COMPREHENSIVE ASSESSMENT OF POSTURAL CONTROL AS A CONCEPTUAL BASIS FOR OPTIMIZING REHABILITATION AND RECOVERY PROGRAMS IN SPORTS

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This literature-based review focuses on the basic physiological aspects of proprioception. Below, we describe and compare a number of biomechanical platforms used to measure postural control in high-class athletes. We define the primary goals of biomechanical assessment of postural problems, paying special attention to the functional performance of proprioceptors and proprioceptive control. We also provide a list of clinical and biomechanical indicators of proprioceptive damage and propose a diagnostic algorithm for assessing static and dynamic impairments in high-class athletes.

Keywords: biomechanics, proprioception, postural balance, functional asymmetry, stabilometry, unstable platforms, balance assessment, diagnostic algorithm, high-class athletes

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ИНТЕГРАЛЬНАЯ ХАРАКТЕРИСТИКА ЭФФЕКТИВНОСТИ ПОСТУРАЛЬНОГО КОНТРОЛЯ КАК КОНЦЕПТУАЛЬНАЯ ПЛАТФОРМА ДЛЯ ОПТИМИЗАЦИИ РЕАБИЛИТАЦИОННЫХ И ВОССТАНОВИТЕЛЬНЫХ ПРОГРАММ В СПОРТЕ

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В обзоре проанализированы данные литературных источников по основным физиологическим аспектам системы проприоцепции. Проведена сравнительная характеристика используемого биомеханического оборудования для диагностики эффективности постурального контроля у спортсменов высокого класса. Определены первоочередные задачи биомеханического обследования при нарушении постурального баланса, среди которых приоритет отдается оценке функциональной состоятельности всех типов проприорецепторов и проприоцептивного контроля. Приведены клинико-биомеханические критерии проприоцептивных нарушений у спортсменов, а также разработанный авторами на их основе алгоритм диагностики статодинамических нарушений у спортсменов высокого класса.

Ключевые слова: биомеханика, проприоцепция, постуральный баланс, функциональная асимметрия, стабилометрия, нестабильные платформы, балансометрия, алгоритм обследования, спортсмены высокого класса

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This review critically analyzes literature covering methodology for diagnosing and monitoring postural control disorders in top ranking athletes. Another point considered here are the design principles behind rehabilitation programs based on proprioceptive capabilities assessments.

Neurology, traumatology and orthopedics make quite an extensive use of medical equipment designed to diagnose and correct changes in speed and strength of movements. However, these indicators fail to fully describe the specifics of adaptation and compensation processes peculiar to various sports activities. Proprioception capabilities assessment and correction enjoyed less attention from the researchers; there is a number of applied methods that differ greatly from each other, especially in defining diagnostic approaches and establishing assessment criteria [1].

Physiological aspects of proprioception

Proprioception (deep or kinesthetic sensitivity) is the perception of body posture and movements, both as a whole and by segments. Understanding proprioception patterns (reception and regulation mechanisms in the first place) allows selecting diagnostic tools that would be effective in both clinical practice and sports biomechanics recognition.

There are three types of structurally and functionally different proprioceptors: muscle spindles, tendon and articular receptors [2].

Muscular spindles run parallel to skeletal muscle and consist of several striated intrafusal muscle fibers. They are attached to the connective tissue (perimysium) of the extrafusal muscle fibers bundle; when the muscle relaxes, receptors expand, which leads to their excitation [2, 3].

Tendon receptors, enclosed in the connective tissue capsule (Golgi body), lie sequentially in the skeletal muscles tendons. Their excitation occurs when the tendon stretches.

Muscle spindles send pulses to α-motoneurons of the spinal cord and excite them, which leads to the stretched muscle's contraction. As the muscle begins to contract, excitation of the muscle spindles disappears or weakens greatly; at the same time, impulses from the tendon receptors reach the spinal cord, Renshaw cells. The latter, when excited, inhibit α-motoneurons of the skeletal muscle, which relaxes. In other words, the muscle alternately contracts and relaxes following impulses the receptors send to its motoneurons [2–4].

