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EDUCATION & TRAINING

Analysis and Fem Simulation Methodology of Dynamic Behavior of Human Rotator Cuff in Repetitive Routines: Musician Case Study

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Abstract

The majority of musculoskeletal injuries located in the shoulder are often due to repetitive or sustained movements that occur in work routines in different areas. In the case of musicians, such as violinists, who have long and daily training routines, the repetitive movements they perform are forced and sometimes the postures are not natural. Therefore, this article aims to study and simulate the dynamic behavior of the glenohumeral joint under repetitive conditions that represent the different postures assumed by a violinist during his daily training. For this purpose, the criteria provided by the RULA (rapid upper limb assessment) method have been used. Subsequently, by using as a reference geometry that of the articulation under study generated and modeled in CATIA®[VERSIÓN 5R21], a FEM analysis has been proposed with the software ANSYS®[VERSIÓN 17.1] simulating the short and cyclic movements of the Humerus of the violinists. With the analysis carried out, thanks to linear and isotropic approximations of the joint, it has been possible to know the approximate dynamic behavior of tissues, muscles and tendons, and the response of the joint in terms of fatigue.

Keywords Musician · FEM analysis · Humerus · Rotator cuff · RULA criteria

This article is part of the Topical Collection on *Education & Training*

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Introduction

The shoulder represents the most unstable and susceptible to injury joint in the human body for its high mobility [1]. In most cases this is due to excessive use of the joint and bad postures in repetitive routines [2–5]. Thanks to the action of the muscles, ligaments and tendons of the rotator cuff (Fig. 2) this type of instability is compensated allowing all kinds of movements [6, 7]. The functional unit of the shoulder includes the proximal humerus, the clavicle and the scapula, and their connections to each other, in addition to the sternum and the rib cage (Fig. 1). Together these elements form the following joints:

- The scapulohumeral or glenohumeral joint (Diarthrosis enarthrosis or spheroidea). It joins the Humerus with the scapula.
- The sternocostoclavicular joint (Diartrosis). It joins the sternum and first rib with the clavicle.
- The acromioclavicular joint (Diarthrosis arthrodes). It links the acromion to the clavicle.

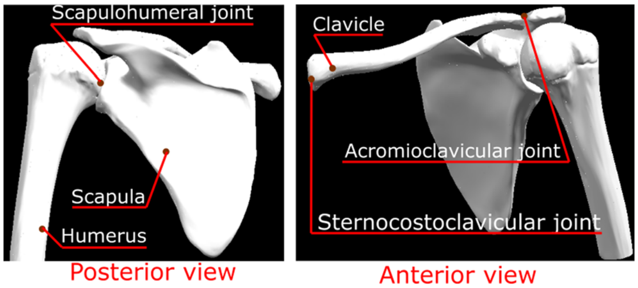

Fig. 1 Shoulder joint

- The omoserratothoracic joint, whose articular surfaces are muscles.

Together these joints allow the upper extremity to rotate up to 180^0 in three different planes. This allows the arm to perform a variety of versatile activities.

The correct knowledge of this articulation is important for those people who carry out repetitive movements. For example, musicians such as violinists who train the shoulder daily and who with excessive use of the instrument leave the shoulder joint susceptible to muscle and nervous lesions, muscular pains, contractures and also structural disorders in the back, neck, arms and hands [8, 9]. The musculoskeletal problems most frequently observed in musicians are: overuse (50%), nerve compression or thoracic outlet syndrome (20%), focal dystonia (10%) [10]. The initial symptoms that often appear are pain, in about 85% of cases, burning sensation, tiredness or heavy limb in one or more parts of the body, and may arise even after a short period of activity [11, 12]. Heming [13] in his study of 107 musicians aged between 16 and 72 years has found that 70% had suffered an injury related to the instrument. Women (72%) and stringed instrument musicians (77%) showed a higher prevalence, together with professional teachers (57%) who harbored the majority of injuries. The absence of pathologies in beginner musicians, in his study, suggests that the most influential risk factor is strongly related to the increase in the use time of the instrument and to the frequency of training. According to recent studies, 25% of orchestra musicians suffer to some pathology as pain in the neck and shoulder. The 35.3% are violinists. It is due to the complex posture of the arms and neck and who usually practice more than 3 h per day [14]. The glenohumeral joint of the shoulder is composed mainly of bones such as scapula (glenoid cavity) and Humerus (humerus head), articular cartilage, and the muscle complex called the rotator cuff. It is formed by the follow muscles:

- Supraspinatus. It is located in the upper area of the shoulder joint; it protects the deltoid muscle from the movement of separation (abduction) of the arm(Fig. 2a).
- Infraspinatus. Its function is to allow the external rotation of the arm (Fig. 2b).
- Subscapular. Its function is to allow the internal rotation of the arm (Fig. 2c).
- Teres minor. Its function is to allow backward stretching, external rotation, bring the arms towards the body (adduction) (Fig. 2d).

