Visualization and Analysis of the Shoulder Joint Biomechanics in Postoperative Rehabilitation*

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Abstract. The research results in the field of computer visualization of the shoulder joint biomechanics are presented. The possibilities of using biomechanical robotic mechanotherapy on the CON-TREX training and diagnostic complex with biofeedback in the rehabilitation treatment of patients after arthroscopic shoulder surgery are shown. The possibilities of additional visualization of magnetic resonance imaging (MRI) data using spectral decomposition methods (shearlet transform and contrasting with color coding) are studied. Experiments with the use of the proposed diagnostic technique are described. The relationship between the MRI data and CON-TREX protocols in planning and implementing rehabilitation procedures is shown. The technique, which allows us to improve the quality and availability of MRI data in the study of the shoulder joint biomechanics during restorative treatment is described.

Keywords: Shoulder Joint, MRI Image, Robotic Mechanotherapy, CON-TREX, Biomechanics, Rehabilitation, Imaging, Image Analysis.

1 Introduction

The study of biomechanics of the musculoskeletal system is a fundamental scientific task in modern sports and rehabilitation medicine. The study of mathematical models of joint movements have created the prerequisites for research and development in this subject area [1-2].

It should be noted that injuries to the structures of the shoulder joint are quite common and account for 16 to 55% of all injuries of large joints. Changes in arthrokinematics with injuries of the shoulder joint depend on the nature and severity of the integrity changes of its structures. Premorbid conditions preceding their damage are actively modeled and investigated.

With the active development of minimally invasive surgical techniques, such as arthroscopy, a constant assessment of the effectiveness of their application and quality examination of the performed reconstructive interventions are required.

2 Methods of Studying Biomechanics

The existing anatomical and biomechanical concepts serve as the basis for clinical assessment methods, which allows the development of grounded and scientifically proved effective technologies and treatment programs for various dysfunctions of this joint [3-4]. Traditionally, biomechanics is focused on modeling aspects of the systemic level of the human body, for example, in the study of the musculoskeletal system. The study of mathematical models of movement has created the preconditions for a large number of scientific investigations and developments [5-7].

There are two main groups of diagnostic methods for studying biomechanics in medicine – kinesiological (muscle testing, dynamometry, myography) and radiation (X-ray, MRI and CT). The use of kinesiological and orthopedic testing with additional methods of radiation diagnostics has long been an integral part of any treatment process [8-9].

In the last 15 years video analysis of movements and virtual reality technologies have actively been used in biomechanics, allowing specialists to obtain a large amount of data on movement patterns and functional state of any segment. The study of locomotion through video analysis of movements have led to a number of new concepts for studying biomechanics of the musculoskeletal system (for example, the "concept of a floating skeleton") as well as to the emergence of a new direction – sanomechanics, which describes the mechanisms of self-healing in restoring previously disturbed movement [10-12].

It has also become possible to perform the 3D control of the effectiveness and individual selection of various types of exercises in the rehabilitation of patients without disturbing the kinematics of the joint [13-14]. This direction is actively complemented by the research of physiologists and kinesiologists, its results revealing many aspects of the functioning of muscle tissues in detail [15-16].

When studying the shoulder joint biomechanics, the interaction of its dynamic and static components is taken into account, which ensures its stability and functionality. The static components include the articular surfaces of the bones, negative intra-articular pressure, capsule-ligamentous apparatus of the joint as well as articular lip of the scapula. Muscles of the rotator cuff and other groups which provide its functional activity are considered to be dynamic [17].

Modern equipment for X-ray, MRI and CT studies is highly adaptable and accurate. However, sometimes these techniques can give false positive results about changes in the tissue structure, which can affect the diagnosis conclusion of a specialist. In this case, the goal of experimental studies is to minimize errors in diagnostics, increase accuracy and make interpretation of the results easier [18-20].

Experiments on the use of robotic mechanotherapy in postoperative rehabilitation of patients with shoulder joint injuries were carried out, where use was made of the kinesiological method of diagnostics during exercises on a training complex CON-TREX with biofeedback, supplemented by the method of radiation diagnostics i.e. magnetic resonance imaging [21].

