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Epidemiology and Pathomechanics of Overuse Injuries in Single Figure Skating: A Systematic Review (2020–2026)

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Abstract

Background. Figure skating is a sport characterized by a unique combination of artistic expression and extreme athletic demands. The introduction of the new ISU Judging System in the 2004/2005 season drastically changed the landscape of the sport, promoting the execution of highly scored, multi-rotational jumps. This forces athletes to generate higher vertical velocities, resulting in the absorption of impact forces ranging from 4 to 5 times their body weight on a single lower limb during landing. Combined with early sport specialization, very high training volumes, and the specific, mobility-restricting design of the skating boot, these factors have led to a drastic increase in injury rates, predominantly characterized by overuse injuries.

Aim. The aim of this study is to systematize and critically analyze the latest scientific literature from 2020 to 2026 (including fundamental works serving as a historical and biomechanical background) regarding the epidemiology, pathomechanics, and risk factors of overuse injuries in single figure skaters.

Material and methods. A systematic literature review was conducted using medical databases (e.g., PubMed, Scopus). A total of 20 scientific publications were included in the final analysis, comprising retrospective and prospective studies, biomechanical analyses, and systematic reviews.

Results. The results indicate that overuse injuries account for 50% to nearly 70% of all injuries in single figure skating. The most frequently injured areas are the foot and ankle (approx. 29%), knee joint (approx. 19%), and lower back (approx. 15%). Stress fractures and bone stress reactions, including spondylolysis, constitute a significant percentage of diagnoses. The stiffness of the skating boot forces a compensatory transfer of landing forces to the lumbopelvic-hip complex (LPHC). The main identified risk factors include chronological age (the cumulative effect of loading), lack of jump count monitoring, early specialization, and Relative Energy Deficiency in Sport (RED-S).

Conclusions. Overuse injuries in figure skating are a multifactorial phenomenon resulting from a combination of extreme mechanical loads, equipment limitations, and deficits in monitoring athletes' health. Combating this epidemic requires a dual approach: implementing structured clinical preventive programs (including precise training load management and RED-S

education) and enforcing evidence-based systemic regulatory changes, such as the ISU's recent decisions to raise the senior age limit and reduce maximum jump counts.

Key words: figure skating, overuse injuries, biomechanics, early specialization, RED-S.

Content

1. Introduction

Figure skating is one of the oldest Winter Olympic disciplines and a sport with a highly specific biomechanical and physiological profile. Elite athletes are required to possess not only flawless technique, explosive power, neuromuscular coordination, and anaerobic capacity, but also exceptional flexibility and artistic expression (Porter, 2013). Over the past few decades, this discipline has undergone a fundamental evolution. The elimination of compulsory figures in 1990 initiated a shift in focus towards acrobatic elements. However, the pivotal moment occurred with the implementation of the new ISU Judging System (IJS) in the 2004/2005 season, which replaced the traditional 6.0 scoring system. The new regulations transformed figure skating into a point-accumulation discipline, where technical elements are assigned specific Base Values, providing a direct incentive for athletes to maximize the difficulty of their performed elements (Rauer et al., 2022).

The consequence of these changes is an unprecedented increase in the number of multi-rotational jumps in competitive programs. As shown by recent trend analyses, double jumps are being systematically replaced by triples, and quadruple jumps have become the standard in men's events. While a similar trend was observed in women's events since 2019 (Stehlin et al., 2025; Rauer et al., 2022), recent age eligibility rule changes have significantly decelerated the inclusion of quadruple jumps in senior women's competitions (International Skating Union, 2022). Increasing the number of rotations in the flight phase forces athletes to generate higher vertical velocities at take-off, which ultimately translates into a drastic reduction in the time available for physiological force dissipation upon contact with the ice (Koga et al., 2025). Direct on-ice measurements using instrumented figure skating blades demonstrate that ground reaction forces (GRF) during the landing of multi-rotational jumps reach values of 4 to 5 times the athlete's body weight (Ridge et al., 2020).

