Shoulder Strengthening Exercises Adapted to Specific Shoulder Pathologies Can Be Selected Using New Simulation Techniques: A Pilot Study

Caecilia Charbonnier[1], PhD, Alexandre Lädermann[2-4], MD, Bart Kevelham[1], MS, Sylvain Chagué[1], MS, Pierre Hoffmeyer[4], MD, Nicolas Holzer[4], MD, PhD

Medical Research Department, Artanim Foundation, Geneva, Switzerland[1]
Division of Orthopedics and Trauma Surgery, La Tour Hospital, Meyrin, Switzerland[2]
Faculty of Medicine, University of Geneva, Geneva, Switzerland[3]
Orthopedics and Trauma Service, University Hospitals of Geneva, Geneva, Switzerland[4]

Conflict of Interest: The authors declare that they have no conflict of interest.

Short Title: Impact of Shoulder Strengthening Exercises on the Shoulder Joint

Corresponding author:

Caecilia Charbonnier, PhD
Artanim Foundation
40, chemin du Grand-Puits – 1217 Meyrin, Switzerland
Telephone number: +41 22 980 91 92
E-mail address: caecilia.charbonnier@artanim.ch

Acknowledgements:

We would like to thank Alain Denis Keller, Emilie Paulin, Suzanne Gard, Corinne Bernimoulin-Schmid and Jean-Luc Ziltener for their participation in this study.

Abstract

Purpose: Shoulder strength training exercises represent a major component of rehabilitation protocols designed for conservative or post-surgical management of shoulder pathologies. Numerous methods are described for exercising each shoulder muscle or muscle group. Limited information is available to assess potential deleterious effects of individual methods with respect to specific shoulder pathologies. Thus, the goal of this pilot study was to use a patient-specific 3D measurement technique coupling medical imaging and optical motion capture for evaluation of a set of shoulder strength training exercises regarding glenohumeral, labral and subacromial compression, as well as elongation of the rotator cuff muscles.

Methods: One volunteer underwent Magnetic Resonance Imaging (MRI) and motion capture of the shoulder. Motion data from the volunteer were recorded during three passive rehabilitation exercises and twenty-nine strengthening exercises targeting eleven of the most frequently trained shoulder muscles or muscle groups and using four different techniques when available. For each exercise, glenohumeral and labral compression, subacromial space height, and rotator cuff muscles elongation were measured on the entire range of motion.

Results: Significant differences in glenohumeral, subacromial and labral compressions were observed between sets of exercises targeting individual shoulder muscles. Muscle lengths computed by simulation compared to MRI measurements showed differences of 0 to 5%.

Conclusions: This study represents the first screening of shoulder strengthening exercises to identify potential deleterious effects on the shoulder joint. Motion capture combined with medical imaging allows for reliable assessment of glenohumeral, labral and subacromial compression, as well as muscle-tendon elongation during shoulder strength training exercises.

Keywords: shoulder pathology; strengthening exercises; rehabilitation; kinematics; biomechanics.

Word count: 3640

Introduction

The ability of health care professionals to correctly advise sportive or non-athletic injured patients is crucial to the rehabilitation process and the prevention of subsequent injuries. Strengthening of shoulder muscles in rehabilitation protocols and sport practice can be achieved by a wide range of different exercises and several types of technique. A better understanding of the effects and repercussions of these exercises on the glenohumeral joint could allow injury prevention (i.e., in case of posterior static subluxation [36] or repairs minimizing stress on the damages structures [24]). Unfortunately, very limited objective data are available to propose recommendations for the design of shoulder strength training protocols.

Simulating muscle deformation during motion and thus measuring elongation in-vivo are challenging. Current physically-based methods (e.g., finite element models) are difficult to set up and limited to simple shoulder motion simulation where loads can be estimated [33, 38]. Moreover, they require accurate muscle segmentation on medical images that remains a complicated task. Other methods have considered the modeling of muscle paths, but to provide valid bone penetration-free deformations, numerous wrapping points or objects must be determined for each muscle segment at various joint positions [3], which becomes even more intricate when simulating the shoulder joint during complex motion such as strengthening exercises.

The aims of this study were thus to devise a simplified technique to simulate rotator cuff muscles during complex shoulder motion and to determine safety of rehabilitation exercises on sensitive shoulder structures. The hypotheses were that such simulation is feasible and that significant differences can be revealed between exercises targeting the same muscle or muscle group.

Methods

Subjects

One healthy right-handed male volunteer (28 years old, 180 cm, 80 kg) participated to the study. No previous shoulder injury or surgery was reported. The dominant arm was used throughout testing. Institutional ethical approval (AMG 12-18) was obtained prior to data collection. All procedures performed in the study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from the individual participant included in the study.

Study variables

The outcome of interest was the impact of a set of common shoulder rehabilitation exercises on articular cartilages and labrum compression, subacromial space height, and rotator cuff elongation.

3D reconstruction, kinematic recording and modeling

All of our experimental protocol is summarized in Figure 1. The volunteer underwent a MR shoulder arthrography. The MRI examination was conducted after a fluoroscopically guided arthrography with a contrast agent and with an anterior approach. MRI was performed with a 1.5 T HDxT system (General Electric Healthcare, Milwaukee WI, USA) and images were acquired in supine and neutral shoulder position. A dedicated shoulder surface coil was used. The following MRI sequences were acquired: 1) an axial Cosmic® 3D fast gradient echo sequence with fat saturation (section thickness 1.8 mm; no gaps; TR/TE ms 6.1/3.0), 2) an axial Cosmic® 3D fast gradient echo sequence (section thickness 4 mm; no gaps; TR/TE ms 5.7/2.8), and 3) an axial Lava® 3D fast gradient echo sequence (section thickness 5.2 mm; no gaps; TR/TE ms 3.7/1.7).

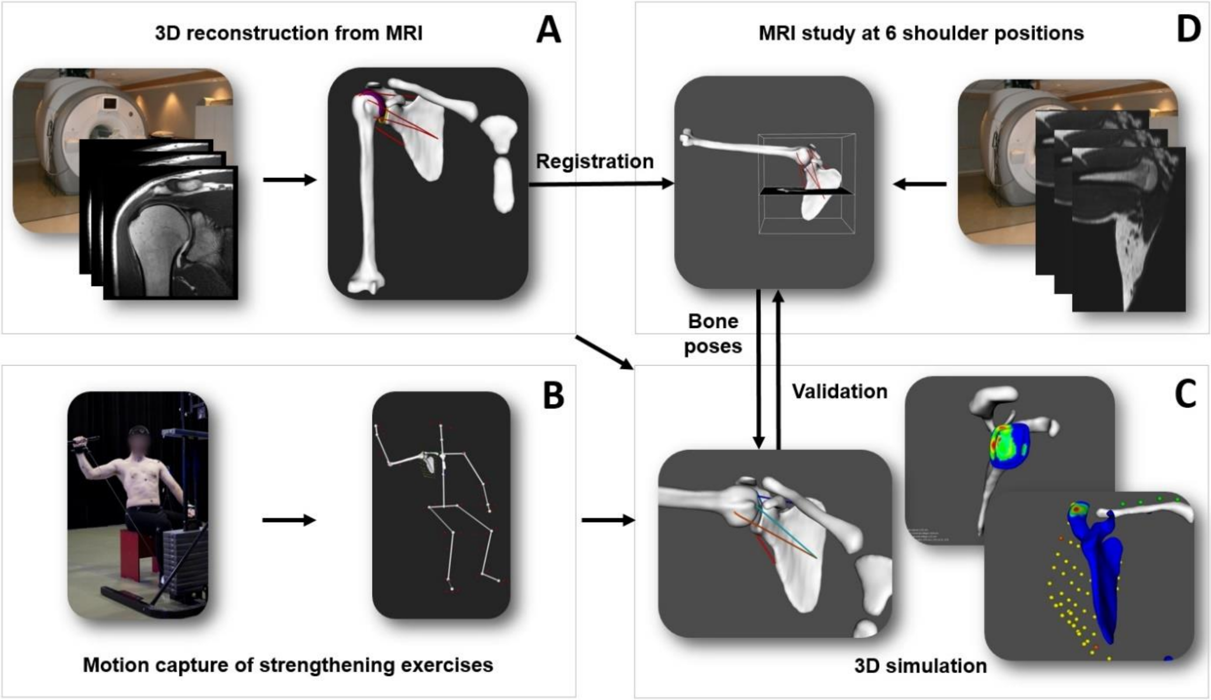

FIGURE 1. Detailed experimental protocol. The subject underwent MRI arthrography to reconstruct the bones, cartilages and muscles paths in neutral pose (A). Shoulder strengthening exercises were recorded using motion capture and the joint kinematics were computed for each exercise using a validated biomechanical model (B). For each exercise, glenohumeral and labral compression, subacromial space height, and rotator cuff muscles elongation were measured on the entire range of motion (C). To validate the muscle simulation technique, an MRI study was performed at six specific shoulder positions (D). For the six MRI poses, muscles paths were reconstructed to obtain reference lengths and the 3D bone models were registered to each pose. These poses were used as input in the simulation. Validation was obtained by comparing the muscles lengths computed by the simulation with those measured on the MRI.

