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Conceptual model of patho- and sanogenesis of the sacroiliac joint osteoarthritis

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Objective. To develop a conceptual model of patho- and sanogenesis of the sacroiliac joint (SIJ) osteoarthritis on base of the known data about the SIJ, the results of our own biomechanical studies of this joint, its ligaments and stabilizing muscles by finite element modelling, data of clinical verification of these results. Methods. The object of the model is the SIJ as a link, which connects the spine and pelvis. The proposed conceptual model is based on the M. Panjabi hypothesis of chronic lumbar pain in the case of partial damage to ligaments, which leads to muscle dysfunction. Results. A new conceptual model of SIJ osteoarthritis was developed. In this model we tried to take into account the limitations of the existing SIJ stability hypotheses and models of the appearance of the pelvic girdle pain, SIJ dysfunction and SIJ arthrosis. The model is based on the results of our own research. It was proved, that patients with SIJ osteoarthritis have an asymmetry of the width of the joint slits, the inclination of the sacrum and pelvis, sacral rotation, hyperlordosis in the L_V*–*S_I *segment. These factors lead to a shift of the horizontal axis of sacral rotational mobility relative to the pelvic bones. This horizontal axis shift leads to the instability of the SIJ on one side of the joint, and to the functional block on another side. The results of these functional changes were damage of the SIJ ligaments-stabilizers, dysfunction of the SIJ muscles-stabilizers, degenerative changes of SIJ elements and pain. The developed model allows to explain the distortion of muscular response pattern in patients with improper SIJ biomechanics in conditions of SIJ osteoarthritis. The increase of the SIJ biomechanics changes enlarges the the muscle response pattern distortion. Conclusions. The developed conceptual model explains many clinical manifestations of the SIJ osteoarthritis and will help to understand better the mechanics of the pelvic girdle pain in such conditions, will improve the results of diagnosis and treatment. Key words. Pelvic girdle pain, sacroiliac dysfunction, sacroiliac joint ligaments, biomechanics, hypothesis.*

Мета. На підставі відомих уявлень про крижово-клубовий суглоб (ККС), результатів власних біомеханічних досліджень методом скінченних елементів особливостей цього суглоба, його зв'язок і м'язів-стабілізаторів, їхньої клінічної верифікації розробити концептуальну модель пато- і саногенезу артрозу ККС. Методи. Об'єктом моделювання була система ККС як ланка, що з'єднує хребет і таз. За основу передбачуваної концептуальної моделі взято модель M. Panjabi виникнення хронічного поперекового болю в разі часткового ушкодження зв'язок, що призводить до порушення функції м'язів. Результати. Розроблено нову концептуальну модель розвитку артрозу ККС, в якій ми намагалися врахувати обмеження наявних моделей стабільності ККС і появу хребтово-тазового болю, виникнення дисфункції та розвитку артрозу ККС. Модель побудована за результатами власних досліджень. Доведено, що у хворих на артроз ККС є асиметрія ширини суглобових щілин, нахил крижів і таза, ротація крижів, гіперлордоз у хребтовому руховому сегменті L_V*–*S_I*. Це призводить до зсуву горизонтальної осі ротаційної рухомості крижів щодо тазових кісток і, відповідно, виникнення, з одного боку, нестабільності ККС, а з іншого, — функціонального блока. Унаслідок цього виникають ушкодження зв'язок-стабілізаторів ККС, біль і порушення функції м'язів-стабілізаторів суглоба і дегенеративні зміні в його елементах. Розроблена модель дає змогу пояснити зміну патерна м'язової відповіді в пацієнтів із порушенням біомеханіки ККС за умов артрозу. Чим більше змінюється біомеханіка ККС, тим більше спотворюється патерн м'язової відповіді. Висновки. Розроблена концептуальна модель пояснює багато клінічних проявів артрозу ККС і допоможе кращому розумінню механізму виникнення хребтово-тазового болю за таких умов, дозволить поліпшити результати діагностики та лікування.*

Key words. Pelvic girdle pain, sacroiliac dysfunction, sacroiliac joint ligaments, biomechanics, hypothesis

Introduction

Non-pregnancy-related lumbar pelvic pain (LPP) is mostly caused by trauma, arthritis, or arthrosis of the sacroiliac joint (SIJ). Some authors report that such pain can account for 20 to 50 % of all cases of lower back pain [1–3]. It was found that in 40 % of cases the cause of such LPP is the presence of a history of L_V–S_I spondylodesis [4–8].

The pain is localized between the *crista iliaca* and the gluteal fold, especially in the projection area of the SIJ. It can radiate to the back of the thigh and groin, the area of *pubis symphysis*. Muscle tone is disturbed, which stabilizes the SIJ and torso in a standing and sitting position while walking. LPP in the European Guide is associated with a violation of the static and dynamic stability of the SIJ during the transmission of vertical loads, due to the coordinated operation of active, passive subsystems and neuromotor control. This condition is called SIJ dysfunction [9–11].

Adequate compression of joint surfaces is achieved as a result of the interaction of all forces passing through the joint [9, 12]. Adequate is the one that is ideally suited to a specific situation, uses sufficient compression of the articular surfaces of the SIJ, and guarantees its porosity with appropriate neuromuscular control. The stability and porosity of SIJ are determined by the force of gravity, the shape of the joint surface, the position of the joint, proprioceptive muscle reflexes, the degree of muscle contraction and ligament tension [9, 12]. Ability to lean is the ability of SIJ to effectively transfer loads through the joint, and it is a dynamic process that depends on many factors.