The function of the rotator cuff is to provide stability at the moment of generating combined movements of: abduction-adduction or flexion-extension with internal and external rotation.

Tendinitis, tendinosis, entrapment syndrome or impingement on the supraspinatus muscle are the most frequently present disorders in the shoulder in the case of the right

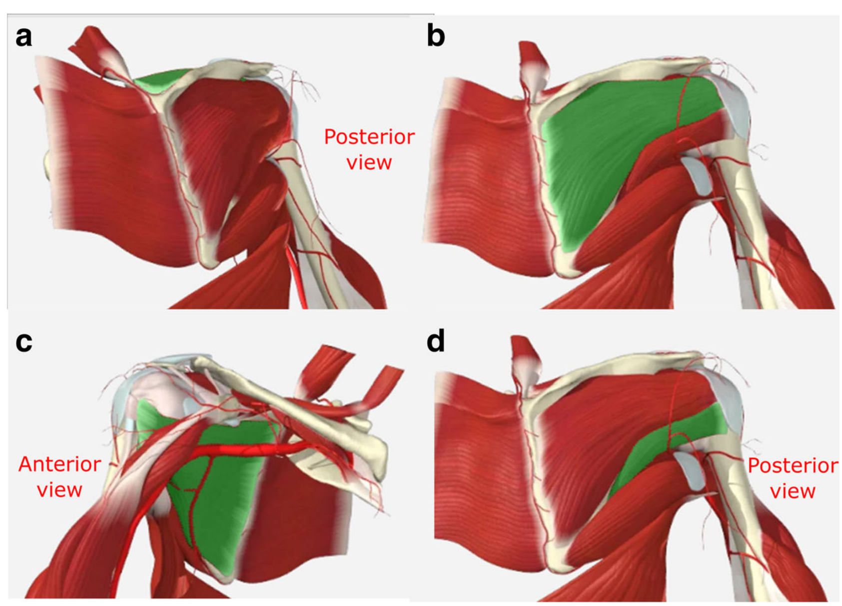

Fig. 2 Rotator cuff muscles in green color: **a** supraspinatus; **b** infraspinatus; **c** subscapular; **d** teres minor

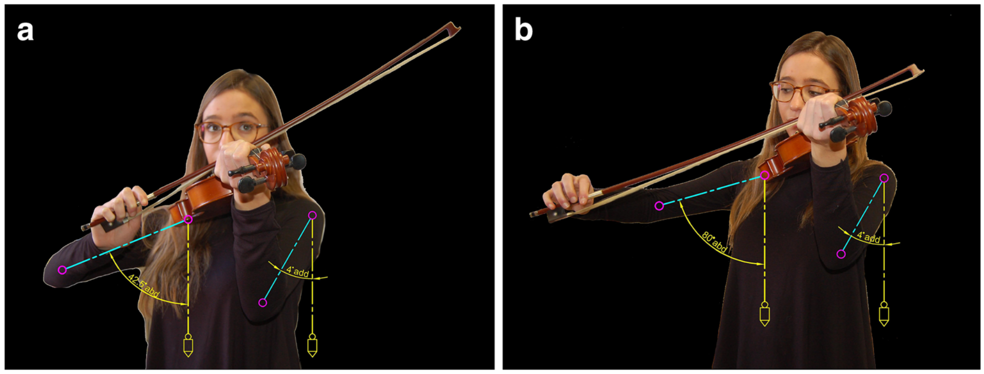

Fig. 3 **a** Right arm with abduction angles of 42.5 degrees. **b** Right arm with abduction angle of 80 degrees

shoulder of the violin and flute players, when there are prolonged positions of abduction or static flexion of the forearm [15]. In the left shoulder there is flexion and sometimes adduction resulting in a rotator cuff friction phenomenon produced for poor blood supply and due to the compression effect of the supraspinatus tendon. For this reason, the strengthening of external rotators and stabilization of the tendon deserves additional attention, such as treatment or prevention [16].

In recent years, the use of FEM simulations has made it possible to improve the characteristics of industrial production processes [17, 18] and the materials used, especially in the medical field [19–23], as well as the studies conducted to simulate the dynamic behavior of human joints [24–26]. For these reasons, in this work models based on usual shoulder positions held by violinists during their practice will be developed and analyzed, considering the role of the rotator cuff in the glenohumeral joint. The representative positions have been obtained from the observation of the position assumed by the arms throughout a routine [27–29]. It has been possible to recreate the selected positions and measure their risk index under the RULA criterion with the help of CATIA®[VERSION 5R21] design software. The RULA method was developed in 1993 by McAtamney and Corlett, (Nottingham University) in order to evaluate individual postures of the upper limbs of the body [30]. The next step was to generate the 3D-models of the articulation maintaining the representative positions of the case under study. Finally, the behavior of the glenohumeral joint and the rotator cuff was simulated considering the effects of gravity and assuming the properties of the materials as linear and isotropic. The developed FEM simulations show the results of the safety factor in a different number of cycles. The observation of their behavior under fatigue and the increase in the number of cycles have allowed to know where the first faults can occur and also how many cycles of repetitive movements are required. The used software provides simulations in order to evaluate the fatigue of the materials, by defining a short cycle internal rotation of the humerus from the positions described above. It is estimated that there is a type of short movement of the rotating humerus maintained by the violinists when performing a long rotation of the elbow and that occurs for each bow or "bow stroke".