Two musculoskeletal radiologists assessed independently the MRI arthrogram for shoulder pathology. The rotator cuff abnormalities [32], the labral lesions [35] and the bony changes [23] were reviewed.

The MR images were manually segmented and a virtual 3D model of the shoulder complex was reconstructed using Mimics software (Materialize NV, Leuven, Belgium). Patient-specific 3D models of the shoulder bones (humerus, scapula, clavicle and sternum), cartilage surfaces and labrum were obtained. The rotator cuff muscles, divided into five components (inferior subscapularis, superior subscapularis, infraspinatus, supraspinatus and teres minor) according to Collins et al. [11], were also modeled using 3D splines. Since anatomically, biomechanically and electrophysiologically differences between the superior and inferior part of the subscapularis have been reported, we analyzed this muscle separately [10]. Attachment sites and trajectories were identified on the MR images.

The next step was motion recording. The volunteer was equipped with a dedicated shoulder markers protocol [6], including sixty-nine spherical retroreflective markers placed directly onto the skin using double sided adhesive tape (see Figure 2). After appropriate warm-up and under the supervision of a physiotherapist, the volunteer was asked to perform three trials of three passive rehabilitation exercises (elevation 45°, elevation wall and table slide) and twenty-nine strengthening exercises, selected on the basis of electromyographic evidence of maximal activity for each muscle, targeting eleven of the most frequently trained shoulder muscles or muscle groups [22, 30, 31] and using up to four different techniques when available: cable bar machine, dumbbell, body weight and TheraBand^{TM} (Hygenic Corporation, Akron, OH, USA). The complete list of exercises is documented in the supplementary material. The weights used during the different exercises were selected by the physiotherapist who asked the volunteer before recording each exercise to perform several trials, checking his ability to safely lift and handle the weights for the exercise while maintaining a good technique. Motion from the volunteer was recorded using a Vicon MXT40S motion capture system (Vicon, Oxford Metrics, Oxford, UK) consisting of twenty-four cameras sampling at 120Hz.

Shoulder kinematics were computed from the markers trajectories based on the definitions suggested by the International Society of Biomechanics [39] and using a validated biomechanical model [6, 7] which accounted for skin motion artifacts and joint translations (i.e. 6 DOF joint model, accuracy: translational error <3 mm, rotational error <4°). More details about the model and its validation can be found in Charbonnier et al. [6]. As a result, the subject’s shoulder 3D models could be visualized at each point of the movement (Figure 2).

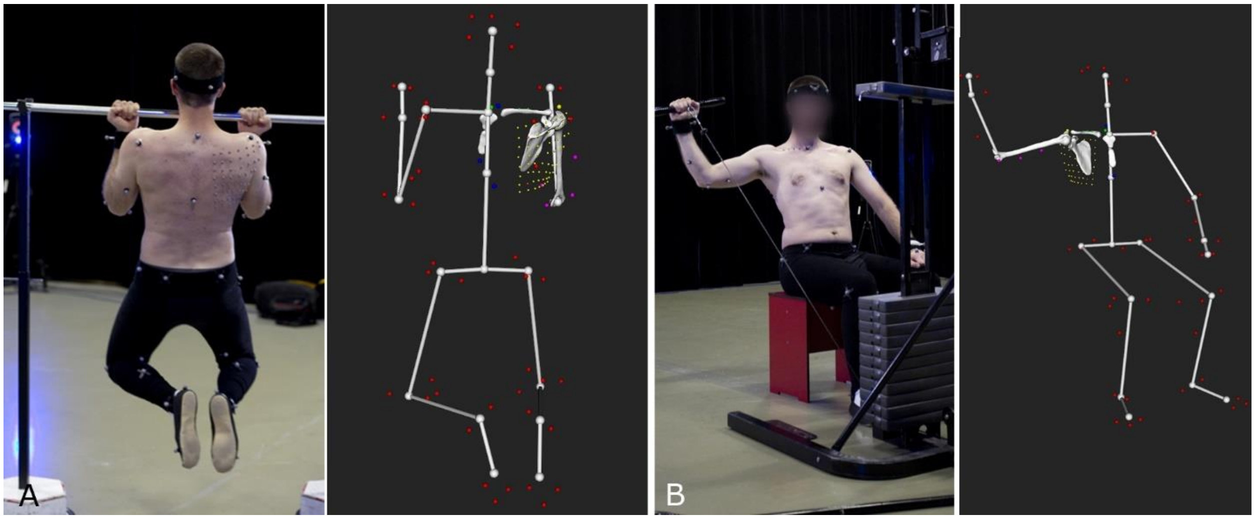

FIGURE 2. Examples of computed postures showing the markers set-up (small colored spheres) and a virtual skeleton used to better visualize and analyze the motion as a whole: A) chin-up exercise and B) cable seated shoulder external rotation exercise.

Evaluation of articular cartilages and labrum compression

During motion simulation, articular cartilages and labrum compression was evaluated on the entire range of motion (ROM) for all tested exercises using a penetration depth method [5, 7]. This method uses a collision detection algorithm to virtually locate contacts between the humeral cartilage, the glenoid cartilage and the glenoid labrum, and computes the surface-to-surface distance (i.e., penetration depth) in millimeter to quantify the topographic extent of compression on each structure.

To document areas of increased compression, the penetration depth distribution on the surface of the cartilages and labrum was represented using a color scale (Figure 3A). Blue was assigned when no collision was detected (penetration depth = 0), while other colors showed the compression zone. Red denoted the area with the highest compression (penetration depth = max).

To describe and report the exact location of the contact zone, the glenoid was divided into eight sectors (position 1, anterior; position 2, anterosuperior; position 3, superior; position 4, posterosuperior; position 5, posterior; position 6, posteroinferior; position 7, inferior; position 8, anteroinferior), as depicted in Figure 3B. The contact zones were hence assigned numbers correlating with their position.

Evaluation of subacromial space height

Subacromial space height was assessed on the entire ROM for all tested exercises by measuring the minimum distance between the inferior acromial surface and the humeral head surface [7]. This distance was calculated in 3D based on the simulated bones models positions and was reported in millimeter. A color scale was used to map the variations of distance on the scapula surface, with red denoting the zone of minimum distance and other colors denoting the areas of increased distance (Figure 3C).

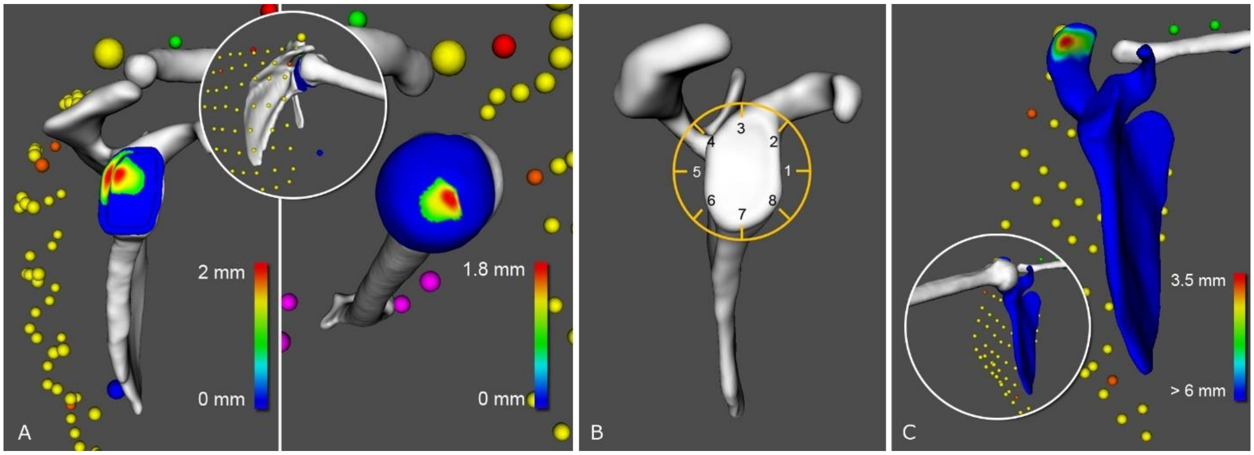

FIGURE 3. A) Visualization of the contact zone during motion (lateral and medial views). The colors represent the penetration depth distribution: blue is assigned when no collision is detected (penetration depth = 0), while other colors show the compression zone. Red denotes the area with the highest compression (penetration depth = max) Note: the humerus and humeral cartilage, respectively the scapula, glenoid cartilage and labrum are not shown for clarity. The small circled image shows the joint pose. B) Glenoid divided into eight sectors (position 1, anterior; position 2, anterosuperior; position 3, superior; position 4, posterosuperior; position 5, posterior; position 6, posteroinferior; position 7, inferior; position 8, anteroinferior) to report the location of the contact zone. C) Visualization of the humero-acromial distance during motion (anterior view). The colors represent the variations of distance between the acromion and humeral head. Red denotes the zone of minimum distance. Note: the humerus is not shown for clarity. The small circled image shows the joint pose.

