BŁASZKÓW, Krzysztof, SZYDŁOWSKA, Sara, ELIAS, Jagoda, BIESIADA, Wiktor, ZUBIAK, Marlena and KAŹMIERCZAK, Dominika. Application of ultrasonography in sports: A systematic review. Journal of Education, Health and Sport. 2025;80:59126. eISSN 2391-8306.
https://doi.org/10.12775/JEHS.2025.80.59126
https://apcz.umk.pl/JEHS/article/view/59126

The journal has had 40 points in Minister of Science and Higher Education of Poland parametric evaluation. Annex to the announcement of the Minister of Education and Science of 05.01.2024 No. 32318. Has a Journal's Unique Identifier: 201159. Scientific disciplines assigned: Physical culture sciences (Field of medical and health sciences); Health Sciences (Field of medical and health sciences).
Punkty Ministerialne 40 punktów. Załącznik do komunikatu Ministra Nauki i Szkolnictwa Wyższego z dnia 05.01.2024 Lp. 32318. Posiada Unikatowy Identyfikator Czasopisma: 201159. Przypisane dyscypliny naukowe: Nauki o kulturze fizycznej (Dziedzina nauk medycznych i nauk o zdrowiu); Nauki o zdrowiu (Dziedzina nauk medycznych i nauk o zdrowiu).
The authors declare that there is no conflict of interests regarding the publication of this paper.
Received: 02.03.2024. Revised: 25.04.2025. Accepted: 26.04.2025. Published: 27.04.2025.

APPLICATION OF ULTRASONOGRAPHY IN SPORTS: A SYSTEMATIC REVIEW

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Abstract

Ultrasonography (USG) plays a crucial role in the diagnosis and monitoring of sports injuries. Due to its accessibility, low invasiveness, and the ability to perform dynamic real-time examinations, USG is widely used in the assessment of muscle, tendon, ligament, and joint injuries. Modern technologies, such as elastography and power Doppler, enable precise analysis of the biomechanical properties of tissues, which facilitates the planning of therapy and rehabilitation. The aim of this study is to conduct a systematic review of the literature on the use of ultrasonography in sports, with a particular focus on its role in injury diagnosis and the optimization of treatment and recovery processes for athletes.

Aim of the review

The aim of this review is to evaluate the role of ultrasonography in the diagnosis and treatment of sports injuries. The advantages of this method, its limitations, and its applications in various sports disciplines are analyzed. Particular attention is given to modern imaging technologies and their impact on the effectiveness of treatment and injury prevention.

Results

Ultrasonography is an effective diagnostic method for detecting sports injuries, particularly in musculoskeletal damage, inflammatory conditions, and monitoring the tissue healing process. Through dynamic imaging, USG allows for real-time assessment of tissue functionality, enabling a more accurate determination of the location and severity of injuries. Modern techniques, such as elastography and the fusion of USG images with MRI, enhance diagnostic precision and facilitate personalized therapy. However, it has been noted that USG has its limitations, especially in diagnosing deep-seated anatomical structures, where magnetic resonance imaging (MRI) remains the more precise modality.

Conclusions

Ultrasonography is an invaluable tool in sports medicine, enabling rapid and effective injury diagnosis as well as rehabilitation monitoring. Its wide availability, capability for dynamic assessments, and low cost make it the first-choice method in many clinical cases. Further advancements in ultrasound imaging technology may contribute to even greater diagnostic precision and more effective therapy planning.

Keywords:

sports ultrasonography, injury diagnostics, musculoskeletal imaging, recovery monitoring, elastography, power Doppler, dynamic ultrasonography, injury prevention, muscle biomechanics assessment, interventional ultrasonography, tendon and ligament imaging, muscle overload evaluation

Introduction

Contemporary professional and amateur sports involve immense physical exertion, which can lead to overuse injuries, trauma, and other sports-related conditions. In response to these challenges, the development of modern diagnostic technologies has become a key element of sports medicine. One of the most dynamically evolving tools is ultrasonography (USG), which has gained widespread use in both the diagnosis and monitoring of sports injuries.

Ultrasonography is characterized by numerous advantages, such as accessibility, low invasiveness, and the ability to perform dynamic real-time examinations. It is used to assess injuries to muscles, tendons, ligaments, and joints, making it an indispensable method in sports medicine. Modern ultrasound techniques, such as elastography and the fusion of USG with MRI imaging, enable increasingly accurate diagnosis of sports-related pathologies and evaluation of treatment effectiveness.