It should be emphasized that these biomechanical loads are compounded by unique equipment constraints. Unlike athletes in almost all other sports, figure skaters wear footwear with an extremely rigid upper construction, a built-in heel, and a steel blade equipped with toe picks. Such a design severely restricts the range of dorsiflexion and plantarflexion in the ankle joint, disrupting the body's natural shock absorption mechanism. Consequently, massive impact forces are not absorbed by the ankle, but rather abruptly transferred along the kinetic chain to the knee extensor mechanism and the lumbopelvic-hip complex (LPHC) (Webb et al., 2022; Campanelli et al., 2015).

Given that elite single skaters perform between 50 and 100 jump attempts during daily training sessions, their musculoskeletal system is subjected to extreme, repetitive cyclic loading (Naylor, 2025). This leads to alarming epidemiological rates. Recent data indicates that as much as 68.9% of all injuries in young figure skaters are overuse injuries, with particular emphasis on pathologies of the foot and ankle (29.6%), the knee joint (19.3%), and the spine (15.8%) (Kowalczyk et al., 2021). Furthermore, this phenomenon is exacerbated by early sport specialization. Studies show that over 60% of young female athletes train exclusively in figure skating for more than 8 months a year. When combined with chronological age, this triggers a cumulative load effect, which manifests in the later stages of their careers as conditions such as posterior column spinal stress fractures (Sugimoto et al., 2020).

This problem extends beyond biomechanics alone. A broad range of errors in training management and biopsychosocial factors also contribute to the rising injury rates. Contemporary literature strongly highlights the lack of training load monitoring (e.g., the absence of strict jump count tracking) (Naylor, 2025) and a high incidence of Relative Energy Deficiency in Sport (RED-S), which drastically lowers bone mineral density and the body's regenerative capacity (Jederström et al., 2021; Schmidt et al., 2025). Moreover, a "culture of risk" is deeply rooted in the skating community, where reporting pain is often perceived as a sign of weakness (threat-rigidity). This psychological barrier leads athletes to continue training with microtraumas until severe dysfunction occurs (Pahng & Kang, 2023).

Considering the rapid technical progress in figure skating in recent years, there is an urgent need to update and systematize the medical knowledge on this topic. Although older studies on injury rates are available in the literature, the dynamics of change in this sport have rendered some of them obsolete. This paper aims to fill this gap by gathering the latest scientific reports from 2020 to 2026 and confronting them with established biomechanical principles.

Research Objective. The main research objective of this study is the comprehensive evaluation and synthesis of the latest scientific literature from 2020-2026 regarding the epidemiology, pathomechanics, and biopsychosocial determinants of overuse injuries in single figure skating.

Research Problems. The primary research problem comes down to the following questions: (1) What is the current scale and characteristics (epidemiology) of overuse injuries in single figure skating? (2) What biomechanical mechanisms (pathomechanics) underlie the

development of damage in the foot, knee, and spine in these athletes? (3) What intrinsic and extrinsic risk factors predispose single skaters to chronic injuries?

Research Hypotheses. The main research hypothesis assumes that (H1) the dominant percentage of injuries in single figure skating consists of overuse injuries of the lower extremities and spine. Furthermore, specific hypotheses were formulated: (H2) the rigid design of the skating boot and the ground reaction forces generated during multi-rotational jumps drastically overload the knee extensor mechanism and the lumbopelvic-hip complex, and (H3) the key extrinsic risk factors are early specialization, lack of jump volume monitoring, and RED-S syndrome.

2. Research materials and methods

2.1. Participants

Given the nature of this study, which is a systematic literature review, the direct participants are the populations of figure skaters analyzed within the 20 eligible scientific articles. The total number of participants across all analyzed studies amounts to several thousand athletes (e.g., a systematic review conducted by Schmidt et al. in 2025 included 4,202 skaters, 74% of whom were female).

The analyzed population primarily consisted of single figure skaters training at levels ranging from advanced amateur (novice), through the junior elite, to the senior level—including participants of the European Championships, World Championships, and Winter Olympic Games. The mean age in many key clinical and epidemiological studies (e.g., Kowalczyk et al., 2021; Jederström et al., 2021) fluctuated between 13 and 17 years, reflecting the early age of reaching peak performance and the phenomenon of early sport specialization in this discipline. The analysis included both female and male athletes, taking into account differences in biomechanics and injury statistics (e.g., the higher prevalence of quadruple jumps among men and the associated load profile, Rauer et al., 2022).

