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# Mechanical risk of rotator cuff repair failure during passive movements: A simulation-based study

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ABSTRACT

*Background:* Despite improvements in rotator cuff surgery techniques, re-tear rate remains above 20% and increases with tear severity. Mechanical stresses to failure of repaired tendons have been reported. While optimal immobilization postures were proposed to minimize this stress, post-operative rehabilitation protocols have never been assessed with respect to these values. Purpose was to use musculoskeletal simulation to predict when the stress in repaired tendons exceeds safety limits during passive movements. Hence, guidelines could be provided towards safer post-operative exercises.

*Methods:* Sixteen healthy participants volunteered in passive three-dimensional shoulder range-of-motion and passive rehabilitation exercises assessment. Stress in all rotator cuff tendons was predicted during each movement by means of a musculoskeletal model using simulations with different type and size of tears. Safety stress thresholds were defined based on repaired tendon loads to failure reported in the literature and used to discriminate safe from unsafe ranges-of-motion.

*Findings:* Increased tear size and multiple tendons tear decreased safe range-of-motion. Mostly, glenohumeral elevations below 38°, above 65°, or performed with the arm held in internal rotation cause excessive stresses in most types and sizes of injury during abduction, scaption or flexion. Larger safe amplitudes of elevation are found in scapular plane for supraspinatus alone, supraspinatus plus infraspinatus, and supraspinatus plus subscapularis tears.

*Interpretation:* This study reinforces that passive early rehabilitation exercises could contribute to re-tear due to excessive stresses. Recommendations arising from this study, for instance to keep the arm externally rotated during elevation in case of supraspinatus or supraspinatus plus infraspinatus tear, could help prevent re-tear.

## 1. Introduction

Despite improvements in rotator cuff surgery techniques, re-tear rate remains above 20% and increases with tear severity (Choi et al., 2012; Hayashida et al., 2012; Parsons et al., 2010; Rotini et al., 2011). Consequently, improved rehabilitation following surgery may contribute to decrease re-tear rate. Since functional outcomes expressing repair integrity were found to decrease after complete immobilization (Arndt et al., 2012; Galatz et al., 2004), early mobilization with passive movements have been recommended (Chang et al., 2014; Millett et al., 2006). However, such protocols can also increase the risk of re-tear (Miller et al., 2011). While optimization of immobilization poses based on mechanical estimation was addressed (Jackson et al., 2013), design of early rehabilitation protocols still relies on empirical observations (Lee et al., 2012). Shea et al. (2012) showed that acute stress experienced by the tendons during movement directly relates to repair failure by applying various loads on repaired cadaveric cuff tendons. Therefore, the lack of evidence that the stress experienced by the healing tendons is held within safe limits may explain this increased risk. An investigation of the mechanical stress in the rotator cuff tendons during rehabilitation exercises related to tear characteristics is then required.

In fact, rehabilitation protocols aim at restoring maximal post-operative shoulder function while minimizing stress in the repaired tendons (Brislin et al., 2007; Lee et al., 2012; Plessis et al., 2011). Therefore, the level of muscle activation, the orientation of the arm, and the movement amplitude during exercises are determinant. Exercises with maximal range-of-motion such as internal and external rotations or elevations in the planes of flexion, abduction and scaption (i.e. in the scapular plane) are often reported in rehabilitation and evaluation protocols (Constant and Murley, 1987; Murphy et al., 2013; Richards et al., 1994). Pendulum exercises (Keener et al., 2010) or scapular

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retractions (McMullen and Uhl, 2000) are also found in a few studies. Among those, external rotations in supine position and various elevations were recommended after a supraspinatus repair (Gimbel et al., 2007; Murphy et al., 2013). Inversely, all exercises and mostly scapular retraction were shown to dangerously activate infraspinatus or supraspinatus (Murphy et al., 2013). Rehabilitation protocols are commonly composed of passive range-of-motion exercises, but no consensus about safe movements guidelines, such as the amplitude and direction, is defined yet (Millett et al., 2006; Murphy et al., 2013). Optimal rehabilitation guidelines that allow maximal joint mobility with minimal stress in the tendon have been addressed (Ghodadra et al., 2009; Jackson et al., 2013), but there is still no consensus for rehabilitation exercises that would best manage both healing and functional objectives. An evaluation of rehabilitation exercises based on passive muscle stress estimation seems appropriate to define amplitude of movement not at risk for repair safety.

Muscle stress cannot be assessed during in-vivo exercises using non-invasive methods. Thus, rehabilitation protocol evaluation is usually limited to functional outcomes comparisons (Arndt et al., 2012; Lee et al., 2012). Such an approach is neither immediate nor preventive. From a mechanical point of view, tendon force and consequently tendon stress increase with both passive muscle forces augmentation (depending on joint configuration that modifies the length of the muscle–tendon unit) (Tsianos and Loeb, 2014) and active muscle forces increase related to muscle activity (Kuriki and Takahashi, 2012). Then, limitation of active motion for six weeks following surgery reduces the risk for failure (Anderson et al., 2002; Lee et al., 2012) by keeping the stress in the healing tendon as low as possible for any given position. Along this perspective, Murphy et al. (2013) evaluated the rotator cuff muscle activity during rehabilitation exercises using fine wire electromyography (Murphy et al., 2013). However, electromyography is insufficient to estimate the total stress applied to the tendon especially its component due to passive muscle–tendon lengthening. Musculoskeletal models based on Hill-type muscle can include the passive tendon and muscle components to better estimate this passive stress during passive movement. In fact, a similar approach was used to predict in vivo stresses in the patellar cartilage during strengthening exercises (Besier et al., 2005; Cohen et al., 2001). Furthermore in comparison with longitudinal studies, simulation is a fast and convenient way to control and test injury related variables such as tear type and size. Consequently, musculoskeletal models coupled with forward kinematic simulation seem a promising alternative to evaluate passive rehabilitation protocols risk based on a tendon stress prediction (Saul et al., 2011).