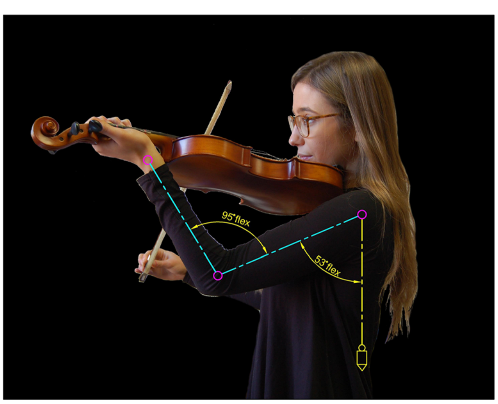

Fig. 4 Flexion angle at 53 degrees of the left arm of the violinist

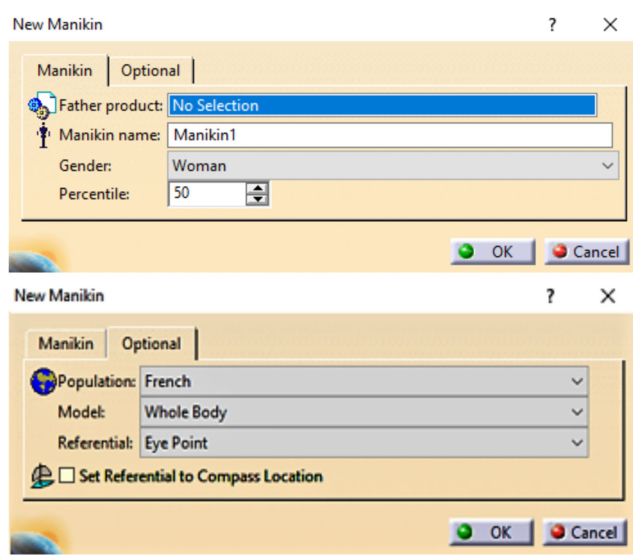

Fig. 5 Ergonomics Tool window of CATIA®

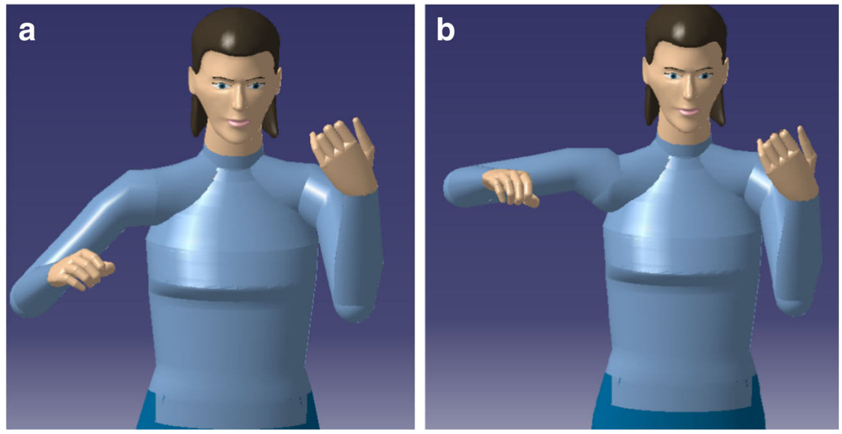

Fig. 6 Flexion angle position of 53 degrees for the left arm and Abduction angle position for the right arm of: **a** 42.5 degrees; **b** 80 degrees

Materials and Methods

RULA Analysis

The most representative postural gestures have been extracted from the sonata performed by a professional violinist woman of 24 years hold. The movements, considered extreme in terms of flexion and abduction, that represent the position of the violinist have been measured in CATIA® in terms of angles. An observational, indirect and digital measurement method is functional and is used for the ergonomic evaluation of the postures [27]. Two positions have been obtained for the "mobile" right arm and one for the "fixed" left arm. The violinist's right arm is in abduction, while his left arm is in flexion. Measuring the minimum and maximum space between a vertical line that assumes the vertical position of the body and the line parallel to the posture of the arms in both situations, the angle of abduction is obtained. In this study, the result of the measurement for the right arm, when the violinist assumes the two positions of abduction shown in Fig. 3, has been 42.5^0 and 80^0. The positions shown in Fig. 3 are the upper and lower limits of the range of abduction movement performed by the arm during this particular practice.