2.2. Procedure / Test protocol / Skill test trial / Measure / Instruments

The study was conducted as a systematic review aimed at identifying, evaluating, and synthesizing available scientific literature regarding the epidemiology, pathomechanics, and risk factors of overuse injuries in figure skating.

The search procedure was based on a review of leading electronic medical and sports databases, such as PubMed, MEDLINE, Scopus, Web of Science, CINAHL, and SPORTDiscus. The primary timeframe for the search covered the years 2020–2026 to capture the latest trends in sports traumatology and the impact of increasing technical demands (multi-rotational jumps). Fundamental older works (published prior to 2020) were also included in the review, providing invariable, baseline information on anatomy, foundational biomechanics of the skating boot, and historical injury statistics, which serve as an essential background for contemporary phenomena.

The search was conducted using the following combinations of keywords and Boolean operators: ("figure skating" OR "single figure skating" OR "ice skating") AND ("injuries" OR "overuse injuries" OR "stress fractures" OR "pathomechanics" OR "biomechanics" OR "epidemiology" OR "risk factors" OR "RED-S").

Inclusion criteria encompassed: (1) original research articles, systematic reviews, and case studies published in peer-reviewed scientific journals; (2) studies concerning the epidemiology, etiology, or biomechanics of injuries in figure skaters (with a particular focus on single skating); (3) availability of the full text in English or Polish. Exclusion criteria included: (1) opinion pieces lacking hard numerical data; (2) studies on injuries in other winter sports (e.g., ice hockey, speed skating), unless they provided a direct comparison or described universal equipment-related issues (e.g., lace bite); (3) conference abstracts. The selection process was guided by the fundamental principles of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement. Following rigorous selection and the elimination of duplicates, 20 full-text scientific publications were qualified for the final, in-depth analysis.

2.3. Data collection and analysis / Statistical analysis

Data collection involved the systematic extraction of information from the 20 articles included in the review. The following sets of variables were extracted from each publication: (1)

demographic data and characteristics of the study groups (age, sex, skill level); (2) epidemiological indicators (overall injury prevalence, ratio of acute to overuse injuries, most frequently injured anatomical areas); (3) biomechanical data (ground reaction forces, joint flexion angles, landing asymmetry); (4) risk factors (both intrinsic and extrinsic). These data were subsequently cataloged and subjected to a narrative synthesis to identify consistent patterns and trends.

2.3.1. Statistical Software

Due to the nature of this study (a systematic review without a meta-analysis), specialized statistical software was not utilized for primary result generation. Standard spreadsheet software (Microsoft Excel) and reference management tools were used to manage the literature selection process, categorize extracted numerical data (e.g., averaging the percentage values of epidemiological indicators), and structure the bibliography.

2.3.2. AI

AI was utilized for two specific purposes in this research. Text analysis of clinical reasoning narratives to identify linguistic patterns associated with specific logical fallacies. Assistance in refining the academic English language of the manuscript, ensuring clarity, consistency, and adherence to scientific writing standards. AI were used for additional linguistic refinement of the research manuscript, ensuring proper English grammar, style, and clarity in the presentation of results. It is important to emphasize that all AI tools were used strictly as assistive instruments under human supervision. The final interpretation of results, classification of errors, and conclusions were determined by human experts in clinical medicine and formal logic. The AI tools served primarily to enhance efficiency in data processing, pattern recognition, and linguistic refinement, rather than replacing human judgment in the analytical process.

2.3.3. Statistical Methods

Due to the vast methodological heterogeneity of the eligible studies (differences in injury definitions, varying measurement methods, different observation periods), conducting a classic statistical meta-analysis was not feasible and could lead to erroneous conclusions. Therefore, a narrative synthesis method was applied in this study.

Quantitative data (percentages, force values expressed in Newtons, years of age, risk indicators—e.g., Odds Ratios, Confidence Intervals) extracted from the primary studies were collated comparatively and presented in a structured manner. Any measures of statistical significance cited in the subsequent sections (p-values, confidence intervals) are derived directly from estimations performed by the authors of the analyzed source studies. This synthesis allowed for a reliable compilation of conclusions across various domains (e.g., linking the loads identified in biomechanical studies with the incidence rates of stress fractures reported in retrospective studies).