Non-optimal ability of the SIJ is determined by excessive mobility of the joint, which leads to increased movement in it, or its stiffness, which causes restriction or blockage of movement and, accordingly, increases or decreases the compression of the joint surface with certain clinical manifestations.

The mobility of SIJ is mainly passive and occurs in three main planes, normally limited to a few degrees [13, 14].

With two exceptions [13, 15], all modern hypotheses aimed at modeling SIJ dysfunction revolve around the assumption of almost flat joint surfaces, and the ridges and depressions that are present on the joint surfaces only increase the friction force. This assumption is based on the theory of «Shape and strength of the circuit», which explains the stabilization of SIJ under the influence of body weight and compression force of the muscles [16–18].

The structural elements that ensure the resilience of SIJ in accordance with the theory of «Shape and strength of the circuit» by A. Vleeming are as follows:

– configuration of interacting articular surfaces, including «dorsocranial hanging» of the sacrum relative to the pelvic bones;

– additional ridges and depressions on the articulating surfaces of SIJ and, as a result, a high coefficient of friction;

– a set of joining connections that are the most powerful in the human body [10, 11, 17, 18].

S. Gracovetsky believes [19] that the articular surfaces of SIJ are not flat, but bent in the form of a propeller and have significant ridges, not only to increase the friction between the articular surfaces, but also to create a tight connection between the sacral bones and pelvis with the possibility of their short circuit in a certain position. The tightness of the SIJ bonds ensures the functioning of the whole node as a whole. The shear forces that pass through the SIJ will be absorbed by the viscoelastic properties of the elements [20, 21].

M. Panjabi developed a dynamic theory of degenerative instability. In experimental works, he investigated the curve of the dependence of the change in the stiffness of the joint elements on the deformation and found on this curve the area that reflects the significant deformation of the joint elements with minimal change in their stiffness. This area of the joint where it can move effortlessly is called the neutral zone. M. Panjabi believes that its value determines the stability of the joint [20, 21].

But in viscoelastic systems the classical scheme of stability does not work. If a «stable» position has been reached, it cannot be stored for a long time, because biological materials are viscoelastic and deform over time under the action of force (Fig. 1) [21, 22].

The deformity will cause trigger pain, which will cause the CNS to unload the overloaded area, especially collagen. Therefore, the stability of viscoelastic systems can be considered a set of related provisions that are selected and modeled by the CNS. The pose is not static; it is a dynamic concept. A completely vertical position consists of alternating different but very close poses [22, 23].

Prolonged loading and unloading of collagen requires the CNS to quickly redirect forces. Many muscles and ligaments are involved in maintaining any posture. This explains why adequate rehabilitation cannot be achieved by performing just one exercise, but a number of exercises should be performed.

According to S. Gracovetsky, the theory of «Shape and strength of the circuit» has certain shortcomings [19]:

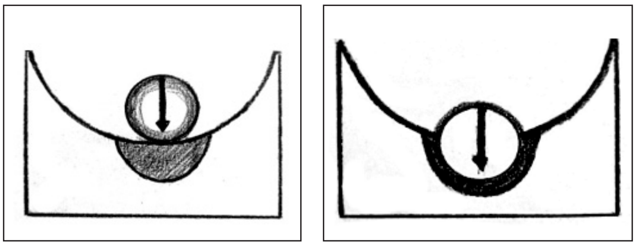

Fig. 1. Stages of deformation of viscoelastic structures of the joint

first, the musculoskeletal force must act all the time to balance the forces of gravity. Collagen is a viscoelastic structure and will begin to stretch over time. If the sprain continues, then in the absence of increased muscle activity, the SIJ will open, the articular surfaces will shift relative to each other and there will be mobility (subluxation). To prevent this, the muscles must constantly generate a compressive force, which increases with the stretching of the ligaments. However, such excessive muscle strain is not observed.

Second, the articular surfaces are oriented in two planes. At the level of the SI vertebra, the articular surface is at an angle of 40°. Below, at the level of the transition from SI vertebra to SII, the articular surface unfolds in the opposite direction to an angle of 10° in the form of a propeller. As a result, large deformations can occur during the movement of the articular surfaces relative to each other. Such a surface can facilitate the displacement of the centers of rotation of the sacrum relative to the pelvis.

Third, the uneven articular surface of SIJ is highly organized. This can be seen in the sections of the pelvis. The main anatomical structure on the articular surfaces is the periarticular ridge, called the SS ridge [19].

According to S. Gracovetsky [19], the idea that the sacral bones hang on the ligaments between the pelvic bones is incorrect. This is due to the fact that viscoelastic collagen bonds should gradually stretch under the action of the load. The SS ridge takes on a significant portion of the vertical load, so the musculoskeletal system of the joint will respond quickly to changes or the emergence of forces aimed at unlocking the joint.

The specific structure of the SIJ allows for limited movements [24] around the SS ridge, resulting in rotation around two main axes associated with the structure of the SIJ. This mechanism is similar to paired movements in the arched joints of the lumbar spine. The articular surfaces SI and SIII determine the two axes of rotational mobility of the sacrum.

Movements of the pelvis during walking are determined by the activity of one of these axes, depending on the lumbar lordosis, especially the lower segments. Presumably, this is the role of SIJ as a connecting part for the implementation of the function of the spine and paired movements of the intervertebral joints in all its departments during vertical standing and walking.