Evaluation of rotator cuff elongation

During motion, muscles were simulated using a position-based dynamics approach [8, 26]. The 3D splines were discretized into a set of connected particles. In contrast to common simulation models for dynamic simulations – which rely on the calculation of forces to determine accelerations, velocities and ultimately particle positions using numerical integration methods – position-based dynamics directly derive position updates from the particle positions itself using constraints. The primary constraint used in our simulations was a straight-forward distance constraint which attempted to keep the distance between two particles equal to a specified rest-length. All constraints were processed one by one in a Gauss-Seidel type manner.

The simple formulation allows for real-time evaluation of the simulation, while remaining inherently stable. While lacking the more physically correct underpinning of more complex simulation methods, the results of this simple formulation are sufficient since in our particular scenario we are interested in length and deformation only.

To prevent interpenetration between the 3D bone models and the splines, continuous collision detection was used [28]. To speed up the computation and to allow for the efficient detection of collisions against the geometrically dense 3D bone models, the moving triangles of the models were embedded in an AABB tree [2]. Collision constraints were generated and added to the simulation whenever a collision was detected, moving potentially penetrating particles back to the surface of the 3D bone model.

To validate the muscle simulation technique, the volunteer underwent a second MRI of the shoulder (note that this acquisition could have been performed at the same time as the first MRI done for 3D reconstruction[1]). MRI was performed with a 1.5 T Ingenia system (Philips Medical systems, Best, The Netherlands) and images were acquired in six specific shoulder positions: 30°, 60° and 90° of abduction, 90° of abduction with maximal external rotation, 90° of abduction with maximal internal rotation, and maximal flexion. A

---

[1] Indeed, the tested subject participated in two different studies. The first MRI done for 3D reconstruction was part of a previous study [7]. We reused the MRI data and 3D reconstructed models from this previous study, but we had to perform this second MRI to validate the muscle simulation, since these data were not acquired previously.

dedicated shoulder surface coil was used. For each shoulder position, a Fast Field Echo (FFE) sequence (section thickness 4.0 mm; no gaps; TR/TE ms 23/4.7) was performed. Validation was obtained by comparing the muscles lengths computed by the simulation with those measured on the MRI in the six specific shoulder positions. This was achieved by registering the 3D bone models to each MRI pose in order to obtain their exact position and orientation to be used as input in the simulation [8]. Reference lengths were obtained by reconstructing the muscles paths as 3D splines for each MRI pose (Figure 4).

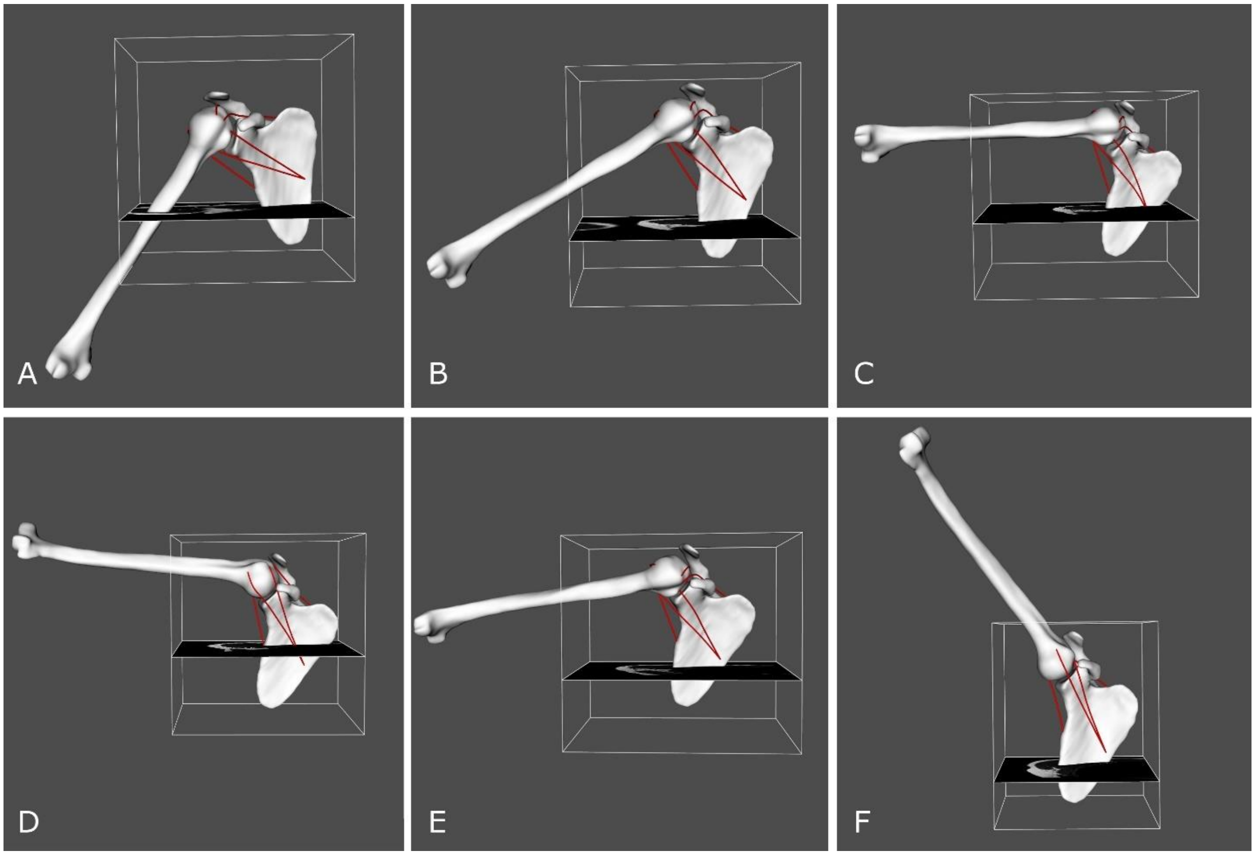

FIGURE 4. 3D bone models registered to each MRI pose with the reconstructed muscles paths used as reference lengths: A) 30° of abduction, B) 60° of abduction, C) 90° of abduction, D) 90° of abduction with maximal external rotation, E) 90° of abduction with maximal internal rotation, and F) maximal flexion.

The proposed simulation technique was then used to compute muscles lengths on the entire ROM during the strengthening exercises. For clarity, the obtained measures were expressed as muscle length variation (ratio of current length in millimeter with respect to the base length in neutral shoulder pose, expressed in %). Moreover, a color scale was used to visualize the length variations of the 3D splines, with warm colors denoting elongation and cool colors indicating compression (Figure 5).

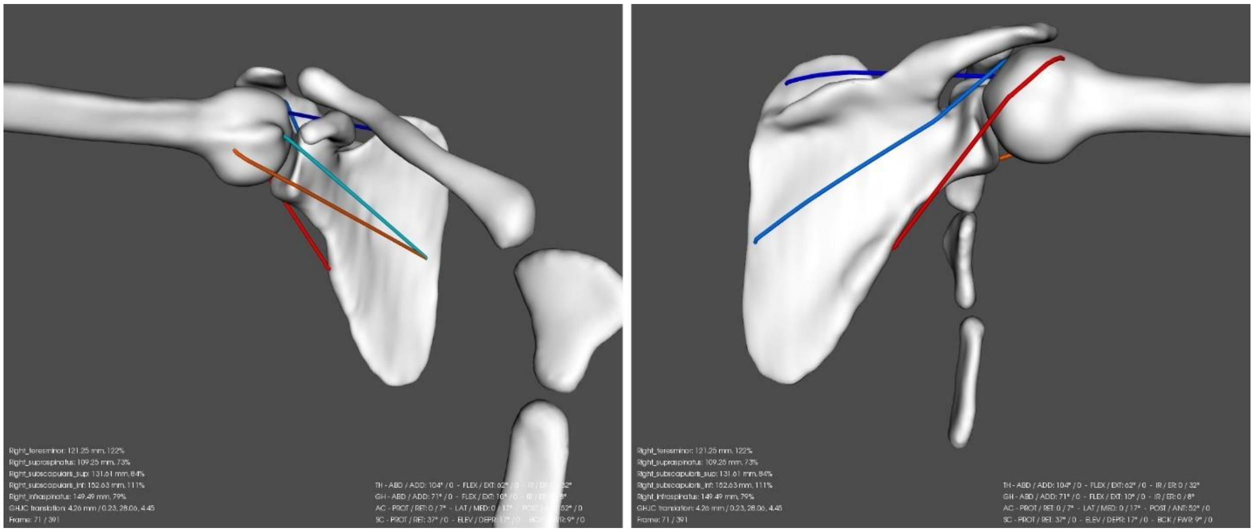

FIGURE 5. Rotator cuff muscles simulation (front and back views). The colors represent the length variations with respect to the neutral shoulder pose: warm colors mean that the muscle is elongated, whereas cool colors mean that the muscle is compressed during motion.