This paper provides a systematic review of the use of ultrasonography in sports. It highlights its role in diagnosing musculoskeletal injuries, evaluates its effectiveness in detecting tissue overuse and microdamage, and discusses advanced imaging techniques used in modern sports medicine. The study aims to emphasize the importance of USG as a tool supporting injury prevention, optimization of rehabilitation processes, and monitoring of athletes' physical condition.

I. The Application of Ultrasonography in Sports

1. Ultrasonography in Sports Traumatology

Ultrasonography (USG) plays a significant role in the diagnosis of sports injuries, particularly in the assessment of muscle, tendon, and ligament damage. It is a fast, relatively inexpensive, and easily accessible method, making it a first-line tool in many cases [20]. A particular advantage of USG is the ability to perform examinations directly at the site of injury – in the locker room, on the field, or at the training center – allowing for immediate decisions regarding the athlete's further participation in competition [20].

Modern techniques, such as elastography and three-dimensional vascular imaging (3D vascular imaging), enable more precise evaluation of damaged structures and monitoring of the healing process [20]. A particularly promising direction of development is shear wave elastography (SWE), which allows for the assessment of the biomechanical properties of muscles and tendons, potentially facilitating the prediction of a full return to fitness [20]. However, there are still some limitations to this method. USG is not optimal for diagnosing injuries to deeper structures, such as the hip joint or cruciate ligaments, where magnetic resonance imaging (MRI) provides more detailed information [1].

2. Advances in Imaging Techniques for the Diagnosis and Treatment of Sports Injuries

The Role of Imaging in Sports Injury Management

Advancements in imaging techniques have significantly influenced the diagnosis and treatment of sports injuries. Modern sports medicine increasingly relies on imaging studies when making therapeutic decisions, both for acute injuries and chronic overuse conditions of the musculoskeletal system [19].

Ultrasonography has gained prominence as the "stethoscope" of sports medicine, allowing for dynamic assessment of anatomical structures and guiding interventional procedures such as ultrasound-guided intra-articular injections. Meanwhile, magnetic resonance imaging (MRI) remains the gold standard for evaluating deep soft tissue injuries, particularly in cases where ultrasound lacks sufficient precision [19].

When to Use Different Imaging Techniques?

The choice of imaging modality depends on several factors, including the nature, location, and stage of the injury. Standard guidelines recommend ultrasound as the first-line diagnostic tool for suspected muscle or tendon tears, inflammation of musculoskeletal structures, and monitoring the effectiveness of treatment for overuse tendinopathies [19].

MRI, on the other hand, is preferred when assessing bone marrow edema, intra-articular ligament injuries, or injuries of unclear etiology. In specific cases, such as suspected stress fractures, computed tomography (CT) may be required [19].

Modern technologies, such as elastography and the fusion of ultrasound images with MRI, allow for even more precise evaluation of anatomical structures. Elastography enables the assessment of the biomechanical properties of tissues, which is particularly valuable in diagnosing early degenerative changes in tendons and ligaments [19].

3. Diagnosis of Muscle Injuries

Muscles are structures that frequently suffer injuries in sports, and ultrasonography is one of the most effective tools for their diagnosis. USG allows for the assessment of the extent of damage, the presence of hematomas, calcifications, and scarring of muscle fibers [13].

In clinical practice, muscle injuries are classified into:

- **Functional injuries – involving overuse and microdamage without visible disruption of the muscle structure.**
- **Structural injuries – including partial and complete muscle tears, which can be easily detected using USG [13].**

Dynamic examination is also crucial in ultrasonographic diagnosis, as it enables the observation of the injured area during movement. In many cases, this allows for a more precise determination of the location and extent of the injury, which is essential for planning treatment and rehabilitation [13].

The use of power Doppler USG facilitates the evaluation of vascularization in affected areas. In the case of acute injury, increased blood flow may indicate active inflammation or an intense healing process [13].

4. USG in Physiotherapy, Sports Orthopedics and the Diagnosis of Upper and Lower Limb Injuries in Athletes

Ultrasonography (USG) has a wide range of applications in physiotherapy, sports orthopedics, and the diagnosis of sports injuries, both in assessing tissue conditions and monitoring treatment progress. It is particularly useful for evaluating tendon injuries, inflammatory changes in joints, and the effectiveness of therapy. In upper and lower limb injuries, USG plays a crucial role by enabling dynamic assessment of soft tissues, ligaments, and tendons. It is especially effective in imaging superficial structures such as tendons, ligaments, and muscles [3].