The aim of the study: on the basis of known ideas about the sacroiliac joint that connects the spine, pelvis and lower extremities, the results of own studies concerning the features of the sacroiliac joint and its relationship by finite element method and verification in patients with arthrosis of the sacroiliac joint, study of the stabilizer muscles of the sacroiliac joint and the vertical position of the body to develop a conceptual model of patho- and sanogenesis of arthrosis of this joint.

Material and methods

The object of modeling is the SIJ system as a link connecting the spine and pelvis. The model concept we envisage is based on M. Panjabi's model of chronic lumbar spine pain in the case of partial ligament damage, which leads to muscle dysfunction [25].

Initial provisions of own researches for construction of a conceptual model of patho- and sanogenesis of SIJ arthrosis

1. Based on a retrospective study of case histories, most patients who underwent spondylodesis at the level of LV-SI for lumbar osteochondrosis, in the remote postoperative period (a year or more) were found to have development or progression of clinical and radiological signs of SIJ arthrosis, i.e. a change in the mobility of the spinal motor segment L_V–S_I results in overload of SIJ elements [26].

2. As a result of mathematical modeling it is proved that the asymmetry of the width of the articular slits of the SIJ, the inclination of the sacrum and pelvis lead to a change in the position of the conditional axis of rotational mobility of the sacrum. This leads from the wide side to the displacement of the position of the conditional axis of rotational mobility of the sacrum forward and downward relative to the pelvis, backward and upward from the narrow side, which causes a significant redistribution of stresses and strains between left and right joints and their ligaments. This causes a functional block of the sacrum relative to the pelvis on the one hand and excessive mobility on the other. Accordingly, there are stresses and strains sufficient to damage of SIJ ligaments-stabilizers and vertical position of the body under the conditions of simulation of the loads available during walking or running [27–31].

3. The majority of patients with SIJ dysfunction (90 %) had an asymmetry in the width of the SIJ joint slits. The rest had the inclination of the pelvis and sacral bones, rotation of the sacral bones. Hyperlordosis at the level of the spinal motor segment $L_V–S_I$ was detected in all patients with SIJ dysfunction [32, 33].

4. Radiography of the pelvis in the frontal plane identified degenerative changes in the joints in all persons with SIJ dysfunction [34].

5. It is proved that changes in the bioelectrical activity (BEA) of the muscles-stabilizers of the SIJ progress with the increase in the degree of asymmetry of the width of the joint slits of the SIJ [35].

Results and discussion

The main provisions of the conceptual model of patho- and sanogenesis of SIJ arthrosis

The leaning ability and stability of SIJ is determined by the normal function of the three subsystems. The first consists of the sacral bones, pelvic bones, ligaments that connect these bones into a single whole, articular cartilage. The second subsystem includes muscles that tighten ligaments and stabilize the ability of the SIJ during movement and in a static position. The third subsystem is shown by the neuromuscular control system (Fig. 2).

SIJ has the functions of structure and transmission. The structural function provides the ability and mobility of SIJ and combines the subfunctions:

– connecting — SIJ connects the pelvis, lower extremities and spine into a single whole;

– skeletal — sacral bones and pelvis are the place of attachment of many muscles and ligaments;

– supportive — supports the entire spine and transmits the weight of the body from the spine to the pelvis and lower extremities, and the reaction force of the support from the pelvis to the spine during walking and running;

– cushioning — softens the shocks that occur under conditions of vertical position of the body during walking, jumping, due to the peculiarities of the anatomical structure and ligaments;

– protective — protection from external influences of important organs of the genitourinary system and main vascular and nervous formations.

The transfer function provides the information needed to accurately characterize a person's posture, position and movement of the sacrum relative to the pelvic bones, the load on the SIJ, to transmit to the neuromuscular control system through numerous mechanoreceptors located in the SIJ ligaments (Fig. 2).

This transmission of impulses from mechanoreceptors provides information to the neuromuscular control system, which helps to ensure the ability to lean and mobility of the SIJ through muscle activity. The achievement of adequate mechanical ability of the SIJ is the main criterion used by the neuromuscular control system.

If the structural function of the SIJ is impaired due to degenerative changes or trauma, the neuromuscular control system enhances the activity of the muscular system to compensate for the loss. A single injury or cumulative microtrauma causes damage to the SIJ ligaments and distorts the signal of the mechanoreceptors located in them.

The latter under the action of external load (walking, running, prolonged sitting) produce a distorted signal in the neuromuscular control system, which is difficult to interpret. There is a spatial and temporal mismatch between the mechanoreceptor signal of normal and damaged connections. The neuromuscular control system, in turn, generates a distorted signal in space and time to activate the stabilizing muscles of the sacroiliac joint and the vertical position of the body. The unnatural activity of these muscles leads to an inadequate feedback signal through