Complex locomotions, like walking, imply synchronized contractions of flexors of one leg and extensors of the other. The contractions are also caused by afferent impulses from muscle and tendon receptors and, respectively, alternating excitation and inhibition of flexor and extensor centers [2]. Biomechanical methods provide explanations of peculiarities of this locomotion.

Joint receptors (mechanoreceptors) are in the capsule, cartilage, ligaments and pericapsular connective tissue. They are distinguished into types depending on their response to amplitude, speed and direction of movement in the joint.

For example, Ruffini endings (corpuscles), which can be found both in the joint's capsule and the surrounding connective tissue (including those lying deep in the dermis and subcutaneous fatty tissue), report articular angles, i. e. relative positions of elements of the joint. They send pulses while the angle remains unchanged, and the intensity of those pulses depend on the angle's value. These mechanoreceptors are considered to be particularly sensitive to extreme angles. Pacinian corpuscles reside in the joint capsule exclusively; they perceive direction and speed of change of its angle. The frequency of pulses they generate grows with that speed. Here, clinical biomechanics allows gathering exhaustive descriptions.

The sensation of movement, same as skin sensitivity (to touch, pressure), results from receptors sending pulses through two main pathways, lemniscus and spinotalamic tracts, which differ significantly in their morphological and functional properties. There is also a third pathway, the Morin lateral pathway, which resembles lemniscus in a number of characteristics.

As far back as in 1922, Miles [5] stressed the importance and versatile role movement control plays in maintaining vertical stability. In 1924, Magnus published his Body Posture, a fundamental work developing Sechenov's ideas on muscles own sensitivity ("dark muscle feeling") and those of Sherington, which pertain to the receptive fields. In the same paper, the Dutch scientist also scrutinized the special group of posture (adjustment) reflexes (Magnus–Klein tonic reflexes) that help maintain posture and balance and described other reflexes enabling animals to stand and walk normally [5].

In 1965, Gurfinkel et al. published the *Human Posture Regulation* paper that laid the foundation for instrumental assessment of proprioception system, which lead to introduction of stabilometry as a biomechanical diagnostics method. Thence, stabilometry helps clinicians assess functions of motor and nervous system, since postural balance tests allow assessing quality of proprioception in a closed kinetic chain [5]. It is the vertical posture maintaining strategy and somatosensory information coming from the foot contacting the support's surface that tell the most about balance control as proprioception indicators [5, 6].

Proprioception: biomechanical diagnostics methods

In the context of postural control rehabilitation, stabilometry allows objective functional monitoring of the progress made [1, 5]. Typically, the deficiency of postural control after trauma or with an orthopedic pathology in the background is considered to be the result of faults in the flow of afferent information generated by ligament and capsule mechanoreceptors. Current stabilometric systems include hardware and software and allow regulation of the degree of mobility of the support platform. Fig. 1 shows such a system.

Important diagnostic criteria describing vertical stability are the statokinesiogram area and the velocity of center of pressure (CoP), as well as the Romberg ratio (ratio of two statokinesiogram areas, one with eyes open and the other with eyes shut). This ratio reveals the functional ability of peripheral and vestibular links of the proprioception system to maintain vertical stability in the absence of visual clues, i.e. when visual posture control does not function.

We believe that current sports medicine does not fully appreciate the potential of the posture stereotype assessment, given the stabilometric diagnostics methods and principles adopted. However, stabilometry is the very tool that allows diagnosing functional postural asymmetries in athletes. Many authors believe that most sports have specific requirements to the athlete's musculoskeletal system and sensory organs; those requirements can imply special symmetry or asymmetry, and practicing those sports means their further development [8, 9]. Morphogenetic features and asymmetry determine how well an athlete can make special moves, i.e. each sport require special types of sensorimotor profiles.

Brain asymmetry's connection to vertical posture maintenance is of special importance. A person can remain upright for a long time when static momenta of all body parts are balanced, which requires adequate proprioceptive control all around.

It should be noted that some stabilometric indicators of functional postural asymmetry reveal special motor skills peculiar to this or that sport. The indicators are mean position and standard deviation of GoP in the frontal plane; they can be used in assessing the technique of performing specific locomotions [9].