Applications of USG in Physiotherapy and Sports Orthopedics

USG is invaluable in the diagnosis and treatment of orthopedic conditions, including:

- **Tendon injuries, such as Achilles tendinopathy, where it allows for the assessment of tendon thickness, echogenicity, and vascularization [11].**
- **Inflammatory joint conditions, such as bursitis or enthesopathy, where power Doppler technology is used to evaluate vascularization and inflammation [11].**
- **Therapy effectiveness monitoring, for example, after shockwave therapy or platelet-rich plasma (PRP) injections [11].**

USG is also a valuable tool for guiding therapeutic procedures, such as intra-articular injections or hematoma aspirations. It enables precise needle placement under image guidance, increasing treatment effectiveness and minimizing complications [11]. However, routine USG use in rehabilitation may not always be necessary, as subjective symptom assessment and functional evaluation are often sufficient for clinical decision-making [11].

USG in the Diagnosis of Upper Limb Injuries

USG is widely used in assessing upper limb injuries, particularly in the shoulder, elbow, and wrist. In diagnosing rotator cuff pathology, ultrasonography has an accuracy comparable to MRI, especially for superficial injuries. One key advantage of USG is its ability to dynamically assess tendon movement and its interactions with surrounding structures, which is difficult to achieve with MRI [1].

Common Upper Limb Applications of USG:

- Rotator cuff injuries – assessment of partial and complete tendon tears [3].
- Biceps long head tendon inflammation, commonly associated with overuse injuries [3].
- Subacromial impingement syndrome, where dynamic USG can reveal shoulder impingement during motion [3].
- Tennis and golfer's elbow – detection of degenerative changes in the tendons at the humeral epicondyles [1].
- Carpal tunnel syndrome – evaluation of median nerve swelling and compression severity [1].

However, USG is limited in imaging cartilage and intra-articular structures. For suspected labral tears, MRI or MR arthrography provides more detailed information [1]. In some cases, additional MRI imaging may be required when USG results are inconclusive [3].

USG in the Diagnosis of Lower Limb Injuries

Ultrasonography plays a key role in diagnosing lower limb injuries, particularly ligament, tendon, and muscle damage. It is the first-line imaging modality for Achilles tendon injuries, allowing rapid assessment of damage severity and differentiation between complete rupture and tendinopathy [1].

Key Lower Limb Applications of USG:

- Achilles tendon injuries – assessment of degeneration, calcifications, and complete or partial ruptures [1].

- Muscle tears and ruptures, such as hamstring injuries [3].
- Ligament injuries, such as medial collateral ligament (MCL) tears, where dynamic USG tests assess joint stability [1, 3].
- Thigh and calf muscle injuries – identification of muscle damage, hematomas, and scar formation [1].

USG is also indispensable for diagnosing chronic tendinopathies and overuse injuries, such as iliotibial band syndrome, which is common in long-distance runners. Real-time imaging helps evaluate the extent of friction between the iliotibial band and the lateral femoral condyle during movement [1].

Using advanced techniques like power Doppler, clinicians can assess neovascularization in diseased tissues, aiding in treatment planning, including shockwave therapy or PRP injections [1].

5. Advanced USG Techniques in Assessing Inflammation in Athletes

Chronic overuse often leads to inflammation of tendons and ligaments, and USG is one of the most accurate tools for diagnosing these conditions. The use of power Doppler technology allows for the assessment of inflammatory activity by analyzing increased vascularization [14].

This enables the differentiation between degenerative tendinopathies and active inflammations, which is crucial for selecting the appropriate treatment strategy. For degenerative tendinopathies, shockwave therapy is often used, while anti-inflammatory treatments are more commonly applied in cases of active inflammation [14].

6. Gender Differences in USG Diagnostics

Studies indicate that there are significant differences in the frequency of sports injuries between men and women. Women are more prone to patellofemoral pain syndrome and anterior cruciate ligament injuries, while men more frequently experience Achilles tendon injuries and ankle ligament damage [25].

Ultrasonography allows for a more detailed analysis of the mechanisms behind these injuries and the identification of gender-specific risk factors, which can contribute to better planning of preventive programs [25].