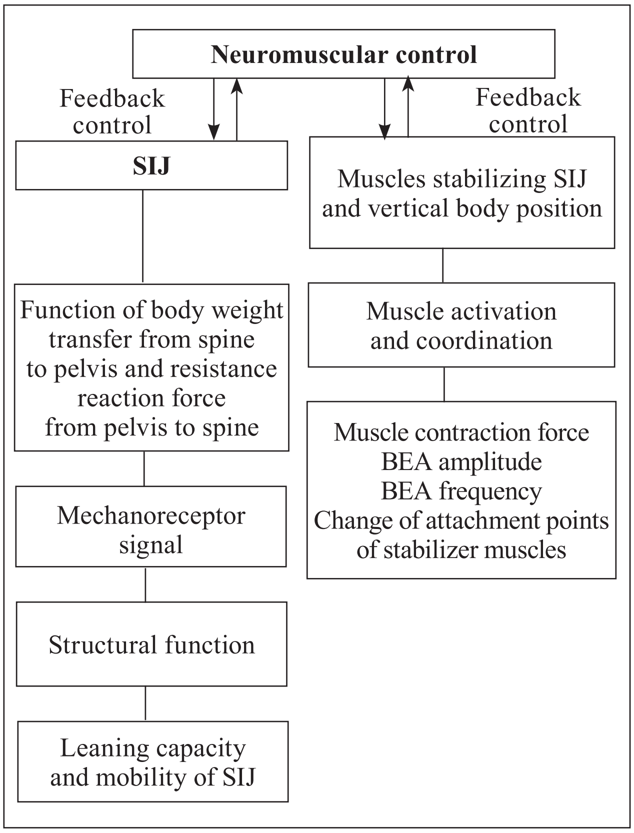

Fig. 2. SIJ stabilization model

the muscle tendon receptors and damaged mechanoreceptors, further disrupting muscle activation.

Distorted muscle activation creates even more stress and strain in all elements of the SIJ and results in further damage to ligaments, mechanoreceptors and muscles, overloading the articular cartilage. Excessive deformations and stresses cause inflammation of SIJ elements, which have extensive nooceptive innervation. Over time, chronic pain may progress. Ligament damage can be «subcritical», without complete rupture, but with destruction of part of the fiber.

Under normal conditions, to change the position of the body in space in response to changes in external load, mechanoreceptors generate a set of signals that describe the state and movement of the sacrum relative to the pelvic bones (Fig. 3).

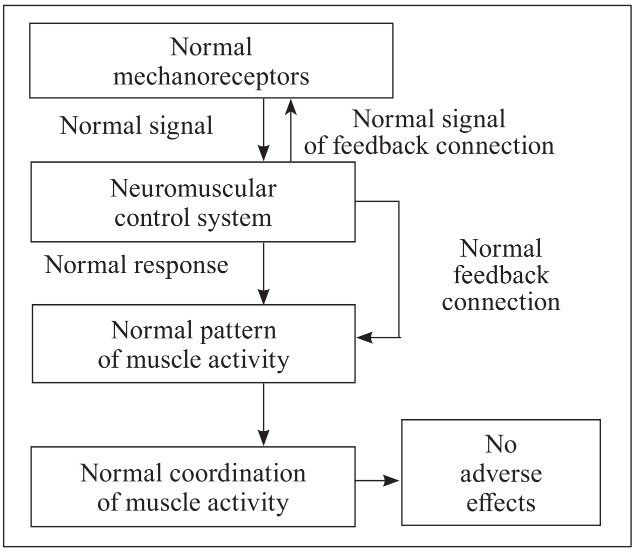

Fig. 3. SIJ stabilization model

These signals are transmitted to a neuromuscular control system, which analyzes them and produces a corresponding pattern of muscle response in the form of activation of certain muscles. The determining fact is the need to preserve SIJ porosity with the minimum possible stress-strain state of its elements. This is achieved, in particular, through feedback from the spindle-shaped nerve endings of the Golgi muscle and bodies located in the tendons of the stabilizing muscles of the sacroiliac joint, as well as from the mechanoreceptors of SIJ ligament. Dynamic synchronization of muscle activation is determined by a set of actions: the selection of the necessary muscles, the activation of each with a certain force and reduction to a specific distance and time.

The integral dynamic system of SIJ is fast, not traumatic and without adverse consequences. SIJ with damaged ligaments functions in a different way (Fig. 4).

Partial ligament damage results in destruction or damage to mechanoreceptors. Under conditions of vertical loading of SIJ, during the transfer of forces from the spine to the pelvis and hip joints, there is a shift along the horizontal axis of rotation of the sacrum relative to the pelvic bones, overstretching, compression and damage to the stabilizing ligaments of the SIJ [27, 28]. This is accompanied by asymmetry and narrowing of the width of the SIJ slits, their fibrosis, inclination of the sacrum, pelvis, rotation of the sacral bones [34].

Damaged mechanoreceptors produce a distorted signal that describes the position of the sacral bones and pelvis in space and time. As a result, the neuromuscular control system receives incorrect signals