An almost constant position for the left arm can be assumed, with the exception of the movements made with the fingers and the wrist (Fig. 4). The same method is also used to size the flexion angle assumed by the violinist's left arm during execution. It is considered a vertical line that represents the upright posture of the body. This line, together with the lines parallel to the profile of the left arm, helps to define the flexion angle of the shoulder and of the elbow. As a result, the left arm has a flexion position of 53^0 with respect to the body (Fig. 4), with an elbow flexion of the 95.8^0 with respect to the forearm and an adduction of 4^0 of the elbow with respect to the shoulder (Fig. 3).

Two possible complete postures, once obtained the abduction limits of the right arm and the fixed position of flexion of the left arm, have been analyzed. These postures are generated in CATIA® by using "Ergonomics Design and Analysis" tool. This tool offers the possibility of creating mannequins with human morphology and interacting with them to simulate daily human activities. As a reference avatar,

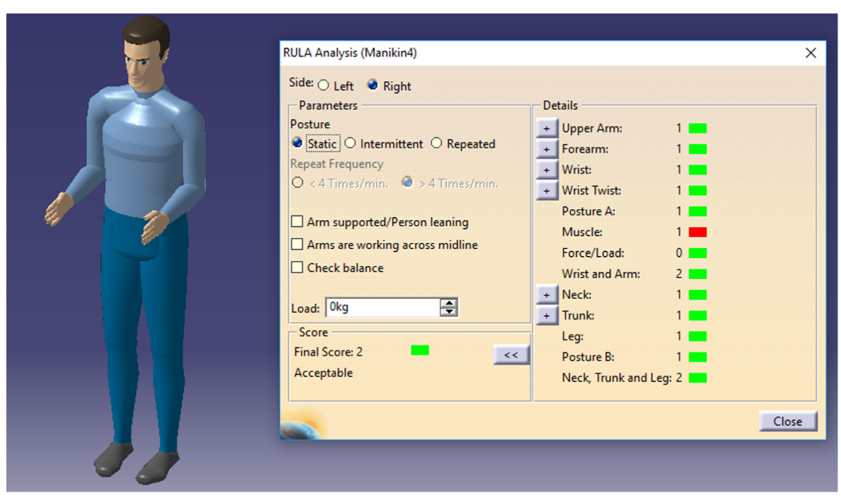

Fig. 7 Result of RULA analysis on a resting position

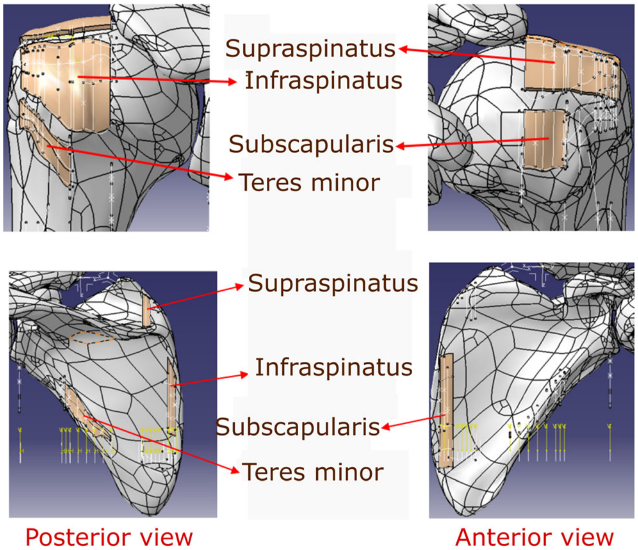

Fig. 8 Models of tendons

a human body of a Caucasian woman belonging to the 50th percentile of the population was created (Fig. 5).

Figure 6 shows the two obtained positions.

The left arm is placed with a flexion of 53^0 and 4^0 of adduction of the shoulder and with a flexion of 95^0 for the elbow, as obtained from Fig. 4. In Fig. 6a, the right arm is positioned with an abduction of 42.5^0, and in Fig. 6b with an abduction of 80^0. Once the postures have been created it has been possible to perform a RULA analysis for each one of them. Assuming that the right arm of the body performs the described abduction postures more than 4 times per minute (common routine for a violinist). The RULA analysis results show by means of a numerical category the levels of action that must be taken on said position. Scores between 1 and 2 indicate that the risk of the task is acceptable and that no changes are necessary, between 3 and 4 indicate that a deeper study of the position is necessary because changes may be required, between 5 and 6 indicate that the changes are necessary and finally 7 indicates that the changes are urgent. Figure 7 shows the result of the RULA analysis on a resting position where the values are all between 1 and 2.