II. Ultrasound Imaging of Muscles and Tendons in Elite Sports

As previously mentioned, ultrasonography (USG) is one of the primary diagnostic tools used to assess muscles and tendons in sports, including elite-level athletics. It is distinguished by its ability to perform dynamic imaging and its relatively low cost compared to magnetic resonance imaging (MRI) [24]. In clinical practice, USG allows for the rapid evaluation of overuse injuries, tears, and inflammatory conditions, as well as the monitoring of soft tissue healing. Real-time imaging enables the assessment of tendon mobility and muscle elasticity [24].

The application of USG in elite sports requires appropriate methodological adjustments and an understanding of factors influencing the quality of imaging results. Standardizing examination positions and controlling biomechanical variables that may affect ultrasound interpretation are crucial aspects [27]. In strength

and endurance sports, ultrasound can be used to monitor training adaptations and detect early signs of muscle and tendon overload [27].

Practical Aspects of USG Implementation in Sports:

- Determining optimal imaging parameters based on the type of physical activity.
- Considering the effects of muscle fatigue on tendon echogenicity and structure.
- Monitoring long-term adaptations of muscle structures at the level of individual muscle fascicles [27].

Modern Ultrasonographic Techniques for Muscle and Tendon Diagnostics

In recent years, Shear-Wave Elastography (SWE) has gained popularity as a precise method for assessing the biomechanical properties of muscles and tendons [29]. This technique quantitatively evaluates tissue stiffness by analyzing the propagation speed of shear waves. The use of SWE in elite sports enables the early detection of pathological changes before clinical symptoms appear [29].

A particularly important application of SWE is monitoring changes in tendon and muscle elasticity throughout the sports season and following injuries. Studies indicate that overloaded or injured tendons exhibit irregular stiffness profiles, which may increase the risk of re-injury [29].

Ultrasound in the Diagnosis of Muscle Injuries

Athletes are particularly prone to muscle injuries, especially in disciplines requiring sudden accelerations and changes in movement direction. USG is the primary tool for diagnosing these injuries, as it allows both structural and functional assessment of muscle tissue [24].

Sports-related muscle injuries are often classified based on ultrasound imaging findings:

- Type I injuries: Microdamage to muscle fibers without significant hematoma.
- Type II injuries: Partial muscle tears with fluid collections.
- Type III injuries: Complete muscle ruptures with fiber retraction and significant hematoma formation [24].

In summary, USG enables effective monitoring of muscle healing dynamics and can be used to estimate the return-to-play timeframe for athletes [24].

Rhabdomyolysis and Ultrasonography

Rhabdomyolysis, a severe condition involving skeletal muscle damage leading to necrosis, can be a major concern in elite sports, especially in high-intensity disciplines. Ultrasound enables the early detection of rhabdomyolysis by identifying characteristic changes such as heterogeneous muscle echogenicity, swelling, and anechoic areas indicative of necrosis [6].

Furthermore, USG can be utilized to monitor recovery after an episode of rhabdomyolysis, providing insight into the restoration of normal muscle architecture and the reduction of swelling [6].

Ultrasound in the Assessment of Muscle Glycogen Stores

Modern ultrasound techniques are being explored for their potential to non-invasively assess muscle glycogen levels. However, research findings on this application remain inconclusive [5]. Some studies have observed a correlation between ultrasound echogenicity and glycogen content, while others question the reliability of this method in evaluating muscle energy status [5].

Due to the lack of definitive evidence, the use of ultrasound for glycogen monitoring in sports remains under investigation. Currently, biochemical methods and magnetic resonance spectroscopy (MRS) remain the standard techniques for assessing muscle glycogen levels [5].

Effects of Immobilization on Muscle Structure

Ultrasound imaging has also been instrumental in studying muscle architecture changes following immobilization, such as after an injury. Advanced techniques, including panoramic USG imaging, allow for the precise assessment of alterations in muscle fascicle length and pennation angle, which are critical factors in rehabilitation planning [26].

III. Diagnosis and Treatment of Sports Injuries

Flexor Pulley Injuries in Climbers

Sport climbing carries a particularly high risk of flexor pulley injuries, which stabilize the flexor tendons and prevent them from separating from the phalangeal bones. The A2 pulley is the most frequently injured, presenting with sudden pain, swelling, and a reduced ability to maintain grip strength [21].

Ultrasound (USG) is the key diagnostic tool for assessing these injuries, allowing for the visualization of pulley ruptures and the presence of tendon subluxation. In dynamic ultrasound examination, flexor tendon bowstringing during finger flexion is a characteristic sign of pulley damage [21].