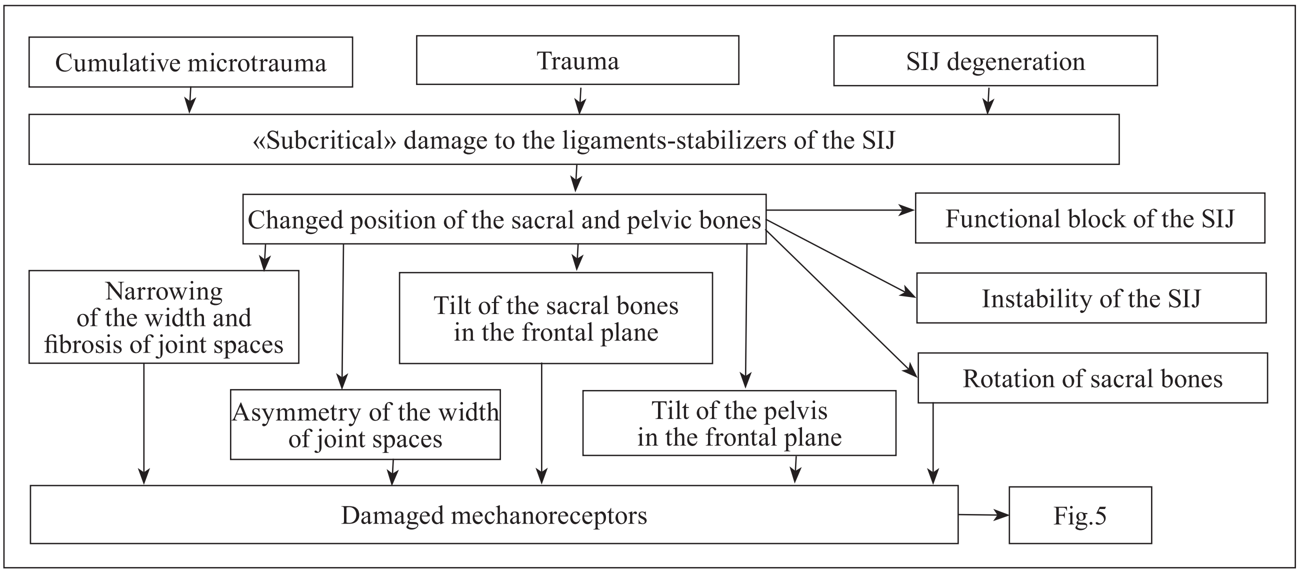

Fig. 4. Model of patho- and sanogenesis of SIJ arthrosis

about the position of these structures and has difficulty in choosing the appropriate pattern of muscle response (Fig. 5).

Accordingly, the neuromuscular control system produces a defective pattern of muscular response, which is most consistent with the position of the sacral bones and pelvis. It directly affects the choice of activated SIJ stabilizing muscles and the vertical position of the body, the activity of each muscle separately, the strength and distance of contraction [25].

The synchronization of the activity of the SIJ stabilizer muscles and the vertical position of the body is disturbed. Additionally, the feedback from the neuromuscular control system and mechanoreceptors also changes, further distorting the pattern of the muscular response. This has its negative consequences: higher stresses and strains, resulting in microdamage to the ligaments-stabilizers of SIJ and, accordingly, mechanoreceptors located in them, dysfunction of the muscles-stabilizers of SIJ and vertical position of the body [20, 21]. As a result, there is a functional unit or instability of the SIJ, or both together (Fig. 4). Over time, these damaging deformations and stresses cause inflammation of nerve structures [36–38] and accelerate the process of degeneration of all elements of SIJ, which generally leads to dysfunction and pain.

Spondylodesis surgery at the level of L_V–S_I has been proved to be one of the main causes of arthrosis of the SIJ [4, 7, 8]. We believe that spondylodesis at the level of L_V–S_I causes a compensatory increase in the mobility of the sacrum relative to the pelvic bones in the adjacent SIJ. This entails an increase in mechanical loads on all elements of the SIJ, the displacement of the axis of rotation of the sacrum relative to the pelvic bones. This can change not only the volume of movements of the sacrum and pelvic bones, but also their direction. This will change the ability to perform and the strategy of achieving mobility of SIJ, will lead to dysfunction and chronic cumulative microtrauma of all its elements.

Initially, we hoped to build a model of patho- and sanogenesis of SIJ taking into account the sagittal spinal-pelvic balance. However, assessment of the literature showed that the authors consider SIJ as a permanently functioning node, in which under the influence of body weight in healthy people the sacral bones have a standard strategy and range of motion relative to the pelvic bones. That is, the sacrum is characterized by rotational mobility forward relative to

