Compensatory muscle activation in patients with glenohumeral cuff tears

Steenbrink, F.

Chapter 1

General introduction

1.1 The Shoulder Laboratory

1.1.1 Background

The generic term “shoulder” usually refers to the glenohumeral joint, the main joint of the shoulder girdle, which further comprises the acromioclavicular joint, sternoclavicular joint and the scapulothoracic gliding plane. The glenohumeral joint is modelled with three degrees of freedom (neglecting translations) and is a ball-and-socket joint. The proximal component is the scapula which consists of a concave glenoid covered with a fibro-cartilage labrum that deepens the glenoid cavity (Cooper et al., 1992). The distal component is the proximal part of the humerus, the convex humeral head. Most of the thoraco-humeral motion, i.e. arm movement with respect to the thorax, takes place at the glenohumeral joint, taking into account approximately 120° of the total arm elevation (Magermans et al., 2005), making it the most mobile joint in the human body. This large mobility results from the small articular surface, as well as the loose connecting ligaments and capsules. The capability of exerting arm forces in any direction in each arm position, while preserving joint stability, demonstrates a complex interplay between the different shoulder muscles. Even in a healthy condition it is very remarkable that the glenohumeral joint remains stable during arm motion, as the shoulder does not have a deep socket like the hip joint, or ligaments that are continuously under tension to preserve stability like in the knee. Stability of the shoulder is therefore different compared to these joints, but very effective with respect to the overall degree of mobility. The humeral head, which is slightly smaller than a billiard ball, is centered precisely on the glenoid, which is approximately the size of a desert spoon. It is amazing that such a configuration allows throwing, lifting, pulling and punching while maintaining joint stability.

The glenohumeral joint is considered mechanically stable when the sum of all internal (muscles, ligaments) and external (gravitational) forces working on the humerus, the resultant force vector, aims through the glenoid surface. This resulting force vector can then be fully compensated by the joint reaction force vector which is always directed perpendicular from the glenoid surface. The capsulo-ligamentous system of the glenohumeral joint is not tight enough to prevent joint dislocation (Bigliani et al., 1996), and although the glenoid labrum deepens the glenoid cavity, it is unlikely that it has any contribution to glenohumeral stability because of its flexible property (Carey et al., 2000). Studies with resections of the labrum showed that the average mechanical contribution of the labrum to glenohumeral stability was not very substantial (Halder et al., 2001). It is therefore not surprising that in absence of any muscle activity, the glenohumeral joint can be dislocated with very little effort (Harryman et al., 1995). Glenohumeral stability, or (re)directing the resultant force vector, is thus mainly controlled by muscle activity (Karduna et al., 1996; Labriola et al., 2005). When the resultant force vector is located outside the glenoid surface it cannot be fully counteracted by the joint reaction force introducing a remaining destabilizing force vector. This destabilizing force component might induce a displacement of the humeral head with respect to the scapula, i.e. glenohumeral instability (Soslowsky et al., 1992), resulting in a (painful) (Soifer et al., 1996) tissue impingement (i.e. subacromial bursa and tendons of supra- and infraspinatus) due to subacromial space reduction (Graichen et al., 1999). To prevent the humeral head from subluxating or dislocating, the muscles spanning the glenohumeral joint must work in a balanced and coordinative way to compress the humeral head against the glenoid surface at all times i.e aiming the resultant force vector working on the humeral head within the glenoid cavity.