Treatment options include conservative management (splinting and a gradual return to loading) or surgical intervention in cases of complete rupture. USG also plays a crucial role in monitoring healing progress and assessing the athlete's readiness to return to climbing [21].

Iliotibial Band Syndrome (ITBS) – The Role of Ultrasound in Diagnosis and Therapy

Z Iliotibial Band Syndrome (ITBS) is a common cause of lateral knee pain in long-distance runners. It results from repetitive tension and friction of the iliotibial band (ITB) against the lateral femoral condyle, leading to irritation and inflammation [12].

Ultrasound imaging is essential for accurately assessing ITB thickness, detecting inflammatory fluid, and visualizing ITB friction over the femoral condyle during knee flexion and extension. Power Doppler can further evaluate inflammatory activity, aiding in treatment planning [12].

Treatment strategies for ITBS include:

- biomechanical adjustments to running technique,
- manual therapy to address muscular imbalances,
- progressive strengthening and stretching exercises.

USG can also be used to monitor treatment effectiveness and determine return-to-sport readiness [12].

Hamstring Injuries – Diagnosis and Treatment

Hamstring muscle injuries are among the most common sports injuries, especially in disciplines requiring sprinting, sudden stops, and rapid directional changes. They are classified into:

- Type I injuries – Occurring during eccentric muscle contraction at high running speeds.
- Type II injuries – Caused by excessive stretching, often during kicking or lunging movements [8].

USG is a crucial tool for differentiating hamstring muscle tears from proximal tendinopathy, which is often chronic and results from repeated overload [8].
Treatment includes:

- Progressive rehabilitation, focusing on increasing eccentric loading and controlled range of motion.
- PRP and corticosteroid injections, though their efficacy in reducing recovery time remains controversial [8].

Tendon Loading in Achilles Tendinopathy

Achilles tendinopathy is a common issue among runners and athletes in jumping sports. The rehabilitation process requires careful biomechanical load management, and USG serves as a key tool for evaluating structural and functional changes in the tendon [9]. Shear-wave elastography (SWE) enables precise assessment of tendon stiffness and can detect abnormalities before clinical symptoms appear, helping prevent recurrence [9]. Studies show that pain does not always correlate with structural changes in USG imaging, emphasizing the importance of comprehensive patient evaluation, including functional parameters [9].

Treatment includes:

- Eccentric training to promote tendon adaptation.
- Gradual load progression to optimize healing.
- Monitoring structural changes in the tendon throughout rehabilitation.
- Return to sport should be based on functional recovery rather than pain resolution alone [9].

Predicting Return to Sport After Muscle Injuries

Imaging studies, particularly USG and MRI, are widely used to assess the extent of muscle injuries and predict the time required to return to sports. The degree of muscle damage correlates with the length of recovery, and ultrasound classifications (e.g., the Peetrons scale) help determine the severity of the injury [22].

Studies on soccer players have shown that the presence of extensive intermuscular damage and intramuscular hematomas can significantly prolong the time needed for recovery. Although MRI provides more detailed information about deep tissue injuries, USG is a more accessible and sufficiently precise method for evaluating superficial muscle damage [22].

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Screening for Tendinopathy Risk

Ultrasonography can be used in the prevention of sports injuries by identifying athletes at risk of developing tendinopathies. In particular, USG is effective in assessing the structure of the Achilles tendon and patellar tendon in long-distance runners [10].

Ultrasound changes, such as tendon thickening, hypoechogenicity, and neovascularization, have been linked to a higher risk of developing pain within the next 12 months. However, not all abnormalities in ultrasound imaging lead to symptomatic tendinopathy – some may simply be a physiological adaptation to training loads [10].

Diagnosis of Inguinal Hernias in Athletes

Chronic groin pain in athletes may result from inguinal hernias, which often remain undiagnosed during standard clinical evaluation. Dynamic ultrasonography allows for real-time assessment of the mobility of inguinal structures, enabling more effective identification of the problem compared to traditional static examinations [30].

Inguinal hernias can be confused with other conditions, such as pubic symphysis inflammation or muscle attachment tears. USG plays a key role in differentiating these pathologies and determining the indications for surgical treatment. Studies show that athletes who undergo inguinal hernia surgery can return to full activity within a few months if the rehabilitation process is appropriately tailored [30].