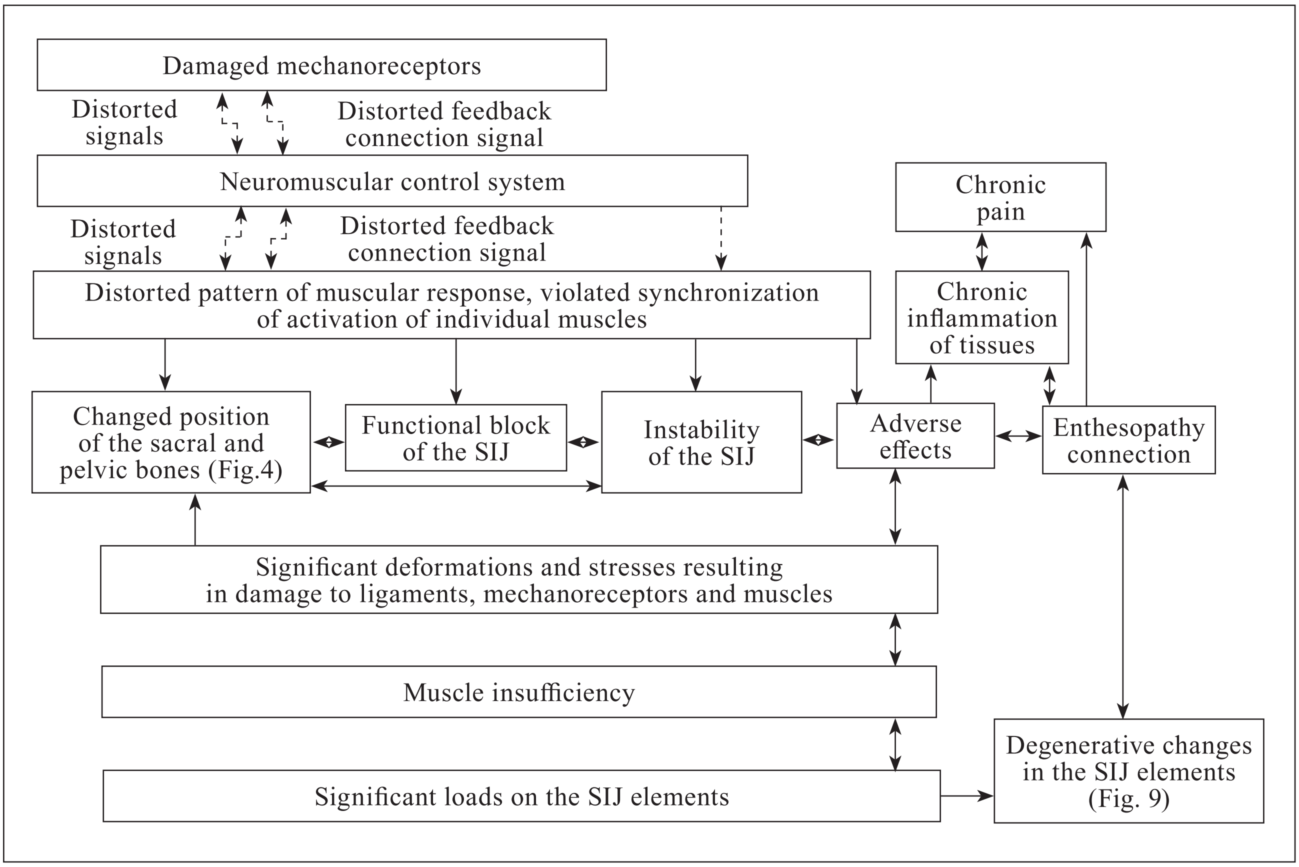

Fig. 5. Model of patho- and sanogenesis of SIJ arthrosis

the pelvis around a constant horizontal axis, the projection of which is located at the level of the SII vertebra. The pelvic bones have rotational mobility in the opposite direction. All this changes in patients with arthrosis of the SIJ [39, 19]. Therefore, to build the model, we applied the concept of adjacent kinematic links in the kinematic circuit.

These changes will be accompanied by degenerative disorders of the SIJ elements, pain and the development of arthrosis (Fig. 6). And in chronic cumulative microtrauma, the SIJ ligament will be accompanied by damage to mechanoreceptors with a subsequent cascade of reactions (Fig. 5). The increase in the volume of mobility of the sacrum relative to the pelvis, the displacement of the axis of mobility of the sacrum is subsequently realized in the functional unit or the instability of the SIJ.

According to the results of our study, arthrosis of the SIJ always corresponds to certain radiometric parameters on the functional radiographs of the SIJ [27, 28, 33, 40]. They directly reflect the function of SIJ, as proved by our research and other authors (Fig. 7).

Asymmetry of the width of the joint spaces is important for the function of the SIJ in the ventral, medial and dorsal departments. We found that joint asymmetry width greater than 1 mm in any SIJ department, or up to 1 mm in all three departments, would be clinically relevant for joint function. The presence of an asymmetry of more than 2 mm in the dorsal part of the SIJ is a prognostically unfavorable factor for conservative treatment and determines the performance of surgery [41].

This causes overload and «subcritical» unilateral or bilateral damage to *lig. sacrospinous, lig. sacrotuberous, lig. coccygeus, lig. iliococcygeus, lig. spinococcygeus*, which are the main stabilizers of the vertical position of the body, stretched under the action of its weight.

All these functional radiographic parameters are compensated by the functional block or instability of the joint (Fig. 8) to restore its resilience and mobility. In addition, one state can pass into another.

Arthrosis of the CSF is always associated with a number of degenerative changes in its elements, namely: the destruction of articular cartilage with a violation of the uniformity and integrity of the joint covering, narrowing the width of the articular fissures to their sclerosis, ligament degeneration, destructive changes in the adjacent bone [34].