In studying the experiment reports of the movements dynamics generated by the biofeedback system of the CON-TREX complex, visual data were represented using spectral decomposition methods (shearlet transformation technique and contrasting with color coding), which made it possible to increase the information content in relation to the arthrokinematics of the dynamic component of the shoulder joint [22].

The indicators of the CON-TREX protocols in dynamics reports are the following: power (W); torque (Nm); general work (J). An example of the data visualization in the reports on dynamics is shown in Fig. 1.

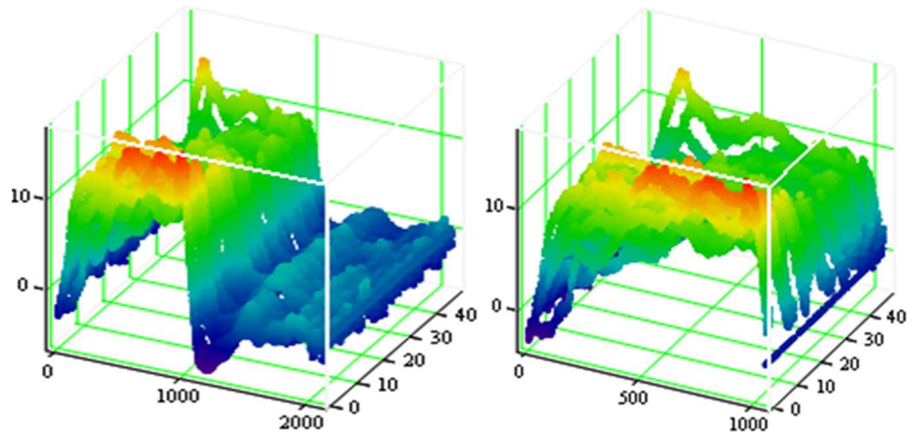

Fig. 1. Dynamic profiles of motion in the CON-TREX complex.

In order to conduct the study of shoulder joint arthrokinematics, methods of radiation diagnostics, radiography, CT or MRI of the joint with additional visualization are proposed for the static component, and dynamometry and kinesiological tests with the subsequent modeling of the data reported for the CON-TREX complex are suggested for the dynamic component .

3 Features of Visualization of MRI Images

In order to increase the information content of MRI images at the first stage the selection of typical model images from a specialized dataset is performed. Then, they are analyzed using the visualization technique described in [23-24].

The visualization technique is based on the algorithms of shearlet transformation and contrasting with color coding of the image [23-24], which as shown by experimental studies allows one to more clearly diagnose the area of acromio-tubercular conflict on the head in the humerus, as well as inflammation of the periarticular bursae in a patient. Better visualization with use of this technique in the case of a complete rupture of the muscle is also observed [25].

Moreover, as is shown by the most illustrative examples, this technique was applied on patients of the test group with the following diagnoses: rupture of the tendon of the supraspinatus muscle of the right shoulder joint, subacromial impingement syndrome, arthrosis of the acromioclavicular joint.

The analysis of a series of the MRI images of patients was performed. In particular, in a series of the images, the clarity of visualization of the supraspinatus tendon injury with the presence of inflammation near the lesion is improved due to the use of shearlet transform algorithms and color coding contrast. An example of the application of the proposed technique for visualizing MRI images is shown in Fig. 2.