IV. Ultrasonography in Sports Cardiology

The Role of Echocardiography in Sports Cardiology

Echocardiography is one of the primary diagnostic tools in sports cardiology, allowing for the assessment of structural and functional changes in athletes' hearts. Intense physical exertion leads to cardiac adaptations, which may manifest as physiological left ventricular hypertrophy (LVH) or pathological changes associated with cardiac overload [7].

A study by the Italian Society of Sports Cardiology highlighted the importance of echocardiography as a screening method, particularly in evaluating the risk of sudden cardiac death (SCD) in athletes.
Proper interpretation of imaging results allows for differentiation between physiological adaptations and pathological conditions such as hypertrophic cardiomyopathy (HCM) or arrhythmogenic right ventricular cardiomyopathy (ARVC) [7].

Italy is one of the few countries where mandatory echocardiographic screening has significantly reduced the incidence of sudden cardiac death in athletes. In contrast, countries that rely mainly on electrocardiograms (ECGs) for screening may fail to detect some underlying heart abnormalities [7].

Hypertrophic Cardiomyopathy in Young Athletes – Diagnostic Potential of USG

Hypertrophic cardiomyopathy (HCM) is the most common genetic heart disease and the leading cause of sudden cardiac death in young athletes. It is typically diagnosed using transthoracic echocardiography (TTE), with cardiac magnetic resonance imaging (CMR) sometimes used for confirmation.

Studies suggest that point-of-care ultrasound (POCUS) performed by trained medical students effectively detects HCM, raising the possibility of implementing ultrasound-based screening programs for athletes [16].

A prospective study of over 2,300 young athletes found that interventricular septal thickness and posterior left ventricular wall thickness measurements enabled early detection of HCM cases. The study reported 5.8% positive screening results, with 5% of cases confirmed as true HCM by a pediatric cardiologist [16].

Despite the high sensitivity of POCUS for detecting HCM, false positives remain an issue. Increased septal thickness alone does not necessarily indicate pathology, as it may also result from physiological cardiac adaptations, particularly in strength-trained athletes [16].

Echocardiographic Differences Among Athletes in Various Disciplines

The cardiac structure of athletes varies depending on their sport.

- Endurance training (e.g., long-distance running) leads to eccentric left ventricular hypertrophy, characterized by increased chamber size.
- Strength training (e.g., bodybuilding, powerlifting) results in concentric hypertrophy, where the ventricular wall thickens without significantly enlarging the chamber [28].

Key echocardiographic differences observed across athletic disciplines:

- Powerlifters and bodybuilders had greater interventricular septal and posterior left ventricular wall thickness than runners and soccer players [28].
- Endurance athletes exhibited a higher left ventricular mass index and greater end-diastolic volume, indicating adaptation to chronic volume overload [28].
- Prolonged QT interval (QTd) was observed in bodybuilders and powerlifters, which may have clinical significance regarding ventricular arrhythmias [28].

These differences underscore the need for individualized echocardiographic assessments to distinguish between physiological adaptations and pathological hypertrophy, which could increase an athlete's cardiac risk [28].

Impact of Echocardiography on Return-to-Sport Decisions

Echocardiography plays a crucial role not only in diagnosing cardiac conditions but also in monitoring athletes after cardiac events. For athletes diagnosed with left ventricular hypertrophy or structural abnormalities, a detailed assessment of diastolic function and arrhythmic risk is necessary before returning to sport [7].

Key factors in return-to-play decisions:

- Degree of left ventricular wall hypertrophy and relaxation abnormalities [7].
- Risk of ventricular arrhythmias, assessed via QT prolongation and echocardiographic remodeling indices [28].
- Extent of myocardial fibrosis, evaluated via CMR in cases with inconclusive echocardiographic findings [7].

V. Ultrasonography in Respiratory Function and the Vascular System

The Role of Ultrasonography in Assessing Respiratory Muscles

Ultrasonography (USG) is increasingly being used to assess respiratory muscle function, including the diaphragm and intercostal muscles. Studies have shown that ultrasound parameters, such as diaphragm thickness at rest and during inhalation, correlate with respiratory muscle strength and overall pulmonary performance [23]. This is particularly relevant for monitoring athletic adaptation of the respiratory system to intense endurance training.

One of the key ultrasonographic parameters is the Diaphragm Thickening Fraction (DTF), which evaluates diaphragm efficiency during breathing. Endurance athletes, such as swimmers and long-distance runners, may develop an adaptive increase in diaphragm thickness, potentially linked to enhanced respiratory efficiency [23].