In addition to peak stress (Ma et al., 2006; Shea et al., 2012), surgery technique (Burkhart et al., 2001; Ma et al., 2006), tear type (Collin et al., 2014; Nho et al., 2009; Yoo et al., 2014), and tear size (Burkhart et al., 2001), are also related to risk of re-tear. The type of tear depends on the nature and number of torn rotator cuff tendons. The tear size is defined by the length of tendon avulsion during surgery. To the best of our knowledge, no study has investigated the effects of rehabilitation guidelines and tear characteristics (i.e. repaired tendon and tear size) on tendon stress during movement (Ross et al., 2014). Therefore, the purpose of this study was to investigate the effect of arm position during passive mobilization on rotator cuff tendon stress after different type and size of tendon tears. For this purpose, safety space of movement was defined and used to test common rehabilitation exercises for mechanical risk. Further to the evaluation of rotator cuff activation during rehabilitation exercises using electromyography from Murphy et al. (2013), the present study uses musculoskeletal simulation to set apart safe and unsafe exercises considered to be performed passively. Since repair failure loads were shown to vary greatly according to the technique of the repair, results will be generated for three thresholds that correspond to distinctive single row techniques for which we know stresses to failure values. Namely those techniques were the simple technique made of two stitches, the arthroscopic technique consisting in a mini-open surgery, and the massive technique with increased number of stitches (Ma et al., 2006). Increased tear size is mainly expected to reduce safe range of elevation. Inversely, number and nature of repaired tendons are expected to mainly influence the amplitude and direction of movement safe for early rehabilitation.

## 2. Methods

### *2.1. Participants and kinematical procedure*

Eight male and eight female right handed healthy subjects (age 24 years, SD 4; height 171 cm, SD 10; body mass 69 kg, SD 11) without history of shoulder pain or injury volunteered after giving their informed consent. The protocol was approved by the local University ethics committee (CÉRSS-2010-1013-P). Prior to the test, in line with a combination of Jackson et al. (2012) and Fohanno et al. (2013) models, 43 skin reflective markers were placed on the pelvis (4 markers), thorax (6), right clavicle (6), scapula (8), humerus (7), forearm (8) and hand (4). Each participant performed six setup trials for locating pelvothoracic, sternoclavicular, acromioclavicular, glenohumeral, elbow and wrist joint and/or axis center.

Subjects were manipulated through a passive protocol composed of seven range-of-motion trials describing three-dimensional (3D) shoulder space of movement as fully described in Haering et al. (2014). In each trial, the arm was moved through maximal elevations in one of seven planes distributed between end range external and internal planes of elevation (Fig. 1a) with maximum internal and external rotations performed at every 30° of elevation (Fig. 1b). The elbow was maintained in 90° flexion during this protocol. In addition, passive rehabilitation exercises as elevations in planes of flexion, scaption and abduction at constant low speed (max. 36° $s^{-1}$) were performed (Constant and Murley, 1987; Murphy et al., 2013; Richards et al., 1994). Each subject was manipulated by one of two operators through the entire protocol. Each trial was recorded by an 18-camera VICON system at 150 Hz.

A kinematical model with a closed loop at the scapulothoracic pseudo-joint including pelvis, thorax, clavicle, scapula, humerus, forearm and hand was personalized using SCoRE and SARA algorithms for locating joint centers and axis based on setup trial (Ehrig et al., 2011; O'Brien et al., 2000). A nonlinear least squares algorithm was used to reconstruct 3D angular joint kinematics for both passive range-of-motion trials and passive rehabilitation exercises (Laitenberger, 2013). Plane of elevation, elevation and axial rotation angles for the glenohumeral and thoracohumeral joints were both extracted for further analyses in this study following the ISB angle sequence recommendation (Wu et al., 2005) with corrected axial rotation for easier understanding (Haering et al., 2014; Phadke et al., 2011). Before computation of average safety spaces of movement for several types and sizes of tears, an average 3D passive space of movement was obtained from the range-of-motions trials encompassing all recorded glenohumeral angle–angle–angle poses (Haering et al., 2014).

### *2.2. Musculoskeletal model*

A musculoskeletal model (Anybody© T/S, Aalborg, Denmark) of the rotator cuff was implemented with segmental parameters and rotator cuff muscle origin/insertions from the Delft shoulder model (Van der Helm et al., 1992). It includes humerus and scapula, and the four rotator cuff muscles namely, subscapularis, supraspinatus, infraspinatus and teres minor (Fig. 2). Three degrees-of-freedom (DoFs) in rotation defined the glenohumeral joint (Fig. 2a). Each muscle is represented by six paths modeled by Hill-type muscle–tendon actuators based on Langenderfer et al. (2004) muscle properties. Anybody's muscle lengths were also adjusted accordingly. As muscle physiological functional lengths are supposed to vary between 0.5 and 1.5 times their optimal