Fig. 1. Stabilometric system [7]

At the same time, GoP velocity and area indicators are functional markers of the static position, which means they can help assess the various influences special types of physical activity have on all parts of the musculoskeletal system. Stabilogram, therewith, is an integral and complex method for evaluating the functional state of the motions regulation system. Clinical assessment of the muscles enabling sport-specific ("working") vertical stance is an essential part of the overall posture control evaluation in sports medicine.

Thus, the ability to stabilize to equilibrium in static (standing, sitting) positions and when moving (walking) is the most important motor-related aspect for the sports medicine. Testing and assessing this ability allows finding various proprioception deficiencies. In addition, rational interpretation of the stabilometric indicators and their comparison to the clinical tests of muscles enabling vertical posture help to improve rehabilitation programs designed for injured athletes and those suffering from musculoskeletal system disorders [10, 11]. Fig. 2 is an example of a stabilogram revealing a pronounced asymmetric stance shown by an athlete.

However, classical stabilometry has its limitations in assessing functions of the proprioceptive system: the latter makes use of the biological feedback principle, i.e. external stimuli lead to changes in the posture regulation strategy. Peripheral analyzer is the link fastest to respond to external stimuli. For the vertical stability regulation system, this analyzer is the ankle joint and the feet. If the support surface is stationary, it is impossible to assess how well does this peripheral analyzer functions when the posture responses are complex, much like those peculiar to the sport of records. In the 1960s, Freeman (trauma surgeon from the US) addressed this problem: unstable platform as part of the lower limbs injury rehabilitation program helped restore the peripheral analyzer's state to the optimal level through activation of foot and ankle receptors [10].

Currently, this or that variation of the unstable platform is widely used in rehabilitation of patients suffering the consequences of spinal cord traumatic disease, spine osteochondrosis complications, surgical treatment of hip, knee and ankle joints orthopedic pathology [10–12]. New methods that imply stimulation of muscles autochthonous to postural balance are developed and introduced. New exercisers are built around these methods; they have rigid and semi-rigid platforms that allow various degrees of angular displacement [12, 13].

However, mechanical exercisers were not designed to allow assessing postural control on an unstable surface. Diagnostics need platforms to have sensors recording athlete's response to their movements during examination. Current systems of this kind can have both a classical stabilometric platform and a less conventional balance rig incorporating a combined accelerometer-gyroscope that reports linear velocities and velocity-angle data against a system of coordinates. Balance metering (balancemetry) is the very method that produces accurate assessment of the functional activity of joint mechanoreceptors when that joint moves in space (Ruffini corpuscles), as well as record velocity of the joint angle change (Pacinian corpuscles). Balance metering systems equipped with an accelerometer and a gyroscope can register even minimal angular movements of the CoP and thus improve both proprioception diagnostics and stimulation during biofeedback sessions [14, 15].

From the point of view of diagnostics, balance metering systems add much value to the assessment of athletes' postural control of athletes. Such systems are also capable of targeted correction of postural disorders affecting biological response to proprioceptive, auditory and visual stimuli. Unlike classical stabilometric systems [16], unstable platform systems require active participation of the patient undergoing proprioceptive disorders treatment. Unstable platform means the patient needs to put effort into maintaining position of the body; the effort goes through muscles that stabilize posture, i. e. autochthonous, gluteal and hamstring muscles [11, 16]. The system's software registers body movements during diagnostics and treatment, which allows both verification of the primary postural control records and comprehensive rehabilitation monitoring [11, 17]. Besides, such systems offer extensive training sessions control tools, which gives the therapist an opportunity to design sessions taking into account the severity of the disease, compensatory reactions by central and peripheral nervous systems and musculoskeletal system, as well as the possible pathologies of these functional systems. Fig. 3 shows a mobile wireless balance metering platform.