Additionally, USG can detect pathological conditions, such as reduced diaphragm mobility, which may indicate respiratory muscle fatigue or more severe dysfunctions, such as phrenic nerve injury [23]. Compared to traditional pulmonary function tests like spirometry or electromyography (EMG), USG offers real-time, non-invasive imaging without requiring complex procedures.

Exercise-Induced Pulmonary Edema in Swimmers

Swimming-Induced Pulmonary Edema (SIPE) is a condition observed in swimmers training in cold water. While its exact mechanism remains unclear, it is associated with fluid accumulation in the alveoli due to increased hydrostatic pressure in the lungs during submersion [18].

Studies have demonstrated that lung ultrasound (LUS) is an effective diagnostic tool for detecting SIPE, as it can identify B-lines – artefacts indicative of interstitial fluid presence in lung tissue. A study involving a large group of cold-water swimmers confirmed LUS-detected pulmonary edema in 64% of athletes who reported dyspnea and coughing [18].

Moreover, a combination of LUS findings, oxygen saturation below 95%, and auscultatory crackles proved to be a highly effective method for diagnosing SIPE [18].

In the sports context, early detection of SIPE is crucial to prevent severe complications and avoid continued exposure to extreme environmental conditions. LUS offers advantages over traditional radiologic methods, as it can be performed on-site at competitions, providing immediate diagnostic results [18].

Ultrasonography in Assessing Vascular Changes in Endurance Athletes

USG is also valuable in evaluating vascular changes that may occur in endurance athletes, such as long-distance runners and cyclists. One notable finding is the presence of non-atherosclerotic arterial wall changes in amateur runners, likely due to prolonged cardiovascular stress [4].

Ultrasound studies have shown that 95% of amateur runners exhibited vascular changes in the lower limb arteries, including:

- Blurring of the intima-media boundary (intima-medial blurring).
- Small wall nodules, primarily affecting the popliteal artery and appearing bilaterally [4].

Notably, these changes did not resemble atherosclerosis, as the athletes had normal lipid profiles and lacked traditional cardiovascular risk factors.

There is speculation that these vascular changes result from mechanical stress, such as repetitive microtrauma and vibrations acting on the lower limbs during prolonged running [4]. However, the clinical significance of these changes remains uncertain. Further long-term studies are needed to determine whether these alterations negatively impact vascular health or represent an adaptive response to prolonged physical exertion.

Application of Ultrasonography in Vascular Function Assessment

Doppler ultrasound is widely used to evaluate blood flow in large vessels and to detect pathologies such as venous thrombosis or arterial stenosis. In sports, ultrasonography can be useful for assessing vascular responses to physical exertion, enabling the identification of abnormalities that may increase the risk of thromboembolic complications [4].

Studies on endurance athletes have shown that prolonged exercise can lead to changes in vascular reactivity, which may impact cardiovascular performance. These observations may have practical implications for planning training programs and assessing the risk of cardiovascular complications in athletes [4].

VI. Specific Applications of Ultrasonography in Sports

Expanded Applications of Ultrasonography in Sports Medicine

Ultrasonography (USG) is widely used in the diagnosis of musculoskeletal injuries, but its applications in sports extend beyond the standard assessment of soft tissues and joints. It is increasingly being utilized in the diagnosis of internal organ injuries and the evaluation of athletes' metabolic parameters [15].

One example is the extended post-traumatic assessment using the eFAST (Extended Focused Assessment with Sonography for Trauma) protocol, primarily used in emergency medicine. It can be useful in diagnosing athletes with chest and abdominal injuries, allowing for the rapid detection of pneumothorax, injuries to parenchymal organs (e.g., liver, spleen), and internal bleeding [15].

Bone Density Assessment in Combat Sports Athletes

Quantitative Ultrasound (QUS) is used to assess bone density, particularly in athletes engaged in weight-bearing sports such as martial arts. Studies have shown that individuals practicing traditional karate and Okinawa Kobudo have higher heel bone mineral density compared to the general population [17].

Long-term training leads to adaptive changes in bone structure, increasing its strength and reducing the risk of fractures. QUS is a non-invasive method that can be used to assess the risk of osteoporosis and analyze the impact of long-term training on bone tissue [17].

Use of Ultrasonography in Movement Biomechanics Analysis

Ultrasonography can also be used as a tool for biomechanical analysis. It has been demonstrated that USG can provide significant information about changes in muscle fiber length and pennation angle in real time, enabling precise assessment of muscle function during movement [2].