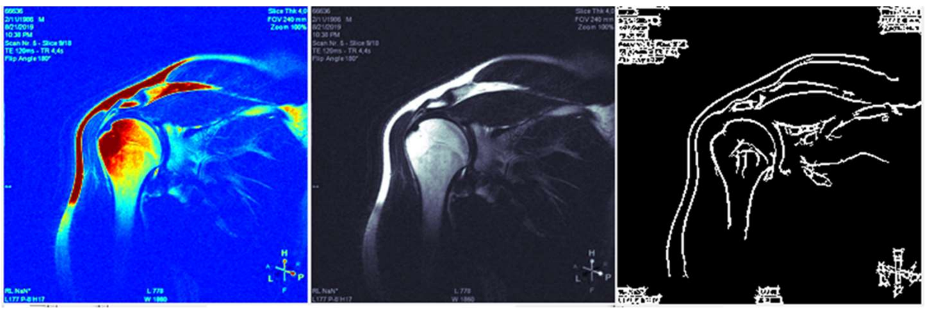

Fig. 2. An example of visualization of the MRI image processing by the shearlet transform and color coding.

The use of the technique in combination for assessing the dynamic and static components allows one to obtain the most complete picture of the functional model of the shoulder joint at any time, as well as quantitative assessments of the quality of rehabilitation for patients after reconstructive operations.

4 Results of Experimental Studies

The experimental study was carried out on the basis of the data of the FSSCC FMBA of Russia (Krasnoyarsk). An open, prospective, randomized study was carried out in two parallel groups with the formation of observation groups and the comparison was made between the clinical studies of individuals in the early and late recovery periods after surgical treatment of shoulder joint injuries using robotic mechanotherapy on the CON-TREX complex with biofeedback.

The study involved men and women aged 18–55 years in the early and late postoperative periods after arthroscopic surgical reconstructive interventions on the shoulder joint, performed for injuries of its structure. For the first group (50 patients), an additional course of robotic mechanotherapy was offered. For the second group (50 patients) standard rehabilitation procedures were offered.

An additional method of treatment for the first observation group included biomechanical robotic mechanotherapy of the affected shoulder joint: the type of load was passive (CPM – continuous passive mobilization) and isokinetic – the ballistic mode. At the same time, one-hour procedures were performed daily during the first 2 weeks and then, 3 times a week (for a course of 20 procedures).

In particular, in the framework of the experimental studies to substantiate the proposed method of rehabilitation, the images were studied in dynamics before and after the surgery in a patient with damage to the articular lip of the scapula in the first study group. The reports on dynamics were obtained from the CON-TREX complex after the patient had completed the daily rehabilitation exercise cycles.

The first series of images shows the patient before the operation: destruction of the scapula lip with partial damage to the supraspinatus tendon, impaired stability of the joint with a high position of the humerus head is visualized (Fig. 3). Visualization with color coding makes it possible to more clearly identify bright areas with the presence of local tissue inflammation after the injury, an abnormality of the homogeneity and density of the tissues of the articular lip in the damaged area.

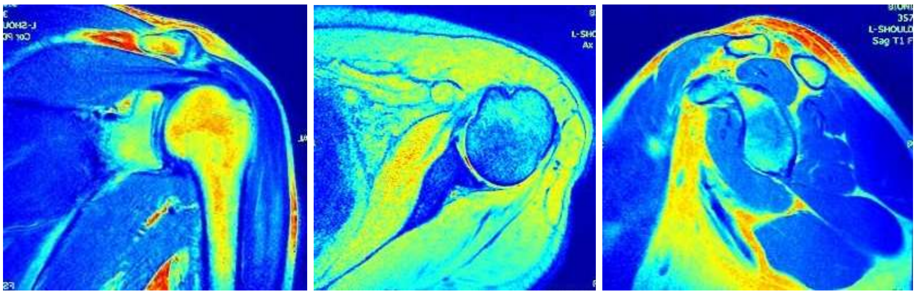

Fig. 3. An example of visualization of MRI before surgery.

The second series of images (Fig. 4) shows the state of the object of interest for the same patient 2 months after the reconstructive surgery. Improved visualization in accordance with the methodology allows one to draw conclusions on the effect of the operation itself and on the adaptation of the body to its consequences.

Visualization and color coding in yellow and red clearly indicate the localization of inflammation in the fascia and periarticular bursae of the joint which is associated with reparative processes in the area of the surgical access and mobilization of the soft tissue sliding using the proposed method of rehabilitation (CON-TREX simulator, massage and therapeutic physical culture), which characterizes the normalization of metabolic processes in them as well as the effectiveness of the specified method.