3D Model

The glenohumeral joint is composed of different sets of tissues such as: bones, ligaments, cartilages, synovial fluid bags, tendons and muscles. In this study the dynamic behavior of those tissues directly related to the support, at the level of efforts, of the joint (bones, tendons and muscles) have been simulated. Using 3D-Builder, a platform that allows to soften textures, to scale, to measure and to cut with some ease, the file with

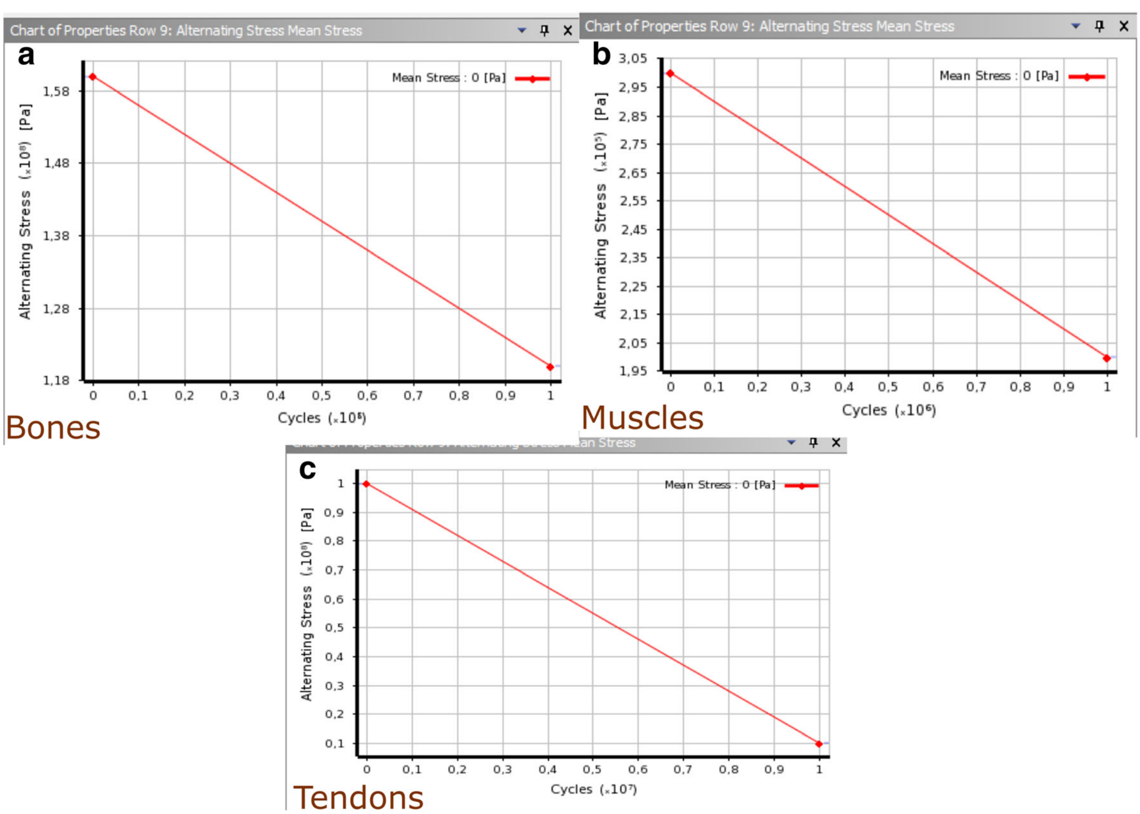

Fig. 9 Material Properties and material behaviors for: **a** Bones, **b** Muscles, **c** Tendons

Table 1 Material properties for the bones, muscles and tendons

	Bones	Muscles	Tendons
Density [kg mm^{-3}]	1,79E-06	1,35E-06	1,35E-06
Isotropic Elasticity			
Derive from	Young's modulus	Young's modulus	Young's modulus
Young's Modulus [MPa]	17200	0,16	2000
Poisson's Ratio	0,41	0,43	0,43
Bulk Modulus [MPa]	31852	0,38095	4761,9
Shear Modulus [MPa]	6099,3	0,055944	699,3
Tensile Yield Strength [MPa]	120	0,1	50
Tensile Ultimate Strength [MPa]	160	0,3	100

extension *.stl has been imported from 3D-scanning of the bony surfaces that make up the shoulder. The first step was to adjust the size of reconstructed bones taking into account the size ratio of the humeral head that depend on sex, age and race. For the case under study, the work of G. R. Milner has been taken into account, which has estimated the average value of the humeral head diameter, in the case of a Caucasian woman from Crete, of 41.2 mm [31]. Once the bones have been obtained in real scale and through a texture smoothing process, the three *.stl files are exported in the CATIA® software. Under the recommendations of Rockwood [32], it has been possible to develop and to locate the tendons in the 3D-model. Once the tendons have been obtained it has been possible to generate the muscles. The result has been a 3D-model of joints consisting of two bones, 4 muscles and 8 tendons (Fig. 8).

In order to guarantee the actual position for the Humerus in the 3D-model, an auxiliary sketch and feature restrictions have been used. These restrictions represent the abduction degree or amplitude of flexion between the humerus and the body. All models have been generated in the required positions and imported in ANSYS®.

Materials

Taking into account the CES-Edupack database® [33] and recent works [6–8, 34] it has been possible to evaluate the properties of the tissues (Fig. 9 and Table 1).