In particular, the hamstrings are often analyzed in terms of movement biomechanics, as their dysfunction is one of the main causes of injuries in athletes. Ultrasonography allows for the evaluation of how

muscle length and tension change during different phases of running or jumping, which can be important for training programming and injury prevention [2].

Moreover, dynamic USG enables the assessment of muscle function under natural conditions, which is not possible with MRI. This allows coaches and physiotherapists to analyze the efficiency of movement techniques and make appropriate training adjustments based on objective data.

Monitoring Tissue Regeneration and Adaptation

Traditionally, ultrasonography (USG) has been used primarily for diagnosing muscle and tendon injuries, but it is now increasingly utilized for monitoring tissue regeneration processes. In elite sports, it is crucial to determine whether soft tissues have fully recovered before an athlete resumes intensive training.

Studies have shown that USG can track changes in tissue echogenicity throughout the healing process. For example, regenerating muscle fibers exhibit structural alterations in muscle layering, which can be detected using advanced ultrasonographic techniques [15].

Additionally, USG is useful in assessing the effectiveness of treatments, such as shockwave therapy or platelet-rich plasma (PRP) injections. By tracking structural changes in tendons and ligaments, ultrasound allows for treatment effectiveness evaluation and helps adjust training loads during the return-to-sport process [15].

Sonographic Assessment of Nerve Structures – Diagnosis of Sports Neuropathies

USG is also used for evaluating sports-related neuropathies, such as carpal tunnel syndrome, ulnar nerve entrapment, and tibial nerve compression. The ability to perform dynamic nerve assessments allows for more precise diagnosis of neuropathies and their rehabilitation monitoring [15].

In sports that require intense upper limb activity, such as tennis or rock climbing, USG is a valuable tool for detecting compression and overuse neuropathies. It can replace costly MRI examinations in cases where rapid assessment and therapeutic intervention are needed [15].

Monitoring Internal Injuries Using USG

In contact sports, such as American football or rugby, internal organ injuries pose a significant health risk for athletes. Ultrasound serves as a rapid and effective diagnostic tool for post-traumatic evaluation, allowing for the detection of internal bleeding and solid organ damage [15].

This application is particularly valuable in competition settings, where quick decision-making regarding whether an athlete can continue playing or needs urgent medical attention is critical. Timely ultrasound assessment can help prevent serious health complications and improve injury management in high-risk sports [15].

Conclusions

Ultrasonography is one of the key diagnostic tools in modern sports medicine. Its wide application in the assessment of musculoskeletal injuries, diagnosis of inflammatory conditions, and monitoring of rehabilitation processes makes it an indispensable element of an interdisciplinary approach to athletes' health.

Due to its accessibility, safety, and the ability to perform dynamic real-time examinations, USG is often the first-choice method in the diagnosis of sports injuries.

Modern ultrasound technologies, such as elastography, power Doppler, and the fusion of USG with MRI imaging, enable even more precise evaluation of anatomical structures and biomechanical properties of tissues. This allows for accurate monitoring of the recovery process and tailoring therapy to the individual needs of athletes.

Despite its many advantages, ultrasonography is not without limitations. For deep anatomical structures, such as the hip joint or cruciate ligaments, magnetic resonance imaging (MRI) remains a more precise method. Nevertheless, in the diagnosis of superficial injuries, assessment of overuse conditions, and support of therapeutic procedures, USG remains an irreplaceable tool.

In summary, ultrasonography plays a fundamental role in modern sports, contributing to more effective injury prevention, optimization of treatment processes, and faster return to full physical fitness. Further research into new imaging technologies will allow for even greater diagnostic precision and further refinement of therapeutic methods used in both professional and amateur sports.

Authors' contribution

All authors contributed to the article. Conceptualization – Krzysztof Błaszków; methodology – Sara Szydłowska, Jagoda Elias; check - Marlena Zubiak, Dominika Kaźmierczak; formal analysis – Wiktor Biesiada; resources – Jagoda Elias; data curation – Wiktor Biesiada; writing - rough preparation – Dominika Kaźmierczak; writing - review and editing – Krzysztof Błaszków, Wiktor Biesiada; visualization – Dominika Kaźmierczak; supervision – Sara Szydłowska; project administration – Krzysztof Błaszków. All authors have read and agreed with the published version of the manuscript.

Disclosures: No disclosures.

Financial support: No financial support was received.

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

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