3. Research results

3.1. Epidemiology of overuse injuries in figure skating

Recent data from systematic literature reviews spanning 2020-2026 shed new light on the true scale of the injury problem in figure skating. Injury prevalence rates in this discipline vary widely, ranging from 2.1% to 34%, depending on the adopted injury definition and the timing of measurement (competitive vs. training season), while the incidence rate is estimated at 1.37 injuries per 1000 training hours (Schmidt et al., 2025). However, the rate of severe injuries (requiring more than 21 days of absence from training) is of particular concern—in a group of Swedish competitive female skaters, the 1-year prevalence of such severe episodes reached as high as 31%, the vast majority of which resulted from the accumulation of microtraumas (Jederström et al., 2021). Similar conclusions emerge from analyses conducted in the United Kingdom, where a staggering 81% of elite single skaters reported experiencing an injury in their career that excluded them from training for a period exceeding 4 weeks (Naylor, 2025).

Unlike contact sports, where acute (traumatic) events dominate, single figure skating is predominantly characterized by overuse injuries of the musculoskeletal system. A retrospective analysis of 864 injuries collected over 15 years (Kowalczyk et al., 2021) clearly illustrates this trend: up to 68.9% of all injuries were classified as overuse injuries, with this rate increasing alongside the athlete's skill level (King et al., 2018). The complexity of skating elements and the asymmetrical nature of landings are reflected in the anatomical location of injuries. Among single skaters of both sexes, the most frequently injured anatomical regions are the foot and ankle (25.4%–29.6%), the knee joint (14.9%–19.3%), and the lower spine and pelvis (13.4%–15.8%) (Kowalczyk et al., 2021).

A phenomenon of critical clinical significance is the exceptionally high percentage of bone tissue injuries (accounting for up to 72% of reported pathologies in some studies), including stress fractures and bone stress reactions (Schmidt et al., 2025). Stress fractures represent nearly 12% to 13% of all injuries in figure skaters, of which a shockingly large proportion (42.2%) is located in the spine, and 32.4% in the foot and ankle region (Kowalczyk et al., 2021; Naylor, 2025). These data demonstrate that the skeletal system of young skaters is subjected to on-ice forces that exceed its natural capacity for remodeling and regeneration.

3.2. Pathomechanics of the most common overuse injuries

The dominance of overuse injuries in figure skating is a direct result of repetitive, multidirectional impact forces acting on the athlete's body, which is confined within a highly unfavorable biomechanical environment—the rigid skating boot. Jumps involving two, three, or four rotations require significant flexion of the hip and knee joints during the propulsion phase and the generation of immense vertical velocity at take-off. This translates into a drastic reduction in the duration of blade-to-ice contact during the landing phase, forcing rapid force dissipation within a very short time window (Koga et al., 2025; Stehlin et al., 2025). Calculations using instrumented blades have shown that vertical ground reaction forces during the landing of merely a double jump reach values of 4 to 5 times the athlete's body weight (Ridge et al., 2020). Considering that the skating boot restricts the natural range of plantarflexion and dorsiflexion in the ankle joint, the entire kinetic energy of the impact is transferred cascadingly up the kinetic chain (Table 1).

3.2.1. Pathomechanics of the foot and ankle

The specific design of the skating boot (a high, stiff heel counter and a built-in heel forcing approximately 15 degrees of plantarflexion) is the primary culprit behind local overuse changes in the distal part of the limb. One of the most common ailments is Haglund's deformity (pump bump), associated with retrocalcaneal bursitis. Studies indicate that its development is strongly correlated with a high-arched foot (cavus foot), which increases the natural angle of the calcaneal tuberosity, leading to mechanical impingement against the rigid heel counter of the boot (Parker & Ho, 2023; Tlougan et al., 2011). Traditional treatment methods, such as the use of heel raises, prove ineffective and often even worsen the fit of the heat-molded boot, which elongates and widens under weight-bearing conditions, becoming too tight for the athlete's foot (Parker & Ho, 2023). Another common pathological entity is 'lace bite', or tendinopathy of the

tibialis anterior tendon. It results directly from the lack of an adipose layer on the anterior aspect of the ankle joint. During dorsiflexion in landings and edge work, the tensing tendons bulge and are compressed by the stiff, unbroken tongue of the skating boot, resulting in inflammation and edema (Levitsky et al., 2020).