The shoulder is driven by 17 muscles, in which some are mono-articular, spanning one joint (with multi degrees of freedom), but the gross is multi-articular, spanning more joints. The muscles from the thorax to the scapula connect the shoulder girdle in a way that there is a support for the humerus, but they can also move the whole shoulder girdle. The shortening range of the larger shoulder muscles is enabled by long fascicle lengths, which, together with the muscle moment arm, enables the shoulder muscles to have a long active force trajectory necessary for the large range of motion (Klein Breteler et al., 1999). The long fascicle lengths also come in handy in cases of non physiological lengthening, i.e. in tendon transfer surgery of either teres major or latissimus dorsi. Roughly speaking, one can distinguish muscles spanning the glenohumeral joint in two groups, namely the prime movers and the prime stabilizers. All muscle contractions affect both mobility of the shoulder as well as stability of the glenohumeral joint (Veeger and van der Helm, 2007), some muscle seem more appropriate for either moving or stabilizing the shoulder. The glenohumeral, or rotator cuff, muscles of the shoulder can be considered as prime stabilisers. Compared to the other shoulder muscles, these cuff muscles have a relative small moment arm, which enable them to be active during a wide variety of tasks without interfering much with the net joint moment. This special anatomy allows the glenohumeral cuff muscles to (re-)direct the resultant force vector working on the humeral head, providing glenohumeral stability during the whole range of glenohumeral joint rotations. Disruptions in the glenohumeral (muscle) force balance are bound to act upon the remaining muscle activation patterns (coordination), directly affecting glenohumeral (in)stability. Although glenohumeral cuff muscle diseases, such as massive cuff tears, rank among the most prevalent musculoskeletal disorders (Yamaguchi et al., 2006), surprisingly little information is available regarding the remaining compensatory muscle responses in such cases, with respect to the framework of glenohumeral (in)stability.

1.1.2 Setting

The department of Orthopaedics at the Leiden University Medical Center focuses on shoulder pathologies in both clinical and basic research projects. In daily hospital care collaborations between the different departments is desirable in order to achieve the best feasible healthcare and treatment for each individual patient. In research however such collaboration appears to be sub-optimal as for most research projects carried out in these hospitals, groups focus on their own speciality. The work for this thesis was accomplished in the Laboratory for Kinematics and Neuromechanics, in the Leiden University Medical Center (research coordinator dr. ir. J.H. de Groot), which entails a close collaboration between the departments of Orthopaedic surgery (head at start of project prof. dr. P.M. Rozing, current head prof. dr. R.G.H.H. Nelissen) and Rehabilitation medicine (head prof. dr. J.H. Arendzen) and more recently with the departments of Neurology and Geriatrics.

The work for this thesis was also done in a close collaboration between the faculty of Human Movement Science of the Vrije Universiteit of Amsterdam, MOVE, and the department of Biomechanical Engineering of the Technical University Delft, in what is called the Dutch Shoulder Group. In this research group the mobility, stability and the loading of the glenohumeral joint plays a central role and the collaboration had a kick-off at the end of the eighties. The scope was to combine knowledge of both the different medical and technical disciplines. In Leiden this has led to successful finished research projects and the development of essential tools for measuring upper extremity function (Meskers, 1998; de Groot, 1999; Stokdijk, 2002; van de Sande, 2008). In the Laboratory for Kinematics and Neuromechanics, a continuum in shoulder research is accomplished in order to understand both normal and pathological shoulder functioning. Clinical questions on the best treatment options for specific shoulder disorders are addressed by searching for the mechanical responses of patients suffering irreparable glenohumeral cuff tears. Knowledge of healthy shoulder functioning appears to be lacking, and research on pathological functioning and the difference from healthy controls seems to be a proper way to learn more about normal functioning.

A shoulder laboratory is constantly developing new tools and improving existing tools, all with the purpose to most accurately register (pathological) shoulder function. By combining different tools from clinical and technical origin, and analyzing outcome crosswise, the shoulder laboratory is a very powerful tool in current state of the art shoulder research. Basically, besides the common measurements like maximal arm force, pain-and function scores, the shoulder laboratory features three main techniques to describe the (pathological) functioning of the human shoulder, which are the assessment of muscle function, (scapula) kinematics and biomechanical shoulder model simulations.