Statistical analysis

For each rehabilitation exercise and for each trial, we calculated through the entire ROM the peak glenoid cartilage and labrum compressions, the minimal subacromial space height and the peak length variation for each muscle. Based on these results and for each muscle group, we classified the strengthening exercises according to their impact on the joint, i.e. from the lowest to the greatest impact according to each measure (e.g., for labrum compression, from the lowest to the greatest compression). Paired Student's *t*-tests were used to determine if the exercises differed for the same muscle group according to the training technique used. A significance level was chosen at $p < 0.05$. For simplicity, the results of the different exercises were also averaged for each muscle group to report high-level muscle group impacts.

For the validation of the muscle simulation technique, we calculated the errors between the muscles lengths computed by the simulation with those measured on the MRI in the six specific shoulder positions.

Descriptive statistics are presented as mean and standard deviations (SD). The statistical software package R, v3.1.2 Portable (Free Software Foundation Inc, Vienna, Austria) was employed.

Results

Evaluation of the MRI arthrogram revealed no shoulder pathology. According to the muscle group and the type of strengthening exercises, important variations in glenoid cartilage and labrum compression (Table 1), subacromial space height (Table 2), and muscles elongation (Table 3) were observed, as indicated by the calculated p-values below the significance level at $p < 0.05$ (see supplementary material).

Glenoid cartilage compression varied up to 1.98 mm and labral compression up to 1.80 mm, with maximal average penetration depths obtained during the strengthening of middle/inferior trapezius, deltoid, supraspinatus, infraspinatus and teres minor. Exercises performed with TheraBand^{TM} had the lowest impact on cartilages compression, whereas exercises executed with the body weight induced the greatest penetration depths. Contacts were all located between the antero- and posterosuperior sectors of the glenoid.

Minimal subacromial height ranged between 0.15 mm to 3.60 mm in average for targeted muscles exercises according to the training technique used. The least favorable target muscles training with respect to subacromial space height were serratus, biceps brachii, pectoralis major and supraspinatus.

Muscle lengths computed by the simulation showed good agreement with respect to MRI measurements in the different positions (Table 4), but were always slightly underestimated due to the nature of the simulation technique that tries to find the shortest path between the two attachment points. The simulated teres minor and subscapularis muscles presented small length errors (mean ratio: -0% and -1%, respectively), while the infraspinatus and supraspinatus muscle lengths were slightly more underestimated by the simulation (mean ratio: -5% and -2%, respectively).

Simulation of the infraspinatus and supraspinatus muscles failed respectively, for one and four strengthening exercises due to the high velocity of the movements. Since the position updates of the bones were so important, the simulation technique could not properly interpolate the spline position even by increasing the interpolation steps. Peak muscle length variations varied from 81% to 135% in average for targeted muscles exercises according to the training technique used. The teres minor and the inferior subscapularis muscles were the most solicited (range: 116-135% and 94-122% respectively). The least favorable target muscles training with respect to rotator cuff elongation were supraspinatus, triceps and serratus.

Classification of exercises according to their impact on the glenoid cartilage and labrum compression, subacromial space height and rotator cuff elongation for each muscle group is provided as supplementary material.

Discussion

Health care professional’s knowledge about exercise technique is necessary to help sportive or non-athletic injured patients make informed choices about ROM recovery and exercises. However, very little data are available regarding the impact of strength training on the pathological shoulder joint. The main result of this study was the demonstration of significant differences between shoulder strength training exercises regarding glenohumeral, labral and subacromial compression, as well as rotator cuff elongation. Dynamic simulation and evaluation of rotator cuff elongation correlated reliably with MRI measurements. We presented a muscle simulation technique based on a patient-specific bone-muscle representation enabling a stable and real time simulation of the rotator cuff during complex shoulder motion. Although the proposed technique is a simplified non-physical approach, it allows gathering valuable clinical data. In particular, the present study offers novel insights into the analysis of cartilage, labrum compression, and rotator cuff deformations and elongations during functional movements. This methodology could be, with further studies, generalized to other muscles, soft tissues (e.g., ligaments) and joints.

Contacts only occurred between the antero- and posterosuperior sectors of the glenoid. This may indicate that some exercises could lead to greater pressure on the labrum and wear on joint cartilage, possibly inducing pain, leading to higher risk of osteoarthritis, extension of labral tears, or preventing repaired structures to heal. This study did not reveal that exercises or movements were deleterious for pathologies such as static posterior subluxation, posterior instability, dislocation arthropathy or glenohumeral instability. Nevertheless, it seems that the natural history of the latter pathologies is related to persistent microinstability rather than anteroinferior cartilage penetration or labral compression [20]. Contrarily, superior cartilage or labral compression, for example seen in internal impingement [18], are frequently encountered during exercises. This correlates with previous studies that reported anterosuperior internal impingement in 29% of the cases and posterosuperior internal impingement in 75% of overhead throwers [19].

Minimization of compression on labral structure in the injured athlete by adaptation of strength exercises has already been reported. Fees et al. [17] demonstrated that cartilages compression varied up to 6.6-fold and labral compression up to 5.7-fold for exercises targeting specific muscle or muscle groups, adding quantitative data to biomechanics for design of pathology-specific exercise recommendations. In the present analysis, glenoid cartilage and labrum compressions were maximal during strengthening of the middle/inferior trapezius, deltoid, and posterosuperior rotator cuff abductors. Potential deleterious effects of exercises on osteoarthritis or superior labral anteroposterior (SLAP) lesions could be found with the elevation wall exercise or with reinforcement of muscles that center the humeral head in the glenoid cavity or stabilize the scapula. On the other hand, exercises or movements that seem to protect such lesions are the ones soliciting the subscapularis, biceps, triceps, latissimus dorsi and superior trapezius muscles which are for instance particularly trained during Nordic walking, oar, paddle, brace stroke, and training with rowing machine or elliptical trainer.

Subacromial impingement and superior rotator cuff pathologies are associated with dysfunction and pain related to the upper extremity [16]. Some evidence exists to support the beneficial effect of exercises but there is no consensus regarding non-operative treatment modalities such as methods, duration and indications [12]. Controversy also exists about the way/manner to center the humeral head in the glenoid cavity either through strengthening deltoideus anterior and teres minor muscles [1, 21] or the entire deltoid muscle, as well as the muscles that stabilize the scapula [12]. The present study revealed that least favorable target muscles training with respect to subacromial space height were serratus, biceps brachii, pectoralis major and supraspinatus. Consequently, dogma about reinforcing muscles that stabilize the scapula and lower the humeral head in order to protect the superior rotator cuff [4, 9, 29] is probably founded. The analysis also showed a decrease of subacromial space passively that has an implication during postoperative rehabilitation. Historically, stiffness has been one of the most dreaded complications after rotator cuff repair. Anchored in recommendations from previous theories, passive ROM was considered to be useful to prevent the latter complication, therefore closed-chain overhead stretches, such as table slide, have been recommended [14]. The present study revealed that the latter exercises do not theoretically seem to particularly protect rotator cuff repair as they decrease the subacromial space compared to other ones. It is nevertheless unclear if a decrease in subacromial space during passive movement is clinically relevant.

Regarding rotator cuff elongation during strengthening exercises, the teres minor and the inferior subscapularis muscles – called the two "forgotten muscles of the rotator cuff" [10, 37] – were interestingly the structures displaying maximal excursion (range: 116-135% and 94-122% respectively). This finding reiterates their importance not only in pathologic conditions but also in a native state in order to control the anteroposterior balance [13, 15]. Consequently, rehabilitation after repair of these two muscles should be avoided for four to six weeks, as most exercises and movements lead to consequent lengthening.

Strengths and Limitations

This prospective study was the first to precisely analyze the impact of the most common shoulder rehabilitation exercises on subacromial space height, articular cartilages, labrum compression and rotator cuff elongation. The information helps the caregiver to alter programs so as to provide protection for joints, tendons, and muscles. The findings are relevant and may change the current approach of conservative or postoperative rehabilitation in various pathologic shoulder conditions. Impacts on compression of several anatomical structures were tested, representing a panoply of frequently encountered conditions such as instability, impingement or rotator cuff pathology. Moreover, patient selection was strict with exclusion of all conditions (hyperlaxity, previous pathology, etc.) that might affect the results.