Various hardware and software biomechanical diagnostics and correction systems apply the described principle of integral assessment of the proprioception system and feature an unstable platform. Fundamental research by Fellicetti,

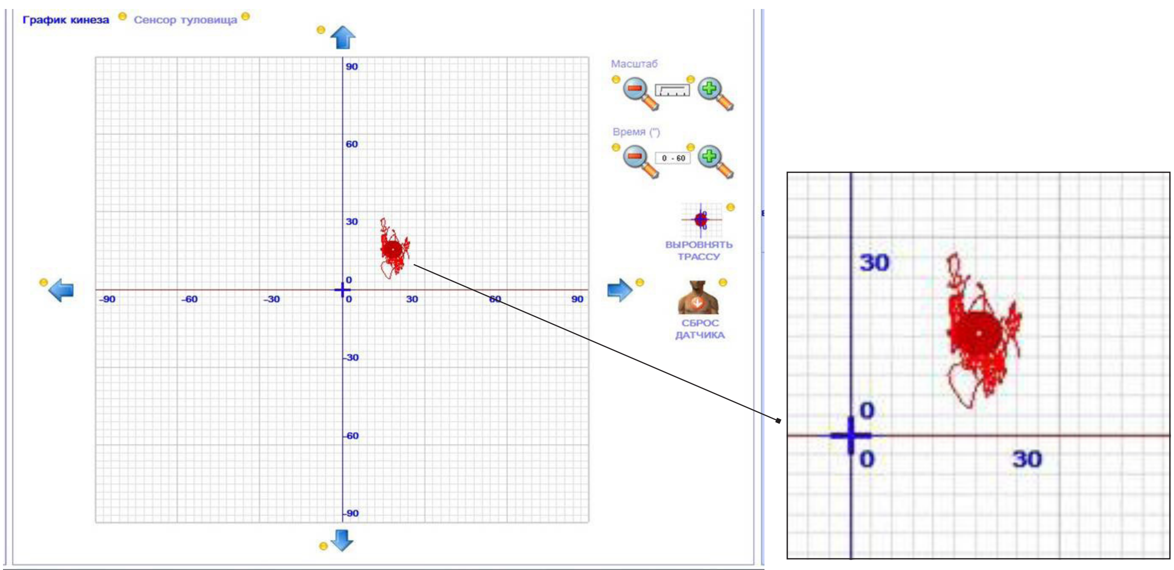

Fig. 2. Stabilogram of an athlete, GoP shifted towards the leading arm and leg. GoP velocity and area are significantly increased with clinical signs of muscular overstrain (right lower limb) in the background

Srivastava, Taly, Gupta, have proved this kind of equipment is highly efficient in treatment of proprioceptive disorders [19].

Baropodometry is one of the most promising methods of assessing postural control in athletes. Unlike stabilometry, baropodometry involves up to several tens of thousands strain gauges. These gauges register even the slightest movements of pressure exerted by feet and allow accurate assessment of CoP area and velocity (major postural diagnostics indicators) and dynamic changes of pressure peculiar to standing, walking, running and special dynamic tests [20].

Baropodometry systems make use of two types of gauges, capacitive and resistive. They register changes in electrical signal or medium resistance between the two plates. Capacitative gauges are more accurate, but their calibration is an intricate process, which is why they are only used in laboratory settings. Clinics find resistive gauge platforms more practical [21].

Baropodometry is developing rapidly. Researchers and designers remedy various faults found in early versions of gauges, like hypersensitivity, thermal sensitivity, unstable operation and insufficient robustness. Today, there are many variations of baropodometry platforms: compact systems for standing position assessment, walkways for gait analysis, treadmills, sensory insoles etc. Baropodometry also allows analysis of the feet's statodynamic function and gait. Baropodometry tests add much value to diagnostics of functional manifestations of flatfoot, monitoring rehabilitation from various neurological and orthopedic feet disorders. Such platforms form part of hardware and software systems designed to analyze movements and aide in manufacturing insole orthoses [20, 21].

Besides, some spine and autochthonous back muscles assessing methods grow more and more popular, including optical topography and regulated inclination trunk antigravitational muscles examination that requires a special set of hardware [22]. It should be noted that diagnostics of dynamic proprioceptive disorders in athletes is more accurate when biomechanical systems are used, those that ensure synchronization of different locomotion indicators registration methods (video analysis, myography), application of inertial systems making use of gyroscopes and accelerometers. We believe that wireless and inertial systems possess the greatest potential for comprehensive biomechanical examination of athletes in general and their proprioception systems in particular.

Another important aspect of the primary and dynamic assessment of postural control quality is local diagnostics of functions of ligaments and joints muscles. Electromyography and thermography are both good choices to this effect [23].