3.2.2. Pathomechanics of the knee joint

The near-complete elimination of the ankle joint from the shock absorption process makes the knee the first joint forced to absorb gigantic impact forces. As many as 70.1% of all knee injuries in this population involve the extensor mechanism, predominantly patellofemoral pain syndrome (PFPS) and patellar tendinopathy (Kowalczyk et al., 2021). Electromyographic (EMG) studies of adolescent skaters reveal that in order to stabilize the joint prior to ice impact, the rectus femoris and biceps femoris muscles undergo extremely strong, early activation. This necessity to almost instantaneously generate peak eccentric force (to decelerate momentum), combined with the lack of support from the distal parts of the leg, induces massive shear forces within the patellar tendon (Koga et al., 2025). Additionally, dysfunctions proximal to the knee joint exacerbate the biomechanical problem—many elite athletes are diagnosed with weakness of the hip abductor muscles (e.g., gluteus medius), which manifests during single-leg landings as Medial Knee Displacement (MKD), generating destructive overload in the patellofemoral joint (Webb et al., 2022).

3.2.3. Pathomechanics of the lumbopelvic-hip complex (LPHC) and spine

Landing difficult jumps on a single, strictly defined lower limb introduces dramatic asymmetry into the musculoskeletal system. Due to the locking of the ankle joint, the lumbopelvic-hip complex (LPHC) becomes a critical buffer absorbing kinetic energy. Isometric studies confirm that the 'landing leg' of skaters exhibits different muscular endurance and higher bone mineral density than the 'take-off leg' (Webb et al., 2022; Rauer et al., 2022). In turn, repetitive, extreme flexion, adduction, and internal rotation in the hip joint during the preparatory and rotational phases of jumps constitute a proven factor contributing to acetabular labral tears, which have been successfully treated in clinical trials through core stabilization strengthening (Theige & David, 2018; Matache et al., 2025; Bolia et al., 2018).

Of particular concern to the medical community is the high rate of lower spine injuries, with an emphasis on posterior column stress fractures (e.g., spondylolysis), which account for as much as 31.9% of diagnoses among patients reporting back pain in this athletic group

(Kowalczyk et al., 2021). The pathomechanics of this phenomenon are based on the repetitive and abrupt combination of two forces: extreme spinal hyperextension (required, among others, in layback or Biellmann spins) and the massive rotational force generated in the air and halted in a fraction of a second during landing (Sugimoto et al., 2020). The summation of these forces disrupts the neural arch, especially in skeletally immature athletes (Bolia et al., 2018).

Table 1. Load transfer and pathomechanical cascade in single figure skating.

Anatomical region	Biomechanical basis	Most common overuse pathologies
Foot and ankle	Forced plantarflexion (approx. 15°); tissue compression by the rigid tongue and heel counter of the boot.	Haglund's deformity, Achilles bursitis, lace bite (tibialis anterior tendinopathy).
Knee joint	Absorption of impact forces (4-5x body weight) in a fraction of a second with a locked ankle joint.	Patellofemoral pain syndrome (PFPS), patellar tendinopathy (jumper's knee).
Lumbopelvic-hip complex (LPHC)	Asymmetrical energy absorption on a single limb; weakness of core stabilization and gluteal muscles causing medial knee displacement (MKD).	Acetabular labral tears.
Lower spine	Abrupt deceleration of rotational forces from the flight phase combined with extreme spinal hyperextensions.	Posterior column stress fractures (spondylolysis), chronic mechanical low back pain (LBP).

(**Source:** Authors' own work)

3.3. Key risk factors

The occurrence of an overuse injury in single figure skating is rarely the result of a single event. The latest epidemiological models indicate that these injuries are multifactorial in nature and arise from the superimposition of individual predispositions (intrinsic factors) and harmful environmental stimuli (extrinsic factors). Systematic literature reviews from 2020-2026

undeniably demonstrate that optimizing these specific areas constitutes the only effective path to reducing injury rates in this sport (Schmidt et al., 2025).