The fatigue behavior of the tendons has been evaluated considering the value in percentage of Ultimate Tensile Strength for different amounts of cycles, by performing tests in vitro on human tendons [35]. Subsequently, it has been possible to generate in ANSYS the material behavior under fatigue conditions according to a linear approximation.

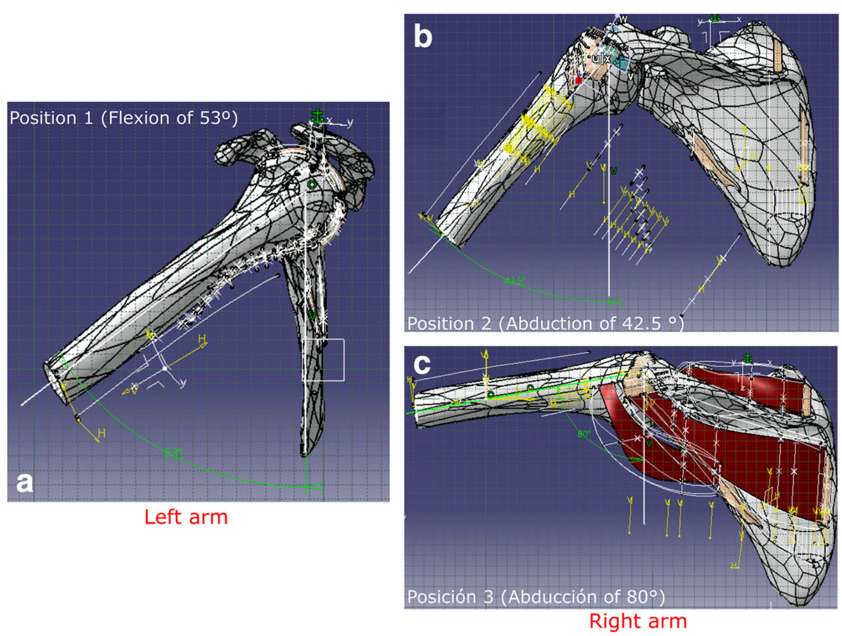

Fig. 10 Position of the left arm with a flexion angle of 53° and with a rotation angle of 4° of the elbow with respect to the shoulder (**a**). Position of the right arm with abduction of 42.5° (**b**) and 80° (**c**). CATIA®

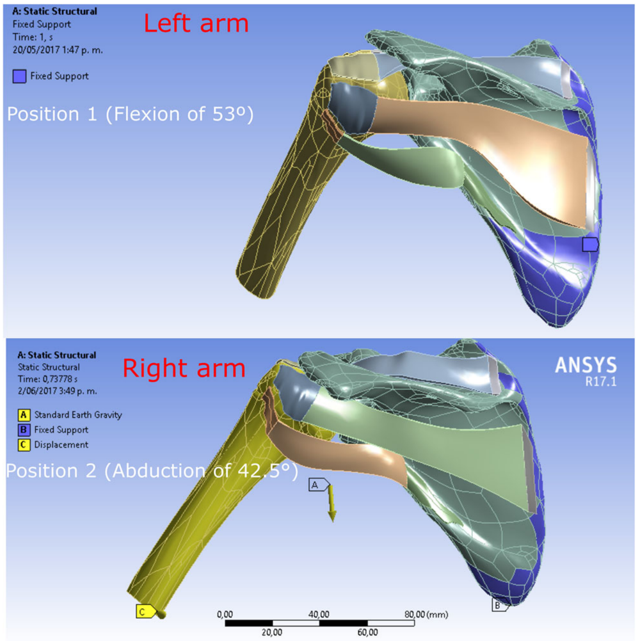

Fig. 11 Models for the ANSYS® simulation of the left arm

Results

From the RULA analysis it can be deduced that:

- The left hemisphere of the body suffers more and therefore is more at risk in its posture than the right in the two analyzed postures.
- In the position of Fig. 6b, when the maximum possible abduction is reached using only the arm without using the clavicle, it is when it is less exposed to injuries compared to the two evaluated positions.
- The results suggest that for the right hemisphere, attention must be paid because it may be that some change in technique is required to prevent injuries.

The results show that the highest risk is taken by the left arm in a position of sustained flexion with a score of 5. Follow the right arm in the case of a repetitive movement to reach the abduction position of 42.5^0 and of abduction of 80^0 with a score of 4. The analysis corroborates that violinists will have injuries when adopting this type of position. However, the analysis cannot locate what area or tissue of the shoulder in which it will occur. For this reason, in this study the dynamic behavior of the joint has been simulated, by using a 3Dmodel of the general shoulder morphology.

Figure 10 shows the positions obtained with the reconstruction in CATIA® of the shoulder joint for the left arm with a flexion of 53^0(a) and for the right arm with an abduction angle of 42.5^0(b) and 80^0(c). It is worth mentioning that all the images of the right shoulder in CATIA® and ANSYS® are made on a left shoulder model, but with the data of the right shoulder.