The homogeneity and density in the tissue structure after the reconstruction is satisfactory with small areas of cicatricial reconstruction. Stabilization of the glenoid lip after the surgical treatment, a more correct ratio between the articular surfaces of the scapula and humerus with the correct placement of implants (screws) in the articular process, characterizes a favorable course of the postoperative remodeling of the joint structure [25-27] (Fig. 4).

Visualization of MRI data based on the Shearlet transform and color coding technique reflects the essence of reparative processes in the joint tissues and degree of restoration of their integrity and functionality. At the same time, it is possible to implement the solution of diagnostic problems and analysis of typical model images including dynamics.

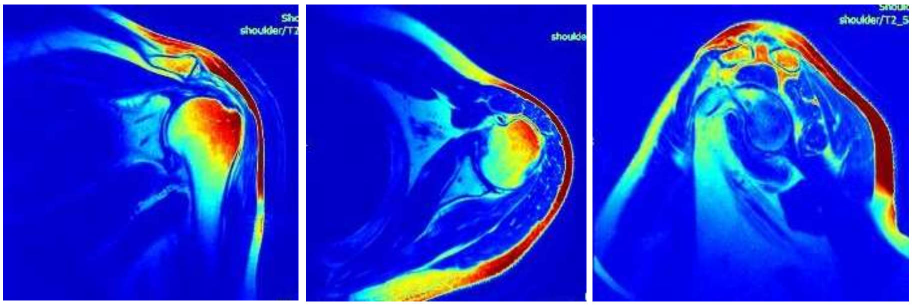

Fig. 4. An example of visualization of MRI images after surgery.

Typical experiments were performed using the image analysis technique, which was successfully applied to the data of the patients group. We managed to improve the quality of diagnostics of pathology elements for the patients undergoing rehabilitation after the reconstructive surgeries on the shoulder joint. It was done by using the proposed method, which more accurately displays the structure, density, integrity and homogeneity of the tissues as well as their functional activity according to the dynamic profiles and reports on the dynamics.

The absence of the tissue destruction areas eliminated by surgical methods as well as the absence of repeated damage during rehabilitation characterize the adequacy of loads in robotic therapy and physiotherapy exercises. In turn, the simulated data from the CON-TREX dynamics reports characterize the degree of functional adaptation to increasing loads during rehabilitation.

The obtained data reflect the state of all the components of a single kinematic model of the joint at a specific point in time in the rehabilitation process. The proposed method of rehabilitation and the applied technique significantly improve the quality of current diagnostics for shoulder joint injuries which opens up prospects for their application in practical medicine.

5 Conclusion

New data were obtained on the effectiveness of using a course of biomechanical robotic mechanotherapy with biofeedback in the rehabilitation of patients after surgical treatment of shoulder injuries. Additionally, the features of its influence on the dynamics of clinical manifestations of the pathological process, as well as on the rate and volume of functional recovery of the affected shoulder joint were studied.

The use of the proposed method of rehabilitation of patients in the early and late recovery period of postoperative rehabilitation through mechanotherapy with an additional study of the features of biomechanics and physiology of joints in the conditions of rapidly developing areas of reconstructive medicine was experimentally substantiated.

The use of the MRI imaging technique makes it possible to more accurately analyze homogeneity, structure, density and integrity as well as functional state of the joint tissues, which is important in the process of studying postoperative remodeling. Moreover, it becomes possible to present these data to specialists in a more accessible and understandable form for analysis.

Correspondence of the obtained data to a specific stage of restoration of the integrity and functionality of joint tissues after injury and surgical treatment makes it possible to create atlases of kinematic models. In turn, the data of such atlases will certainly find a wide application in the examination of the restoration of patients' ability to work.

The introduction of this method of rehabilitation with the elements of a step-by-step examination into practice will significantly accelerate the development of new effective programs for the therapy and rehabilitation of diseases and injuries of the shoulder joint as well as improve treatment results.

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