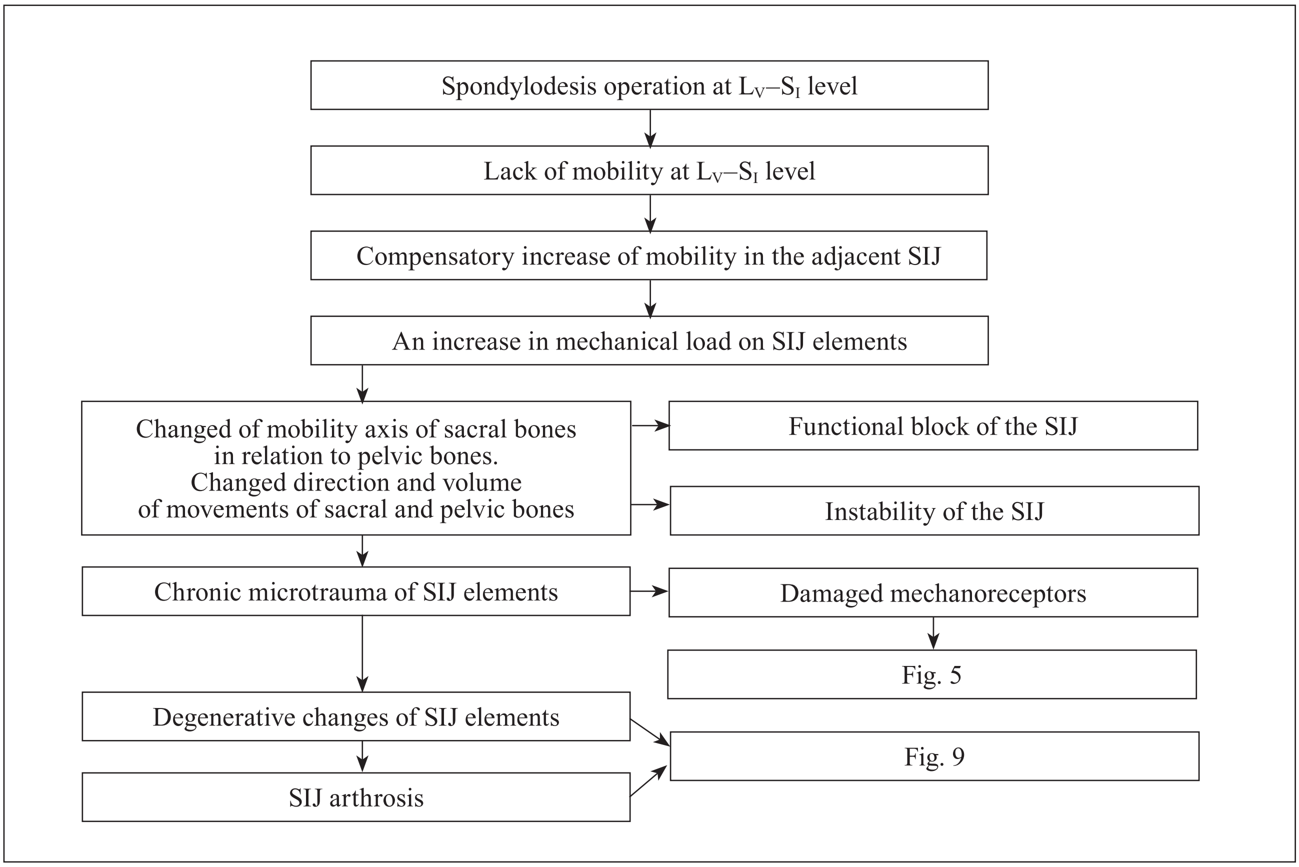

Fig. 6. A model of SIJ arthrosis development following L_V–S_I spondylodesis

On radiography, this will be manifested by subchondral sclerosis, uneven articular surfaces of the SIJ, osteophytes, ossification of ligaments, bone bridges (Fig. 9).

In addition, ligament damage heals poorly and leads to premature degeneration [42, 43]. Thus, damaged ligaments are often the cause of chronic pain in the form of enthesopathies. Besides, since ligaments are viscoelastic structures, their long-term exposure, even loading only 30 % of their tensile strength, can cause damage and the development of enthesopathies [36–38, 44].

Conclusions

The proposed model of patho- and sanogenesis of SIJ focuses on mechanoreceptor damage and the actual connection. Destructive changes in them lead to a shift of the axis of horizontal mobility

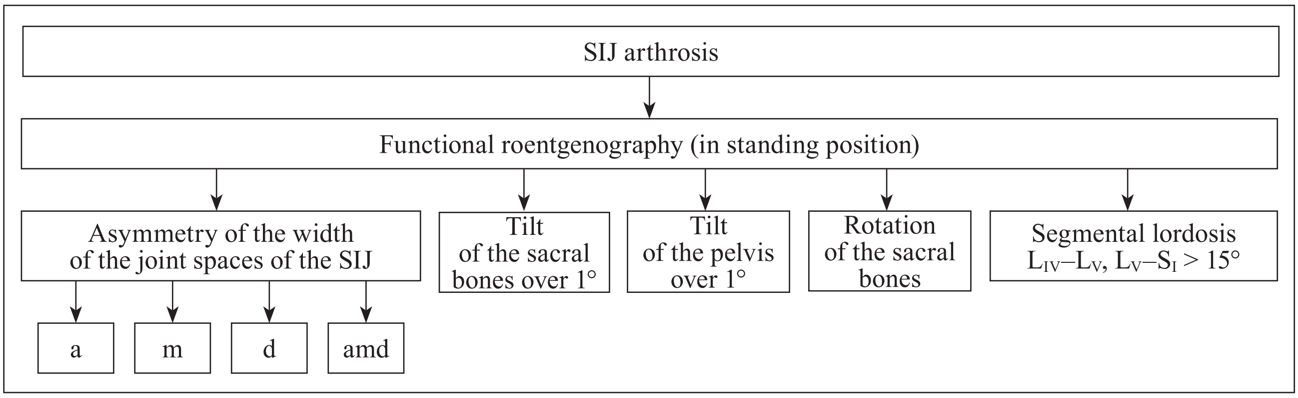

Fig. 7. Radiological parameters of the sacral bones, pelvis, lower segmental lordosis directly determine the function of the SIJ: ventral (a), medial (m) and dorsal (d) departments, amd — asymmetry in all departments