However, there were several limitations that warrant discussion. First, only one patient was tested due to the complexity of analysis and the number of exercises. This prevents us from correlating the results to patient-specific anatomy and findings may be different in shoulders with pathology. However, if for example one muscle or one muscle group is deficient, testing of the concerned muscles would be by definition ineffective, whereas the testing of the remnant muscles would remain valid. Nevertheless, the goal of this study was not to recommend exercises in case of complete or massive involvement (e.g., complete and massive rotator cuff tear with anterosuperior escape) but rather in subtle or postoperative insufficiency. Moreover, our goal was to perform a pilot study to attest the validity of the methods developed before performing clinical studies with more subjects or patients suffering from various pathologies. Second, the accuracy of the kinematics computation from motion capture data could be criticized. Glenohumeral orientation and translation errors were respectively within 4° and 3 mm for each anatomical plane [6], which is acceptable for clinical use in the study of shoulder pathology. Although the translations could be significant with our model, it has been previously demonstrated that the computed translation patterns and amplitudes were in good agreement with published data [6, 7, 19]. Third, our proposed techniques are non-physical and irrespective of many loads, as no physical model allowing simulation of articular cartilages and labrum compression, and rotator cuff elongation exists. Fourth and last, we based our analysis of subacromial impingement on acromio-humeral distance [27]. Nevertheless, previous theories about acromio-humeral distance have been questioned. Indeed, it is unclear if the height of the subacromial space really plays a role, as it is now considered as a neo-articulation – the permanent contact between the humeral head and coraco-acromial arch during elevation of the arm being normal [34]. There is also growing evidence suggesting that distinct scapular morphologies and not simply subacromial impingement may accelerate the underlying degenerative process [25].

Conclusion

To our knowledge, this study represents the first screening of shoulder strengthening exercises to identify potential deleterious effects on the shoulder joint using a patient-specific measurement method coupling motion capture and medical imaging. The findings described in this paper will assist the health professionals to safely rehabilitate patients after shoulder injury.

References

1. Ainsworth R, Lewis J (2007) Exercise therapy for the conservative management of full thickness tears of the rotator cuff: a systematic review. Br J Sports Med 41(4):200–210
2. van den Bergen G (1997) Efficient collision detection of complex deformable models using aabb trees. J Graphics Tools 2(4):1–14
3. Blemker SS, Delp S (2005) Three-dimensional representation of complex muscle architectures and geometries. Ann Biomed Eng 33(5):661–673
4. Bury J, West M, Chamorro-Moriana G, Littlewood C (2016) Effectiveness of scapula-focused approaches in patients with rotator cuff related shoulder pain: A systematic review and meta-analysis. Man Ther 25:35–42
5. Charbonnier C, Assassi L, Volino P, Magnenat-Thalmann N (2009) Motion study of the hip joint in extreme postures. Vis Comput 25(9):873–882
6. Charbonnier C, Chagué S, Kolo F, Chow J, Lädermann A (2014) A patient-specific measurement technique to model the kinematics of the glenohumeral joint. Orthop Traumatol Surg Res 100(7):715–719
7. Charbonnier C, Chagué S, Kolo F, Lädermann A (2015) Shoulder motion during tennis serve: dynamic and radiological evaluation based on motion capture and magnetic resonance imaging. Int J CARS 10(8):1289–1297
8. Charbonnier C, Kevelham B, Chagué S, Läderman A, Ziltener JL, Hoffmeyer P, Holzer N (2015) A simplified technique to estimate rotator cuff elongation during complex shoulder motion. In: 29th International Congress of Computer Assisted Radiology and Surgery, Barcelona, Spain, Int J CARS
9. Christensen B, Andersen K, Rasmussen S, Andreasen E, Nielsen L, Jensen S (2016) Enhanced function and quality of life following 5 months of exercise therapy for patients

with irreparable rotator cuff tears – an intervention study. BMC Musculoskelet Disord 17(1):1–8

10. Collin P, Lädermann A, Bourg ML, Walch G (2013) Subscapularis minor–an analogue of the teres minor? Orthop Traumatol Surg Res 99(4 Suppl):S255–S258
11. Collin P, Matsumura N, Lädermann A, Denard P, Walch G (2014) Relationship between massive chronic rotator cuff tear pattern and loss of active shoulder range of motion. J Shoulder Elbow Surg 23(8):1195–1202
12. Collin P, Gain S, Huu FN, Lädermann A (2015) Is rehabilitation effective in massive rotator cuff tears? Orthop Traumatol Surg Res 101(4 Suppl):S203–S205
13. Collin P, Treseder T, Denard P, Neyton L, Walch G, Lädermann A (2015) What is the best clinical test for assessment of the teres minor in massive rotator cuff tears? Clin Orthop Rel Res 473(9):2959–2966
14. Denard P, Lädermann A, Burkhart S (2011) Prevention and management of stiffness after arthroscopic rotator cuff repair: Systematic review and implications for rotator cuff healing. Arthroscopy 27(6):842–848
15. Denard P, Koo S, Murena L, Burkhart S (2012) Pseudoparalysis: The importance of rotator cable integrity. Orthopedics 35:e1353–e1357
16. Downie B, Miller B (2012) Treatment of rotator cuff tears in older individuals: a systematic review. J Shoulder Elbow Surg 21(9):1255–1261
17. Fees M, Decker T, Snyder-Mackler L, Michael A (1998) Upper extremity weight-training modifications for the injured athlete: A clinical perspective. Am J Sports Med 26(5):732–742
18. Gerber C, Sebesta A (2000) Impingement of the deep surface of the subscapularis tendon and the reflection pulley on the anterosuperior glenoid rim: a preliminary report. J Shoulder Elbow Surg 9(6):483–490

19. Lädermann A, Chagué S, Kolo F, Charbonnier C (2016) Kinematics of the shoulder joint in tennis players. J Sci Med Sport 19(1):56–63

20. Lädermann A, Denard P, Tirefort J, Kolo F, Chagué S, Cunningham G, Charbonnier C (2016) Does surgery for instability of the shoulder truly stabilize the glenohumeral joint?: A prospective comparative cohort study. Medicine 95(31):e4369

21. Levy O, Roberts S, Copeland S (2005) The role of anterior deltoid re-education in patients with massive irreparable degenerative rotator cuff tears. Orthop Proc 87-B(3 Suppl):384–384

22. McCann P, Wootten M, Kadaba M, Bigliani L (1993) A kinematic and electromyographic study of shoulder rehabilitation exercises. Clin Orthop Relat Res 288:179–188

23. Meister K, Andrews J, Batts J, Wilk K, Baumgarten T (1999) Symptomatic thrower's exostosis. arthroscopic evaluation and treatment. Am J Sports Med 27(2):133–136

24. Miller R, Popchak A, Vyas D, Tashman S, Irrgang J, Musahl V, Debski R (2016) Effects of exercise therapy for the treatment of symptomatic full-thickness supraspinatus tears on in vivo glenohumeral kinematics. J Shoulder Elbow Surg 25:641–649

25. Moor B, Wieser K, Slankamenac K, Gerber C, Bouaicha S (2014) Relationship of individual scapular anatomy and degenerative rotator cuff tears. J Shoulder Elbow Surg 23(4):536–541

26. Mueller M, Heidelberger B, Hennix M, Ratcliff J (2007) Position based dynamics. J Vis Comun Image Represent 18(2):109–118

27. Neer C (1972) Anterior acromioplasty for the chronic impingement syndrome in the shoulder. J Bone Joint Surg 54(1):41–50

28. Provot X (1997) Collision and self-collision handling in cloth model dedicated to design garment. In Computer Animation and Simulation'97 (pp. 177-189). Springer, Vienna

29. Reijneveld E, Noten S, Michener L, Cools A, Struyf F (2017) Clinical outcomes of a scapular-focused treatment in patients with subacromial pain syndrome: a systematic review. Br J Sports Med 51(5):436–441

30. Reinold M, Wilk K, Fleisig G, Zheng N, Barrentine S, T TC, Cody R, Andrews GJJ (2004) Electromyographic analysis of the rotator cuff and deltoid musculature during common shoulder external rotation exercises. J Orthop Sports Phys Ther 34:385–394

31. Reinold M, Escamilla R, Wilk K (2009) Current concepts in the scientific and clinical rationale behind exercises for glenohumeral and scapulothoracic musculature. J Orthop Sports Phys Ther 39:105–117

32. Snyder S, Pachelli A, Pizzo WD, Friedman M, Ferkel R, Pattee G (1991) Partial thickness rotator cuff tears: results of arthroscopic treatment. Arthroscopy 7(1):1–7

33. Terrier A, Larrea X, Camine VM, Pioletti D, Farron A (2013) Importance of the subscapularis muscle after total shoulder arthroplasty. Clin Biomech 28:146–150

34. Voisin J, Ropars M, Thomazeau H (2014) The human acromion viewed from an evolutionary perspective. Orthop Traumatol Surg Res 100(8 Suppl):S355–S360

35. Walch G, Boileau P, Noel E, Donell S (1992) Impingement of the deep surface of the supraspinatus tendon on the posterior glenoid rim: an arthroscopic study. J Shoulder Elbow Surg 1:238–245