3.3.1. Extrinsic factors: Training load, early specialization, and equipment

The most evident modifiable risk factor identified in recent literature is improper load management. During a single on-ice session, elite skaters perform between 80 and 100 attempts of multi-rotational jumps. Unfortunately, research conducted among the British skating elite (Naylor, 2025) revealed a shocking fact: none of the surveyed athletes systematically monitored the number of jumps performed, and only 13% were aware of the existence of the acute:chronic workload ratio. The lack of such tracking leads to sudden spikes in training volume during pre-competition periods, which researchers attribute to 50% to 100% of all stress fractures. A systematic review confirms that participating in more than 12 training sessions per week and a general increase in time spent on the ice drastically and statistically significantly elevate the risk of overuse injuries (Schmidt et al., 2025).

This issue is inextricably linked to the phenomenon of early sport specialization. Surveys conducted in the United States showed that a staggering 62% of young female single skaters are fully specialized—they have abandoned other disciplines, train exclusively in figure skating, and spend over 8 months a year on the ice, with an average volume of 11.3 hours per week (Sugimoto et al., 2020). Narrow specialization at the early school-age stage leads to a lack of comprehensive motor development, and the repetition of the same asymmetrical movement patterns under an extreme training regimen inevitably leads to musculoskeletal overload.

These factors are further compounded by equipment flaws. It has been shown that a boot-foot length difference constitutes an independent, proven risk factor for pathologies of the ankle joint and foot (Schmidt et al., 2025). As demonstrated in clinical trials, the foot widens and elongates under weight-bearing conditions, which means that a boot heat-molded in a seated position becomes excessively tight in a training environment (Parker & Ho, 2023).

3.3.2. Relative Energy Deficiency in Sport (RED-S)

Another extrinsic risk factor gaining prominence in recent literature is Relative Energy Deficiency in Sport (RED-S). Figure skating, as a highly aesthetic sport, imposes immense pressure on athletes to maintain a low body mass in order to optimize the moment of inertia

and facilitate rotation in jumps (Koga et al., 2025). Studies of a Swedish population of female skaters revealed a direct correlation between the number of meals skipped per week and the risk of experiencing severe (excluding from training for >21 days) and chronic injuries (Jederström et al., 2021). Prolonged low energy availability (LEA) disrupts endocrinological processes (including the regulation of the hypothalamic-pituitary-gonadal axis), leading to primary or secondary amenorrhea in many female athletes, which drastically inhibits natural bone turnover processes. Research also confirms the widespread prevalence of diagnosed micronutrient deficiencies (including iron and vitamin D) in this group. Given that figure skaters train in indoor arenas year-round, vitamin D deficiency combined with RED-S constitutes a critical predisposing factor for the development of stress fractures and delayed muscle fiber regeneration (Naylor, 2025).

3.3.3. Intrinsic factors: Cumulative effect, anatomy, and the psychology of pain

Among intrinsic risk factors, anatomical and functional parameters stand out, such as a high foot arch (predisposing to the development of Haglund's deformity) (Parker & Ho, 2023) and reduced mobility and flexibility of the quadriceps and hamstring muscle groups (Schmidt et al., 2025). A key predictor of recurrent injuries is also a history of previous trauma—athletes with a prior stress fracture have more than double the risk of sustaining another bone tissue injury (Schmidt et al., 2025).

Paradoxically, one of the strongest independent predictors for the occurrence of lower spine injuries and severe injury episodes turned out to be chronological age within the youth and junior population (Sugimoto et al., 2020; Jederström et al., 2021). The authors explain this phenomenon through the so-called "cumulative effect". Overuse injuries, such as spondylolysis, do not develop overnight. They are the result of the systematic accumulation of tissue microtraumas resulting from repetitive landings and torso contortions over a multi-year career, which eventually exceed the compensatory threshold of a young, still immature skeleton (Sugimoto et al., 2020). As age increases, so does the difficulty of the performed programs, which is associated with higher kinetic forces.