Figure 11 shows the models for the ANSYS® simulation of the left arm with a flexion of 53^0(a) and for the right arm with an abduction angle of 42.5^0(b).

The way in which the simulation software evaluates the fatigue in the different models is based on the evaluation of the behavior of the S-N material curves [35–37] and the Stress-Life criterion, by using the following equation:

$$\frac{\Delta\sigma}{2} = \sigma_f (2N_f)^b \quad (1)$$

$$\sigma_f = \textit{Fatigue strength coefficient } (\textit{Y intercept in SN curve})$$
$$b = \textit{Fatigue strength exponent } (\textit{slope of data in SNcurve})$$

Once the geometries and the starting positions have been generated, the properties of the aforementioned materials are assigned and the dynamic behavior of the shoulder is simulated at 10, 10800 and 50000 cycles. As the arc strike occurs in a time equal to 1 s, 10 cycles represent 10s, this means that 10800 cycles represent 3 h. This represents the estimated time of daily and continuous practice of a violinist.

Table 2 shows the results that relate the position to the critical risk zone.

Discussions

The results represent the time in which the area under study begins to show problems in order to continue resisting the conditions of cyclic loading. The approximations used in the

Table 2 Results of ANSYS simulation for right arm and for the left arm

Position (degrees)	Critical zone (Connection)	Minimum life cycle safety factor 1 (Cycles)	Time (Hours)
Flexion 53^0	Supraspinatus Muscle - Tendons Subscapular muscle-tendon Humerus	6218	1,7
Abduction $42,5^0$ with a rotation of 4° of the elbow with respect to the shoulder	Supraspinatus Muscle-Tendons Infraspinatus Muscle-Tendons	7617	2,1
Abduction 80^0	Teres Minor Muscle- Tendons	14903	4,14

simulation have not considered the variations in the abduction angle, in the cycle time and in the depth of the rotation that depend on the order of the musical notes that will be executed. These variables are difficult to quantify and probably will dilate the fatigue effect. These variations are important for the arm and elbow, but the shoulder will continue to have short and cyclical movements. The supraspinatus muscle is affected by both movements of flexion and abduction. Even when the movement has a great amplitude, (80^0 or 90^0), the musician can suffer the syndrome of entrapment (compression syndrome). Due to these results, it could be said that this connection with their respective tendons is the critical zone. Fatigue can manifest itself in a matter of hours due to unnatural, highly frequent or sustained positions.

The critical zones of the FEM simulation have been found in the flexion movements of 53^0 of the left shoulder, and in abduction of the right shoulder of 42.5^0 and 80^0 (Table 2).

The detected critical points are the origin of the supraspinatus, the origin and insertion of the infraspinatus and the insertion, origin and muscular belly of the teres minor for abduction of 42.5^0. This can be explained considering that the supraspinatus is the starter or initiator of abduction. It is fundamental in the first grades of abduction, but reaches its maximum efficiency and electromyographic activity around 90^0. The deltoid is its main synergistic muscle in the first time of abduction (up to 90^0), and it offers its effectiveness in the last stages of the abduction movement of this first time, so it collaborates when approaching 80°, not at the beginning [38]. Something similar happens with the long biceps [38].

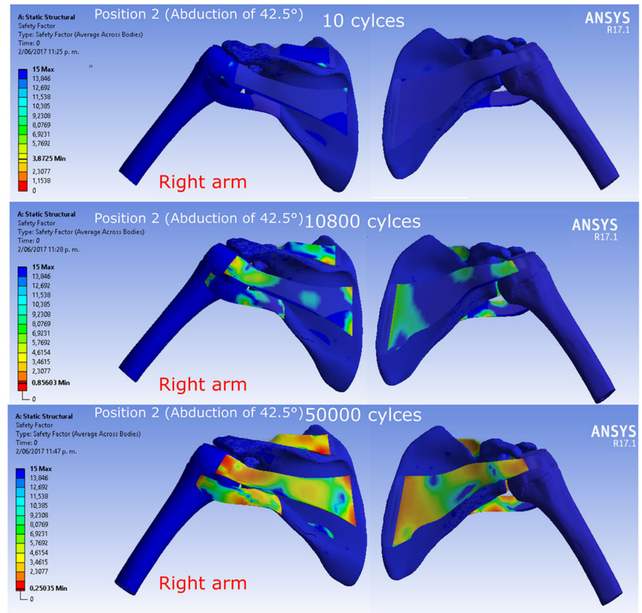

Fig. 13 Results of the fatigue simulation for 10, 10800 and 50000 cycles for the right arm with an Abduction angle of 42.5 degrees

The least fatigue was detected for an abduction of 80^0. In this case the critical points are the origin of the supraspinatus and the origin and insertion of the infraspinatus. This can be explained considering that the abduction of the arm to execute the technical movement of the violin is not a pure movement. It automatically carries with it a progressive flexion of the arm in which the biceps and the trapezius collaborate, and a