36. Walch G, Ascani C, Boulahia A, Nové-Josserand L, Edwards T (2002) Static posterior subluxation of the humeral head: An unrecognized entity responsible for glenohumeral osteoarthritis in the young adult. J Shoulder Elbow Surg 11(4):309–314

37. Walch G, Nové-Josserand L, Liotard J, Noel E, Tavernier T, Barthélémy R (2005) L’Epaule: une approche pluridisciplinaire, Sauramps Medical, Montpellier, chap Le petit rond (teres minor): l’oublié de la coiffe, pp 237–244

38. Webb J, Blemker S, Delp S (2014) 3D finite element models of shoulder muscles for computing lines of actions and moment arms. Comput Meth Biomech Biomed Eng 17(8):829–837

39. Wu G, van der Helm F, Veegerc H, Makhsouse M, Royf PV, Angling C, Nagelsh J, Kardunai A, McQuadej K, Wangk X, Wernerl F, Buchholzm B (2005) ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - part II: shoulder, elbow, wrist and hand. J Biomech 38:981–992

TABLE 1. Peak penetration depth (mm) on the glenoid cartilage and labrum averaged by muscle group and for each passive exercise

Muscle group	**Glenoid cartilage**		**Labrum**	
	Mean	**SD**	**Mean**	**SD**
Deltoid	1.61	0.10	1.59	0.07
Supraspinatus	1.51	0.02	1.55	0.02
Infraspinatus + teres minor	1.54	0.04	1.59	0.04
Subscapularis	0.63	0.65	0.51	0.44
Biceps	0.85	0.42	0.62	0.28
Triceps	1.20	0.75	1.19	0.77
Latissimus dorsi	1.04	0.68	0.99	0.93
Superior trapezius	0.00	0.00	0.00	0.00
Middle + inferior trapezius	1.64	0.31	1.62	0.21
Pectoralis	0.96	0.76	1.16	0.36
Serratus	1.28	0.45	1.25	0.63
Passive exercise				
Elevation 45°	1.17	0.06	1.27	0.05
Elevation wall	1.42	0.05	1.50	0.02
Table slide	1.41	0.03	1.16	0.02

TABLE 2. Minimal subacromial space height (mm) averaged by muscle group and for each passive exercise

Muscle group	**Mean**	**SD**
Deltoid	1.76	1.60
Supraspinatus	1.29	0.38
Infraspinatus + teres minor	1.70	0.74
Subscapularis	2.08	0.39
Biceps	0.97	0.46
Triceps	1.38	1.04
Latissimus dorsi	1.79	0.41
Superior trapezius	2.11	0.45
Middle + inferior trapezius	2.38	0.76
Pectoralis	1.27	0.03
Serratus	0.91	1.06
Passive exercise		
Elevation 45°	0.62	0.24
Elevation wall	0.60	0.25
Table slide	0.53	0.13

TABLE 3. Peak length variation (%) of the rotator cuff muscles averaged by muscle group and for each passive exercise

Muscle group	Subscapularis inferior		Subscapularis superior		Infraspinatus		Supraspinatus		Teres minor	
	Mean*	**SD**	**Mean***	**SD**	**Mean***	**SD**	**Mean***	**SD**	**Mean***	**SD**
Deltoid	111%	6%	91%	5%	97%	4%	93%	6%	127%	7%
Supraspinatus	117%	1%	93%	2%	94%	5%	89%	6%	123%	4%
Infraspinatus + teres minor	113%	6%	94%	2%	95%	3%	90%	2%	122%	4%
Subscapularis	104%	3%	93%	3%	95%	3%	90%	3%	121%	2%
Biceps	102%	5%	93%	3%	98%	2%	94%	5%	118%	1%
Triceps	105%	15%	92%	1%	93%	14%	87%	14%	123%	5%
Latissimus dorsi	105%	5%	94%	3%	102%	2%	97%	3%	119%	1%
Superior trapezius	95%	0%	92%	0%	103%	1%	96%	1%	117%	2%
Middle + inferior trapezius	107%	4%	94%	4%	101%	4%	97%	1%	125%	5%
Pectoralis	108%	1%	96%	8%	98%	1%	97%	0%	127%	11%
Serratus	110%	3%	90%	6%	92%	10%	82%	12%	129%	6%
Passive exercise										
Elevation 45°	112%	0%	94%	0%	100%	0%	95%	0%	122%	1%
Elevation wall	117%	1%	95%	1%	97%	1%	93%	2%	117%	0%
Table slide	110%	0%	89%	0%	95%	1%	89%	1%	132%	0%

* Percentage > 100% means that the muscle is elongated, otherwise it is compressed during motion

TABLE 4. Errors (mm) between the muscles lengths computed by the simulation with those measured on MRI in the six shoulder positions (n = 6)

Muscle	**Mean* ± SD**	**Ratio** (mean ± SD)**
Infraspinatus	-8.6 ± 4.6	-5% ± 2%
Subscapularis inferior	-0.7 ± 0.4	-1% ± 0%
Subscapularis superior	-1.1 ± 0.7	-1% ± 0%
Supraspinatus	-3.6 ± 2.3	-2% ± 2%
Teres minor	-0.5 ± 0.1	0% ± 0%

* Values are negative, meaning that the simulation tended to underestimate the length
** Error reported as length variation (ratio of current length with respect to the base length in neutral pose)

Supplementary material

Table S1: Peak penetration depth (mm) on the glenoid cartilage with location of the contact zone for each exercise (n = 3)*. Exercises are classified according to their impact on the joint.

Muscle trained	Weight (kg)	Exercise	Location**	Mean	SD	*P* value[†]
Deltoid	-	Elevation with TheraBand	3,4	1.49	0.04	
	10	Cable Bar Upright Row	2	1.63	0.01	0.036
	2.5	Dumbbell Lying Rear Delt Row	2,3	1.70	0.18	0.233
Supraspinatus	-	Elevation with TheraBand	3,4	1.49	0.04	
	2	Cable Seated Front Lateral Raise	2,3	1.50	0.01	0.707
	2.5	Dumbbell Lateral Raise	3	1.54	0.05	0.454
Infraspinatus + teres minor	-	Elevation with TheraBand	3,4	1.49	0.04	
	2	Cable Seated Shoulder External Rotation	2	1.52	0.06	0.431
	1	Dumbbell Seated Shoulder External Rotation	2	1.55	0.02	0.173
	body	Inverted row (small amplitude)	2,3	1.59	0.12	0.390
Subscapularis	4	Cable Standing Shoulder Internal Rotation	3	0.21	0.21	
	-	Internal Rotation with TheraBand	3	0.31	0.14	0.629
	2.5	Dumbbell Seated Shoulder External Rotation on the Floor	3	1.37	0.19	0.037
Biceps	2.5	Dumbbell Curl	3	0.59	0.17	
	8	Cable Curl	3	0.62	0.08	0.764
	body	Chin Up	3	1.34	0.06	0.017
Triceps	1	Dumbbell Kick Back	3	0.34	0.35	
	2	Cable Bent-over Triceps Extension	4	1.48	0.06	0.032
	body	Bench Dip	2	1.76	0.15	0.034
Latissimus dorsi	4	Cable Standing Row	2	0.55	0.19	
	2.5	Dumbbell Lying Row	2	1.52	0.01	0.014
Superior trapezius	2.5	Up Shoulder with TheraBand	NA	0.00	0.00	-

	-	Dumbbell Shrug	NA	0.00	0.00	-
Middle + inferior trapezius	2.5	Dumbbell Bent-over Row	2	1.36	0.06	
	body	Inverted Row (large amplitude)	2	1.60	0.03	0.041
	4	Cable Rowing	3	1.98	0.01	0.002
Pectoralis	2.5	Push-up Dumbbell Bench Press	3	0.42	0.14	
	body	Push-up	2,3	1.49	0.02	0.005
Serratus	2.5	Dumbbell Incline Shoulder Raise	4	0.76	0.05	
	2	Cable Incline Shoulder Raise	3	1.53	0.11	0.005
	body	Incline Push-up	2,3	1.54	0.11	0.005

* Data are reported for the participant performing three trials for each exercise

** Location of the contact zone around the glenoid according to our documentation (2 = anterosuperior, 3 = superior, 4 = posterosuperior)

[†] *P* values obtained with use of Student's *t*-test

Table S2: Peak penetration depth (mm) on the labrum with location of the contact zone for each exercise (n = 3)*. Exercises are classified according to their impact on the joint.