1.2 Tools

1.2.1 Muscle function

Shoulder muscle function can be studied by experimentally assessing muscle activation using electromyography (EMG), either by surface or fine-wire electrodes. Because of modulation effects of muscle moment arms during arm motion the most dependable interpretations of EMG can be done when recorded during isometric tasks (de Groot et al., 2004). EMG analysis in this thesis is therefore solely recorded during isometric contractions in a static and critical (de Groot et al., 2006) arm position. In order to achieve the contributions of a muscle(group) to glenohumeral joint loading we asked patients/subjects to exert arm forces in various directions perpendicular to the longitudinal axis of the humerus. Muscle activation will be provoked depending of the different loading directions, allowing us to compare glenohumeral shoulder muscle function between patients and healthy subjects. By relating the level of EMG to the direction of arm force exertion we are able to describe normal arm muscle coordination and discriminate pathological conditions (de Groot et al., 2006). This method (de Groot et al., 2004; Meskers et al., 2004) is unique in its sort as for now, and based on an earlier reported electromyography technique (Flanders and Soechting, 1990; Barnett et al., 1999).

1.2.2 Kinematics

Clinical outcome on interventional studies or descriptive studies on shoulder pathologies will often contain an analysis of kinematics, or movement recordings of the shoulder. Several motion analysis systems are available, but since shoulder movements are mainly three-dimensional, an electromagnetic system seems to be most suitable, because the view of the sensors cannot be blocked like in most other (camera) systems. The "Flock of Birds" (FoB) is a six-degree of freedom electromagnetic tracking device (Ascension Technology Corp, Burlington, VT, USA) for obtaining 3D kinematical data. It consists of an extended range transmitter and several wired receivers, which, for shoulder kinematic recordings are attached to the thorax, scapulae and both upper and lower arms. A freely movable receiver mounted on a stylus then is used to point out different bony landmarks. Position and orientation of the stylus receiver are recorded together with the position and orientation of the segment receivers which is required to define the position of the receivers relative to the bony segments of interest. The bony landmarks of the thorax can be related to the thorax receiver, the bony landmarks of the scapula to the scapula receiver and the humerus bony landmarks to either the upper-or forearm receiver. 3D positions of the bony landmarks can be reconstructed in every recorded arm position from the orientation and position of the bone receivers (Meskers et al., 1998). The recorded arm kinematics can subsequently be used as input for biomechanical model simulations.

1.2.3 Model simulation

Inverse-dynamic simulations, using the Delft Shoulder and Elbow Model (DSEM)(van der Helm, 1994), are used in this thesis to estimate muscle forces to compare them to EMG data and to study the activation of muscles that were not (easily) accessible with EMG electrodes. Furthermore the DSEM is used to calculate the direction of the glenohumeral joint reaction force vector to investigate glenohumeral (in)stability, which cannot be measured simultaneously with muscle activation in a movement laboratory setting. The DSEM is a musculoskeletal model consisting of 139 functional different muscle elements (van der Helm et al., 1992; Veeger et al., 1997; Klein Breteler et al., 1999). The model can be used to estimate the joint reaction force and the individual muscle forces. From the position and orientation of the thorax, clavicle, scapula, humerus, radius and ulna the moment arms of all modelled muscle(element)s with respect to the joint can be calculated. The effect of muscle activation in each recorded arm position can be studied using the Potential Moment Vector (PMV). With this the agonists and antagonists for a specific task can be identified (Veeger and van der Helm, 2007). For every task and in every position several synergists can be identified. We must assume that the distribution of muscle forces over the available muscles is done according to an optimalisation principle. This is necessary, since at the shoulder joint the number of potential synergists exceeds the number of required synergists. This is called the indeterminacy or load sharing problem, which must be solved using an optimalization criteria (Dul et al., 1984; van der Helm, 1994; Meskers, 1998; Praagman et al., 2006) taking muscle size, maximal muscle force (determined by the physiological cross-sectional area ($PCSA$) and the pennation angle) and the force-length relation into account. Besides the desired 'task moment', muscles generate undesirable secondary moments around other degrees of freedom, e.g. by bi-and triarticular muscles or 2 and 3 degrees of freedom joints like the glenohumeral joint. These moments on their turn must be compensated by additional muscle moments. Simultaneously the already mentioned stability of the glenohumeral joint must be preserved.