The complete clinical picture is concluded by biopsychosocial determinants. In the highly competitive skating environment, a specific culture of ignoring pain is prevalent. In light of appraisal theory and the threat-rigidity thesis, athletes often perceive stressors (such as a microtrauma) as a threat to their position on the team or their career. This evokes anxious

emotions, leading to an avoidance attitude and the choice of "silence" rather than openly reporting the issue to the medical staff ("voice") (Pahng & Kang, 2023). Such psychological suppression of early warning signals from the body allows for uninterrupted participation in training until an overuse injury develops into a full-blown fracture or inflammation, forcing a multi-month break from the sport. Understanding these mechanisms confirms that protecting a figure skater's health requires an approach that goes beyond orthopedics and biomechanics alone.

4. Discussion

This systematic literature review from 2020-2026 confirms the primary research hypothesis that musculoskeletal overuse injuries constitute the dominant and ever-growing health problem in single figure skating. The extracted epidemiological data, indicating that nearly 70% of all diagnosed injuries are overuse in nature (Kowalczyk et al., 2021), fully reflect the transformation this discipline has undergone over the past decades. Historically, in studies published in the 1980s and 1990s, the ratio of acute to overuse injuries was much more balanced, and in some cases, traumatic events even predominated. The current reversal of this trend is indisputably linked to the paradigm shift in judging (the ISU Judging System) and the exponential increase in the number of multi-rotational jumps, as confirmed by recent trend analyses from the World Championships (Rauer et al., 2022). The sport has evolved from a discipline based on the precision of tracing compulsory figures into an extreme acrobatic-endurance sport.

The central point of discussion regarding pathomechanics remains the unresolved "skating boot paradox". On the one hand, in response to increasing impact forces and the need to stabilize the ankle joint during landings from triple and quadruple jumps, manufacturers have significantly increased the stiffness of the footwear. On the other hand, as evidenced by modern biomechanical analyses using instrumented blades (Ridge et al., 2020) and electromyographic studies (Koga et al., 2025), this very stiffness drastically impairs the human body's natural ability to dissipate kinetic energy. Immobilizing the ankle joint in plantarflexion transfers destructive forces (amounting to 4-5 times body weight) to the knee extensor mechanism and the lumbopelvic-hip complex (LPHC). These findings correlate with clinical studies indicating an alarming rate of spinal stress fractures and patellofemoral joint pathologies in young athletes (Kowalczyk et al., 2021). Furthermore, traditional methods of managing local foot overloads (e.g., heel raises in the treatment of Haglund's deformity) prove ineffective in light of new

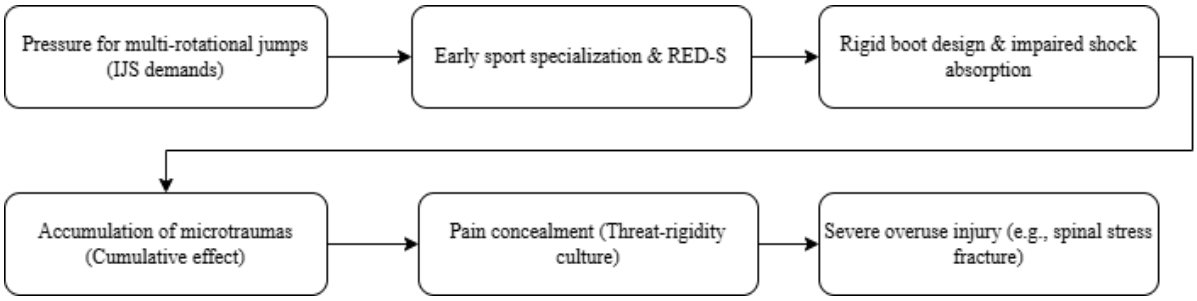
research, as they disrupt the fit of the heat-molded boot to a foot that expands under weight-bearing conditions (Parker & Ho, 2023; Tlougan et al., 2011).