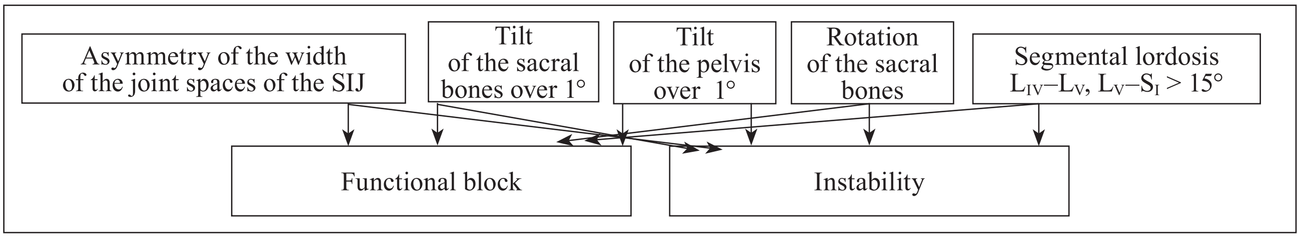

Fig. 8. Functional changes aimed at restoring the leaning capacity and mobility of the SIJ

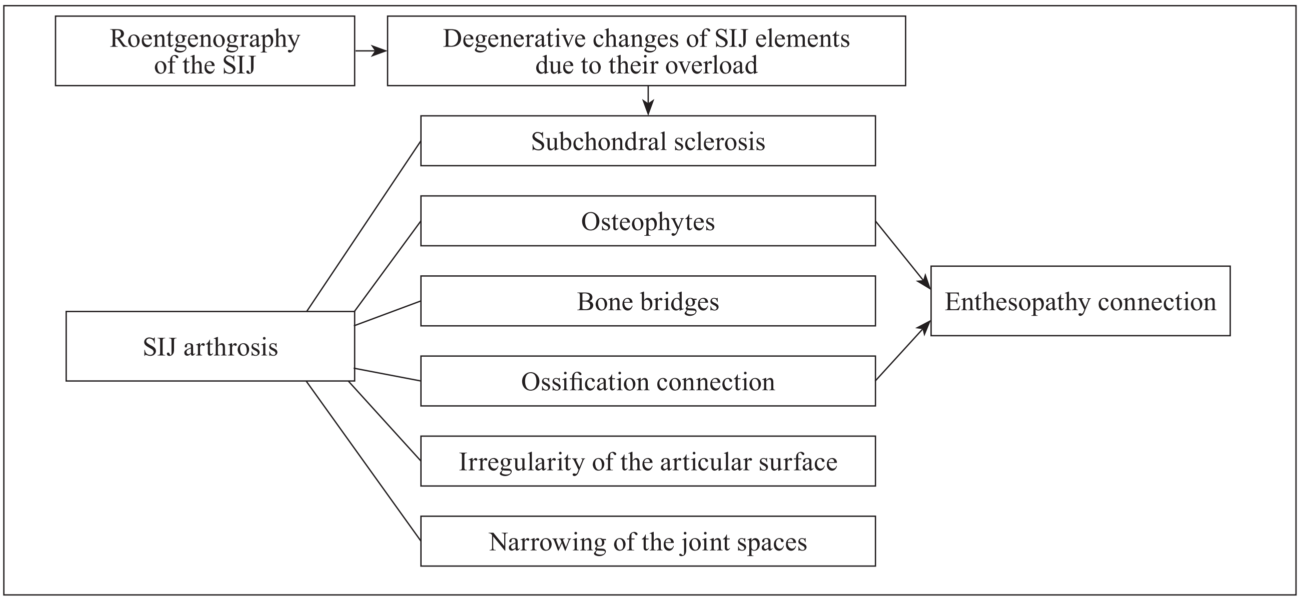

Fig. 9. Degenerative changes of the SIJ in arthrosis on radiography

of the sacrum relative to the pelvic bones, functional block or instability of the SIJ separately or together. This causes the elements of the SIJ to be overloaded and, consequently, to transmit a distorted signal to the neuromuscular control system, producing an inadequate pattern of muscle response and SIJ dysfunction. The more the SIJ biomechanics change, the more the muscle response pattern is distorted.

The developed model provides an explanation of the change in the pattern of muscular response in patients with impaired biomechanics of SIJ in conditions of arthrosis. In the case of ligament damage in patients with LPP, the distorted signal of mechanoreceptors and patterns of muscle response lead to changes in the stabilization of the SIJ, its leaning ability and mobility.

Muscle coordination is the synchronization of the activation of different muscles for optimal stabilization of the SIJ. Synchronization comprises activation of individual muscles with a certain force and at a specific distance.

In case of ligament damage, mechanoreceptors generate distorted signals that may contradict the expected neuromuscular control system. Assessment of such signals may activate both synergistic and antagonist muscles to stabilize the SIJ. This reaction can become chronic, the likelihood of such a pattern of muscle response increases significantly with increasing biomechanical changes in SIJ. The described situation is accompanied by damage to muscles, their functional inability, atrophy, causing dysfunction and disability of the SIJ. Restoration and training of a normal pattern of muscular response will help to restore the ability to move and mobility of the SIJ, to eliminate chronic pain.

This model certainly has some limitations, as LPP is a multifactorial problem and cannot be explained by a single model. However, the proposed model allows us to explain our results and elaborate a coherent algorithm for diagnosis and treatment of patients with SIJ and LPP arthrosis.

Conflict of interest. The authors declare no conflict of interest.

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CONCEPTUAL MODEL OF PATHO- AND SANOGENESIS OF THE SACROILIAC JOINT OSTEOARTHRITIS

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