While it is not possible to predict the required combination of muscle activation from anatomy books for a healthy shoulder, more strongly this will be impossible in case of lost muscle forces as a result of for example a rotator cuff tear, when compensating muscle activation is needed. Model simulations can help to simulate healthy shoulder function and to understand the response to simulated pathologies. Model outcome can be used for crosswise validation and interpretation with data obtained from *invivo* EMG recordings to study the mechanical effect the muscle activation on glenohumeral (in)stability.

1.3 Aim of this thesis

The aim of this thesis is to demonstrate in patients suffering from glenohumeral cuff tears that activation of the remaining muscles is deviating from muscle activation in healthy subjects. It is hypothesized that during arm elevation moment exertion, deltoid activation is increased in these patients to compensate for lost cuff elevation moment contributions, which painfully jeopardizes glenohumeral stability. To preserve glenohumeral stability, arm *ad*ductor muscles are hypothesized to activate during arm elevation tasks, compensating for lost stabilizing muscle forces, but restricting arm functionality. In this thesis the biomechanical principles of compensatory muscle activation are studied in relation to glenohumeral (in)stability and related to arm function (Range of Motion, function-and pain scores). Knowledge of compensatory muscle activation will provide new insights in future assessment and treatment options for patients with a glenohumeral cuff tear or cuff insufficiencies.

1.4 Outline of this thesis

Compensatory muscle responses (de Groot et al., 2006) in patients with glenohumeral cuff tears were suggested to be imposed by a trade-off between glenohumeral stability and arm mobility, and triggered by pain due to glenohumeral instability and subacromial tissue clamping. Therefore muscle activation in patients with rotator cuff tears were studied before and after subacromial pain suppression (**Chapter 2**). The mechanical properties of the shoulder were thus left unaltered and solely the pain stimulus was suppressed.

Besides being the result to the cuff pathology, muscle activation might also be external load magnitude dependent. This could lead to misinterpretation of activation patterns as being pathological while in fact they are the result of increased maximal arm force after an intervention, such as tendon transfer surgery. The effect of external arm load magnitude loading on muscle activation was assessed both experimentally on healthy subjects and by biomechanical model simulations (**Chapter 3**).

Biomechanical model simulations were also used to study the effect of incrementing cuff tear sizes on the remaining muscle activations and consequences for glenohumeral (in)stability (**Chapter 4**). The contribution of muscle activity on glenohumeral stability was investigated by running shoulder model simulations repeatedly without and with an active modelling constraint for glenohumeral stability.

A clinical intervention to restore arm mobility and decrease pain in patients with irreparable cuff tears is the teres major muscle tendon transfer, which would restore the adverse compensatory muscle activation in these patients with cuff tears (de Groot et al., 2006). Based on previous model simulations (Magermans et al., 2004a; Magermans et al., 2004b) we hypothesized that clinical improvement after a teres major tendon transfer involves alterations in muscle activation. Clinical results were investigated and related to changes in teres major muscle activation before and after its tendon transfer (**Chapter 5**).

Besides having an effect on the humeral head, the teres major potentially also has an effect on scapula orientation. Scapula lateral rotation in shoulders affected by a cuff tear, was compared to lateral rotation of the non-affected contra-lateral shoulder. To study the specific effect of the teres major, lateral rotation after a teres major or a latissimus dorsi tendon transfer was assessed (**Chapter 6**). Additionally, teres major activation was related to scapula lateral rotation and pain scores.

A deferential arm moment loading protocol, based upon compensatory muscle activations, was used on patients suffering from glenohumeral cuff insufficiency and on healthy subjects (**Chapter 7**). Musculoskeletal modeling was applied to analyze muscle forces and glenohumeral (in)stability while electromyography was used to assess muscle activation experimentally.

In the last chapter, the main findings of this thesis are discussed alongside potential clinical implications and suggestions for future research (**Chapter 8**).