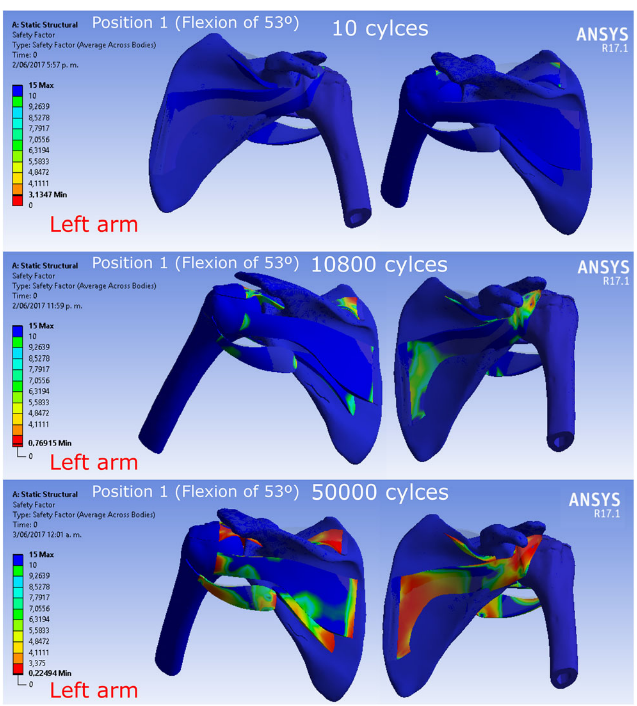

Fig. 12 Results of the fatigue simulation for 10, 10800 and 50000 cycles for the left arm with a flexion angle of 53 degrees and with a rotation of 4° of the elbow with respect to the shoulder

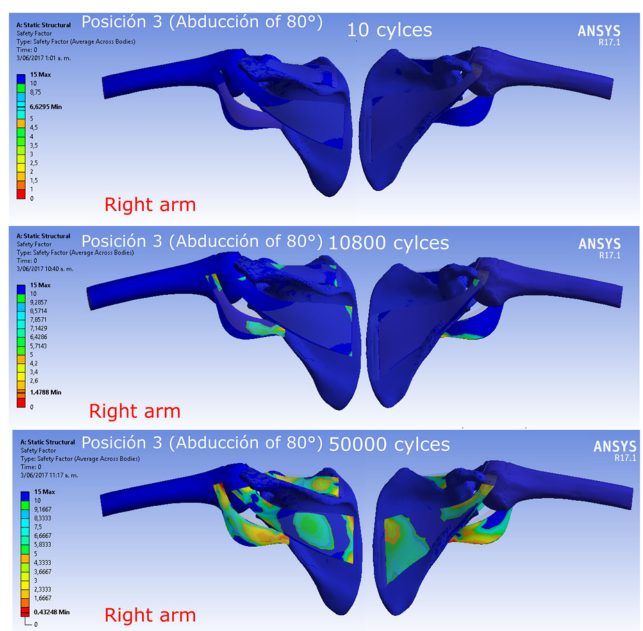

Fig. 14 Results of the fatigue simulation for 10, 10800 and 50000 cycles for the right arm with an Abduction angle of 80 degrees

simultaneous external rotation of the arm on its longitudinal axis (Codman Paradox) [38–40]. In addition to this, when the arm abduction approaches 90°, the supraspinatus tendon reaches the horizontal and achieves an anatomically favorable position (Figs. 12, 13 and 14). This is due to the insertion, the origin of the supraspinatus muscle and the start of the supraspinatus tendon are contained in a horizontal plane that favors its passage through the supraspinatus canal [38].

Conclusions

In this study the level of risk was evaluated, observing and measuring the representative positions of the routine of a musician playing the violin by performing a RULA analysis. Subsequently, thanks to the simulation in ANSYS it has been possible to predict, approximately, the number of cycles associated with a time of activity related to the routine for which a possible injury will be generated. This work has allowed to identify and locate the first joint fault. The results imply that this is the limit that the violinist can afford in order to practice continuously and that after this limit she will feel an increase in fatigue and pain. Future studies can be useful to determine an approximation of the life cycles of tissues by assuming a continuous rhythm for movement. However, they are living tissues that have associated a recovery rate that prolongs their useful life. The result should be taken as the pain threshold that the violinist will suffer when his safety factor is less than 1. Pain is the main signal that the body must feel before a possible injury. Also with the developed methodology of analysis and simulation it will be possible to extend the study to other joints and/or case of study where the subject performs repetitive movements or routines.

Compliance with Ethical Standards

Conflict of Interest Manuel Islan declares that she has no conflict of interest. Fernando Blaya declares that he has no conflict of interest. Pilar San Pedro declares that he has no conflict of interest. Roberto D'Amato declares that he has no conflict of interest. Emilio Lechosa Urquijo declares that he has no conflict of interest. Juan Antonio Juanes declares that he has no conflict of interest.

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

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