Muscle trained	Weight (kg)	Exercise	Location**	Mean	SD	*P* value†
Deltoid	-	Elevation with TheraBand	3,4	1.54	0.02	
	10	Cable Bar Upright Row	2	1.57	0.04	0.257
	2.5	Dumbbell Lying Rear Delt Row	2,3	1.67	0.04	0.039
Supraspinatus	2	Cable Seated Front Lateral Raise	2,3	1.53	0.02	
	-	Elevation with TheraBand	3,4	1.54	0.02	0.742
	2.5	Dumbbell Lateral Raise	3	1.57	0.02	0.032
Infraspinatus + teres minor	-	Elevation with TheraBand	3,4	1.54	0.02	
	1	Dumbbell Seated Shoulder External Rotation	2	1.59	0.06	0.249
	body	Inverted row (small amplitude)	2,3	1.61	0.15	0.521
	2	Cable Seated Shoulder External Rotation	2	1.62	0.02	0.001
Subscapularis	-	Internal Rotation with TheraBand	3	0.20	0.19	
	4	Cable Standing Shoulder Internal Rotation	3	0.32	0.20	0.059
	2.5	Dumbbell Seated Shoulder External Rotation on the floor	3	1.02	0.16	0.003
Biceps	2.5	Dumbbell Curl	3	0.41	0.14	
	8	Cable Curl	3	0.52	0.07	0.283
	body	Chin Up	3	0.94	0.02	0.021
Triceps	1	Dumbbell Kick Back	3	0.30	0.32	
	2	Cable Bent-over Triceps Extension	4	1.55	0.01	0.020
	body	Bench Dip	2	1.72	0.12	0.018
Latissimus dorsi	4	Cable Standing Row	2	0.33	0.23	
	2.5	Dumbbell Lying Row	2	1.64	0.05	0.013
Superior trapezius	2.5	Up Shoulder with TheraBand	NA	0.00	0.00	-
	-	Dumbbell Shrug	NA	0.00	0.00	-
Middle + inferior trapezius	2.5	Dumbbell Bent-over Row	2	1.39	0.01	
	body	Inverted Row (large amplitude)	2	1.65	0.01	0.001

	4	Cable Rowing	3	1.80	0.02	0.001
Pectoralis	2.5	Push-up Dumbbell Bench Press	3	0.91	0.10	
	body	Push-up	2,3	1.42	0.09	0.038
Serratus	2.5	Dumbbell Incline Shoulder Raise	4	0.52	0.02	
	2	Cable Incline Shoulder Raise	3	1.55	0.05	0.001
	body	Incline Push-up	2,3	1.67	0.07	0.001

* Data are reported for the participant performing three trials for each exercise

** Location of the contact zone around the glenoid according to our documentation (2 = anterosuperior, 3 = superior, 4 = posterosuperior)

[†] *P* values obtained with use of Student's *t*-test

Table S3: Minimal subacromial space height (mm) for each exercise (n = 3)*. Exercises are classified according to their impact on the joint.

Muscle trained	**Weight (kg)**	**Exercise**	**Mean**	**SD**	***P* value**†
Deltoid	10	Cable Bar Upright Row	3.60	0.43	
	-	Elevation with TheraBand	0.95	0.23	0.014
	2.5	Dumbbell Lying Rear Delt Row	0.71	0.44	0.022
Supraspinatus	2	Cable Seated Front Lateral Raise	1.69	0.12	
	2.5	Dumbbell Lateral Raise	1.21	0.25	0.029
	-	Elevation with TheraBand	0.95	0.23	0.012
Infraspinatus + teres minor	body	Inverted row (small amplitude)	2.73	1.38	
	1	Dumbbell Seated Shoulder External Rotation	1.56	0.16	0.243
	2	Cable Seated Shoulder External Rotation	1.55	0.15	0.243
	-	Elevation with TheraBand	0.95	0.23	0.130
Subscapularis	-	Internal Rotation with TheraBand	2.52	0.41	
	4	Cable Standing Shoulder Internal Rotation	1.98	0.33	0.018
	2.5	Dumbbell Seated Shoulder External Rotation on the Floor	1.75	0.24	0.080
Biceps	8	Cable Curl	1.29	0.24	
	2.5	Dumbbell Curl	1.18	0.11	0.648
	body	Chin Up	0.45	0.27	0.077
Triceps	1	Dumbbell Kick Back	2.24	0.03	
	body	Bench Dip	1.69	0.11	0.010
	2	Cable Bent-over Triceps Extension	0.22	0.08	0.000
Latissimus dorsi	4	Cable Standing Row	2.07	0.15	
	2.5	Dumbbell Lying Row	1.50	0.05	0.030
Superior trapezius	2.5	Dumbbell Shrug	2.43	0.34	
	-	Up Shoulder with TheraBand	1.80	0.17	0.032
Middle + inferior trapezius	4	Cable Rowing	3.25	0.38	
	body	Inverted Row (large amplitude)	2.07	0.07	0.035

	2.5	Dumbbell Bent-over Row	1.83	0.30	0.003
Pectoralis	2.5	Push-up Dumbbell Bench Press	1.29	0.53	
	body	Push-up	1.25	0.75	0.955
Serratus	body	Incline Push-up	2.12	0.59	
	2	Cable Incline Shoulder Raise	0.47	0.26	0.046
	2.5	Dumbbell Incline Shoulder Raise	0.15	0.10	0.024

* Data are reported for the participant performing three trials for each exercise

† *P* values obtained with use of Student's *t*-test

Table S4: Peak length variation (%) of the inferior subscapularis muscle for each exercise (n = 3)*. Exercises are classified according to their impact on the joint.

Muscle trained	**Weight (kg)**	**Exercise**	**Mean****	**SD**	***P* value**†
Deltoid	2.5	Dumbbell Lying Rear Delt Row	107%	1%	
	10	Cable Bar Upright Row	108%	1%	0.359
	-	Elevation with TheraBand	118%	1%	0.011
Supraspinatus	2	Cable Seated Front Lateral Raise	116%	1%	
	2.5	Dumbbell Lateral Raise	118%	0%	0.010
	-	Elevation with TheraBand	118%	1%	0.012
Infraspinatus + teres minor	body	Inverted row (small amplitude)	103%	1%	
	1	Dumbbell Seated Shoulder External Rotation	114%	1%	0.004
	2	Cable Seated Shoulder External Rotation	115%	0%	0.001
	-	Elevation with TheraBand	118%	1%	0.004
Subscapularis	4	Cable Standing Shoulder Internal Rotation	103%	1%	
	2.5	Dumbbell Seated Shoulder External Rotation on the Floor	103%	1%	0.321
	-	Internal Rotation with TheraBand	107%	1%	0.070
Biceps	8	Cable Curl	97%	0%	
	2.5	Dumbbell Curl	100%	0%	0.007
	body	Chin Up	107%	1%	0.005
Triceps	body	Bench Dip	94%	0%	
	1	Dumbbell Kick Back	99%	1%	0.030
	2	Cable Bent-over Triceps Extension	122%	1%	0.000
Latissimus dorsi	4	Cable Standing Row	101%	2%	
	2.5	Dumbbell Lying Row	108%	0%	0.030
Superior trapezius	2.5	Dumbbell Shrug	95%	0%	
	-	Up Shoulder with TheraBand	95%	0%	0.292
Middle + inferior trapezius	4	Cable Rowing	103%	0%	
	2.5	Dumbbell Bent-over Row	107%	0%	0.002

	body	Inverted Row (large amplitude)	111%	1%	0.004
Pectoralis	body	Push-up	107%	0%	
	2.5	Push-up Dumbbell Bench Press	109%	1%	0.076
Serratus	body	Incline Push-up	108%	1%	
	2.5	Dumbbell Incline Shoulder Raise	109%	0%	0.837
	2	Cable Incline Shoulder Raise	114%	2%	0.043

* Data are reported for the participant performing three trials for each exercise

** Percentage > 100% means that the muscle is elongated, otherwise it is compressed during motion

† *P* values obtained with use of Student’s *t*-test

Table S5: Peak length variation (%) of the superior subscapularis muscle for each exercise (n = 3)*. Exercises are classified according to their impact on the joint.