Biomechanical assessment of proprioception in athletes: methodology principles

The range of diagnostic equipment described above allows optimal and comprehensive assessment of athletes' postural stereotypes. In addition, such tools help reveal the symptoms of proprioception disorders, find proof backing clinical examination data, monitor proprioceptive data changes during the rehabilitation process [24]. However, our experience and various research efforts undertaken throughout the world suggest that the biomechanical equipment in question plays the most important role in designing rehabilitation programs [25].

Correct interpretation of clinical and biomechanical examination data require understanding of statodynamic peculiarities of various sports, preferences as to the arm or leg, physiological aspects influencing the supporting and dominating lower extremity [26].

Speaking of athletes, the main postural control diagnostics principles are:

• characterization of manifestation (degree) of asymmetry resulting from sports activities;

• vertical stability analysis - general, on one leg, when moving (motor coordination test);

• identification of the primary link in the proprioceptive disorders pathogenesis.

Postural asymmetry is a necessary component of an athlete's postural stereotype complex assessment. Signs of morphological and functional asymmetries can be found in major afferent elements, central and efferent posture control departments. Finding out the degree of asymmetry in athletes is closely related to ontogenetic features and the dominance of the "working" hand/leg in a particular sport [27–33].

In addition, it is necessary to assess the postural stereotype stability (control) both when the athlete takes the main stance and when he/she stands on one leg [28–30]. Gribble et al. [28] conducted a systematic comparative review of studies covering clinical and biomechanical aspects of athletes (competitive sports) and non-athletes doing the Star coordination test. This test is aimed at clinically assessing the vertical balance of the testee, who needs to stand on one leg and reach zones around him/her with the other leg. The postural biomechanical diagnostics data (stabilometry and baropodometry included) proved that the CoP shifts towards the dominating lower extremity when the testee takes the stance. Also, it was found that the testee's balance is better when he/she is standing on the dominating leg (applies to professional athletes, left for left-handed, right for right-handed) [28]. The results back the "working" asymmetry theory and the CoP shift toward the dominant lower limb as influenced by the functional requirements of the sport in question [34–36].

Fig. 3. Balance metering platform [18]

Biomechanical examination algorithm

Examination stage	Diagnostic method
Primary postural examination	• Classical stabilometry • Computer optical topography • Standard baropodometry
Identification of common proprioceptive balance disorders, vertical position	• Stabilometry (Romberg test) • Baropodometry (test on one leg)
Identification of statodynamic disorders of proprioception	• Balance metering (mono axis and multi axis tests) • Baropodometry (dynamic tests, frontal and sagittal directions) • Movements and gait analysis (video recorder, inertial wireless gauges, treadmill with baro-platform) • Examination of function of the trunk's antigravitational muscles, regulated inclination
Identification of functional local changes in muscles, ligaments and joints	• Electromyography • Thermography

These changes can be considered a manifestation of adaptive reorganizations of postural control. When physical overstrain is significant and also due to injuries, changes in practicing (different shoes, cover, position on the playing field), the posture regulation adaptation processes may be disrupted. Such a disruption may lead to disadaptation of intermuscular interactions, and if no correction measures are taken, appearance of compensatory changes. The latter up the risk of development of chronic musculoskeletal disorders in athletes [37–39].

Clinical and biomechanical criteria of disadaptation are:

1. pain in the overstrained part;
2. CoP shift towards the overstrained part;
3. functional deficiency of the muscles responsible for keeping the overstrained part's joints stable;
4. appearance of the secondary changes in parts undergoing compensatory changes.

Many years of clinical and biomechanical research in athletes allowed us to develop the following biomechanical examination algorithm (see table).

The results of the examination lead to the development of goals, structure, sequence of rehabilitation measures for athletes suffering from various proprioception system disorders.

CONCLUSION

We believe that the approach described above is the best option, since it takes into account the interrelationship between physiological capabilities of functional systems and training-related adaptation and compensatory processes specific to this or that nervous and musculoskeletal system pathology. It should also be emphasized that only complex biomechanical diagnostics allows obtaining meaningful data, which, in turn, can help to correctly assess the athlete's functional fitness and choose the most optimal way to stabilize and enhance it.

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