of the kinematic and dynamic behavior of the shoulder mechanism. J Biomech 1994;27:527-550. DOI: 10.1016/0021-9290(94)90064-7

120 van der Helm FC. A finite element musculoskeletal model of the shoulder mechanism. J Biomech 1994;27:551-569. DOI: 10.1016/0021-9290(94)90065-5

121 Van der Helm FC, Veeger HE, Pronk GM, Van der Woude LH, Rozendal RH. Geometry parameters for musculoskeletal modelling of the shoulder system. J Biomech 1992;25:129-144. DOI: 10.1016/0021-9290(92)90270-b

122 van der Windt DA, Koes BW, de Jong BA, Bouter LM. Shoulder disorders in general practice: incidence, patient characteristics, and management. Ann Rheum Dis 1995;54:959-964. DOI: 10-1136/ard.54.12.959

123 Vecchio P, Kavanagh R, Hazleman BL, King RH. Shoulder pain in a community-based rheumatology clinic. Br J Rheumatol 1995;34:440-442. DOI: 10.1093/rheumatology/34.5.440

124 Veeger HE, Van der Helm FC, Van der Woude LH, Pronk GM, Rozendal RH. Inertia and muscle contraction parameters for musculoskeletal modelling of the shoulder mechanism. J Biomech 1991;24:615-629. DOI: 10.1016/0021-9290(91)90294-w

125 Vitale MA, Arons RR, Hurwitz S, Ahmad CS, Levine WN. The rising incidence of acromioplasty. J Bone Joint Surg Am 2010;92:1842-1850. DOI: 10.2106/jbjs.i.01003

126 Yamaguchi K, Sher JS, Andersen WK, Garretson R, Uribe JW, Hechtman K et al. Glenohumeral motion in patients with rotator cuff tears: a comparison of asymptomatic and symptomatic shoulders. J Shoulder Elbow Surg 2000;9:6-11. DOI: 10.1016/s1058-2746(00)90002-8

127 Yamamoto A, Takagishi K, Osawa T, Yanagawa T, Nakajima D, Shitara H et al. Prevalence and risk factors of a rotator cuff tear in the general population. J Shoulder Elbow Surg 2010;19:116-120. DOI: 10.1016/j.jse.2009.04.006