Muscle trained	**Weight (kg)**	**Exercise**	**Mean****	**SD**	***P* value**†
Deltoid	10	Cable Bar Upright Row	86%	1%	
	-	Elevation with TheraBand	92%	1%	0.001
	2.5	Dumbbell Lying Rear Delt Row	96%	2%	0.021
Supraspinatus	2	Cable Seated Front Lateral Raise	91%	1%	
	-	Elevation with TheraBand	92%	1%	0.004
	2.5	Dumbbell Lateral Raise	95%	0%	0.025
Infraspinatus + teres minor	-	Elevation with TheraBand	92%	1%	
	body	Inverted row (small amplitude)	93%	1%	0.642
	2	Cable Seated Shoulder External Rotation	95%	1%	0.000
	1	Dumbbell Seated Shoulder External Rotation	96%	1%	0.015
Subscapularis	2.5	Dumbbell Seated Shoulder External Rotation on the Floor	91%	1%	
	4	Cable Standing Shoulder Internal Rotation	92%	1%	0.354
	-	Internal Rotation with TheraBand	97%	0%	0.031
Biceps	8	Cable Curl	89%	0%	
	2.5	Dumbbell Curl	93%	0%	0.001
	body	Chin Up	96%	0%	0.001
Triceps	2	Cable Bent-over Triceps Extension	91%	1%	
	body	Bench Dip	91%	0%	0.507
	1	Dumbbell Kick Back	93%	0%	0.013
Latissimus dorsi	2.5	Dumbbell Lying Row	92%	0%	
	4	Cable Standing Row	96%	2%	0.076
Superior trapezius	2.5	Dumbbell Shrug	92%	0%	
	-	Up Shoulder with TheraBand	92%	1%	0.149
Middle + inferior trapezius	4	Cable Rowing	92%	0%	
	2.5	Dumbbell Bent-over Row	92%	1%	0.737

	body	Inverted Row (large amplitude)	98%	1%	0.004
Pectoralis	body	Push-up	91%	1%	
	2.5	Push-up Dumbbell Bench Press	102%	1%	0.009
Serratus	2.5	Dumbbell Incline Shoulder Raise	84%	1%	
	body	Incline Push-up	92%	1%	0.004
	2	Cable Incline Shoulder Raise	95%	2%	0.011

* Data are reported for the participant performing three trials for each exercise

** Percentage > 100% means that the muscle is elongated, otherwise it is compressed during motion

† *P* values obtained with use of Student's *t*-test

Table S6: Peak length variation (%) of the infraspinatus muscle for each exercise (n = 3)*. Exercises are classified according to their impact on the joint.

Muscle trained	**Weight (kg)**	**Exercise**	**Mean****	**SD**	***P* value†**
Deltoid	10	Cable Bar Upright Row	93%	0%	
	-	Elevation with TheraBand	97%	0%	0.002
	2.5	Dumbbell Lying Rear Delt Row	102%	1%	0.004
Supraspinatus	2	Cable Seated Front Lateral Raise	88%	1%	
	-	Elevation with TheraBand	97%	0%	0.004
	2.5	Dumbbell Lateral Raise	98%	0%	0.004
Infraspinatus + teres minor	2	Cable Seated Shoulder External Rotation	91%	0%	
	1	Dumbbell Seated Shoulder External Rotation	93%	1%	0.051
	-	Elevation with TheraBand	97%	0%	0.001
	body	Inverted row (small amplitude)	97%	1%	0.004
Subscapularis	2.5	Dumbbell Seated Shoulder External Rotation on the Floor	92%	1%	
	-	Internal Rotation with TheraBand	95%	1%	0.009
	4	Cable Standing Shoulder Internal Rotation	97%	1%	0.015
Biceps	8	Cable Curl	97%	0%	
	2.5	Dumbbell Curl	97%	0%	0.035
	body	Chin Up	101%	2%	0.043
Triceps	2	Cable Bent-over Triceps Extension	83%	2%	
	1	Dumbbell Kick Back	103%	1%	0.002
	body	Bench Dip	-	-	-
Latissimus dorsi	2.5	Dumbbell Lying Row	100%	1%	
	4	Cable Standing Row	103%	1%	0.088
Superior trapezius	-	Up Shoulder with TheraBand	102%	1%	
	2.5	Dumbbell Shrug	103%	0%	0.079
Middle + inferior trapezius	body	Inverted Row (large amplitude)	96%	2%	
	2.5	Dumbbell Bent-over Row	102%	0%	0.023

	4	Cable Rowing	103%	1%	0.032
Pectoralis	2.5	Push-up Dumbbell Bench Press	98%	1%	
	body	Push-up	99%	0%	0.041
Serratus	2.5	Dumbbell Incline Shoulder Raise	81%	1%	
	2	Cable Incline Shoulder Raise	95%	2%	0.004
	body	Incline Push-up	100%	0%	0.001

* Data are reported for the participant performing three trials for each exercise

[**] Percentage > 100% means that the muscle is elongated, otherwise it is compressed during motion

[†] *P* values obtained with use of Student's *t*-test

Table S7: Peak length variation (%) of the supraspinatus muscle for each exercise (n = 3)*. Exercises are classified according to their impact on the joint.

Muscle trained	**Weight (kg)**	**Exercise**	**Mean****	**SD**	***P* value**†
Deltoid	10	Cable Bar Upright Row	88%	1%	
	-	Elevation with TheraBand	91%	0%	0.056
	2.5	Dumbbell Lying Rear Delt Row	100%	1%	0.001
Supraspinatus	2	Cable Seated Front Lateral Raise	83%	1%	
	-	Elevation with TheraBand	91%	0%	0.001
	2.5	Dumbbell Lateral Raise	94%	0%	0.001
Infraspinatus + teres minor	2	Cable Seated Shoulder External Rotation	88%	1%	
	1	Dumbbell Seated Shoulder External Rotation	89%	0%	0.062
	-	Elevation with TheraBand	91%	0%	0.009
	body	Inverted row (small amplitude)	92%	1%	0.008
Subscapularis	2.5	Dumbbell Seated Shoulder External Rotation on the Floor	87%	1%	
	4	Cable Standing Shoulder Internal Rotation	91%	0%	0.006
	-	Internal Rotation with TheraBand	92%	1%	0.009
Biceps	8	Cable Curl	91%	0%	
	2.5	Dumbbell Curl	92%	1%	0.013
	body	Chin Up	100%	1%	0.007
Triceps	2	Cable Bent-over Triceps Extension	77%	1%	
	1	Dumbbell Kick Back	97%	1%	0.001
	body	Bench Dip	-	-	-
Latissimus dorsi	2.5	Dumbbell Lying Row	95%	1%	
	4	Cable Standing Row	99%	1%	0.077
Superior trapezius	-	Up Shoulder with TheraBand	96%	0%	
	2.5	Dumbbell Shrug	97%	0%	0.075
Middle + inferior trapezius	4	Cable Rowing	96%	1%	
	2.5	Dumbbell Bent-over Row	97%	1%	0.518

	body	Inverted Row (large amplitude)	-	-	-
Pectoralis	2.5	Push-up Dumbbell Bench Press	97%	2%	
	body	Push-up	-	-	-
Serratus	2.5	Dumbbell Incline Shoulder Raise	74%	1%	
	2	Cable Incline Shoulder Raise	91%	3%	0.010
	body	Incline Push-up	-	-	-

* Data are reported for the participant performing three trials for each exercise
[**] Percentage > 100% means that the muscle is elongated, otherwise it is compressed during motion
[†] *P* values obtained with use of Student’s *t*-test

Table S8: Peak length variation (%) of the teres minor muscle for each exercise (n = 3)*. Exercises are classified according to their impact on the joint.

Muscle trained	**Weight (kg)**	**Exercise**	**Mean****	**SD**	***P* value†**
Deltoid	-	Elevation with TheraBand	121%	1%	
	2.5	Dumbbell Lying Rear Delt Row	125%	1%	0.044
	10	Cable Bar Upright Row	135%	1%	0.001
Supraspinatus	2.5	Dumbbell Lateral Raise	120%	2%	
	-	Elevation with TheraBand	121%	1%	0.430
	2	Cable Seated Front Lateral Raise	128%	2%	0.061
Infraspinatus + teres minor	body	Inverted row (small amplitude)	117%	1%	
	-	Elevation with TheraBand	121%	1%	0.007
	2	Cable Seated Shoulder External Rotation	122%	1%	0.003
	1	Dumbbell Seated Shoulder External Rotation	127%	1%	0.005
Subscapularis	4	Cable Standing Shoulder Internal Rotation	120%	1%	
	-	Internal Rotation with TheraBand	122%	1%	0.133
	2.5	Dumbbell Seated Shoulder External Rotation on the Floor	123%	0%	0.058
Biceps	2.5	Dumbbell Curl	117%	0%	
	8	Cable Curl	118%	0%	0.002
	body	Chin Up	119%	1%	0.075
Triceps	1	Dumbbell Kick Back	118%	1%	
	2	Cable Bent-over Triceps Extension	122%	0%	0.013
	body	Bench Dip	129%	2%	0.006
Latissimus dorsi	4	Cable Standing Row	119%	3%	
	2.5	Dumbbell Lying Row	120%	1%	0.590
Superior trapezius	2.5	Dumbbell Shrug	116%	0%	
	-	Up Shoulder with TheraBand	119%	1%	0.013
Middle + inferior trapezius	body	Inverted Row (large amplitude)	122%	2%	
	2.5	Dumbbell Bent-over Row	123%	1%	0.816

	4	Cable Rowing	131%	2%	0.060
Pectoralis	2.5	Push-up Dumbbell Bench Press	119%	1%	
	body	Push-up	135%	2%	0.006
Serratus	2	Cable Incline Shoulder Raise	124%	3%	
	2.5	Dumbbell Incline Shoulder Raise	128%	1%	0.149
	body	Incline Push-up	135%	1%	0.013

[*] Data are reported for the participant performing three trials for each exercise

[**] Percentage > 100% means that the muscle is elongated, otherwise it is compressed during motion

[†] *P* values obtained with use of Student’s *t*-test