Another key aspect of the discussion is the phenomenon of early specialization and load management. Contemporary medical literature unequivocally condemns early specialization in youth sports, pointing to its association with burnout and an elevated risk of injury. Meanwhile, in figure skating, this phenomenon has become systemic—over 60% of young female athletes train exclusively in this discipline for more than 8 months a year (Sugimoto et al., 2020). The consequence of this regimen is the "cumulative effect" identified in research. Overuse injuries in skaters do not correlate directly with a single, measurable training error in a given week, but rather with chronological age—they are the result of thousands of asymmetrical landings compounding over years on an immature skeleton (Sugimoto et al., 2020). It is both astonishing and highly concerning that, despite widespread knowledge of the destructive impact of repetitive forces, rigorous monitoring of jump counts is still not practiced among the skating elite (Naylor, 2025). Implementing jump counting systems (analogous to the pitch counts used in baseball) should constitute an absolute preventive priority for the coming years.

Fortunately, growing concerns regarding the biomechanical health of skaters have recently been reflected in systemic regulatory changes by the International Skating Union (ISU). To combat early specialization and protect immature athletes from the aforementioned cumulative effect, the ISU raised the minimum age for senior competitors to 17 years, which fully took effect in the 2024/2025 season (International Skating Union, 2022). Furthermore, to directly reduce mechanical overload, the maximum number of jumps in the free skate will be officially reduced from seven to six starting from the 2026/2027 Olympic cycle (International Skating Union, 2024). Moreover, as of early 2026, the ISU Council has been debating even more radical reforms, such as severe point penalties for falls and the potential introduction of jump-free artistic programs. These initiatives aim to explicitly discourage athletes from attempting elements beyond their physical capabilities and represent a crucial institutional step in injury prevention.

A review of the latest literature also highlights the critical role of systemic and psychological factors, which were often marginalized in older studies. The discovery of a strong, statistically significant association between skipping meals and the occurrence of severe injury episodes (Jederström et al., 2021; Schmidt et al., 2025) sheds light on the hidden epidemic of RED-S (Relative Energy Deficiency in Sport). In the culture of aesthetic sports, the pressure to

maintain a low body mass leads to chronic low energy availability (LEA), which impairs bone mineral density and directly paves the way for stress fractures of the spine and foot. Conversely, the psychological phenomenon of threat-rigidity explains why athletes conceal pain—the fear of losing their status within the group leads to so-called "silence" instead of proactively seeking medical help ("voice") (Pahng & Kang, 2023). This proves that overuse injuries are not exclusively an orthopedic issue, but an interdisciplinary one. The complex interplay of these biomechanical, systemic, and psychological factors is summarized in Figure 1.



(**Source:** Authors' own work)

Figure 1. The multifactorial cascade of overuse injuries in single figure skating.

Practical implications and preventive strategies. The conclusions drawn from this review allow for the formulation of evidence-based medicine (EBM) preventive guidelines. First, rigorous monitoring of training volume is essential, including daily and weekly jump count tracking, to avoid sudden spikes in the acute:chronic workload ratio (Naylor, 2025). Second, off-ice training must be redefined—instead of focusing solely on power generation, it should place immense emphasis on strengthening the muscles stabilizing the lumbopelvic-hip complex, particularly the gluteus medius. Eliminating medial knee displacement (MKD) during landing will drastically reduce patellofemoral joint overload and protect the spine from absorbing impact forces (Webb et al., 2022; Theige & David, 2018). Third, structured nutritional education and regular screening for vitamin D and iron deficiencies should be implemented in every skating club, serving as proven RED-S prophylaxis (Naylor, 2025). Furthermore, due to the specific nature of treating acetabular labral tears or stress fractures, surgical interventions should be a last resort, and the priority must be interdisciplinary conservative treatment involving physiotherapists, dietitians, and sports psychologists (Matache et al., 2025).

Limitations of current research. A critical evaluation of the identified literature from 2020-2026 (as well as studies serving as background research) reveals certain methodological limitations that need to be addressed in future studies. According to the latest reviews (Schmidt et al., 2025), the majority of available studies in figure skating are characterized by a moderate risk of bias (QUIPS – Quality in Prognostic Studies), which largely stems from their retrospective nature. Relying on questionnaires and athletes' memory (recall bias) leads to an underestimation of true injury rates. Another fundamental problem is the lack of standardized injury definitions. Studies differ in their classification of time-loss (e.g., an injury causing a one-day absence vs. an absence lasting over 21 days), which precludes conducting a precise statistical meta-analysis. Additionally, a massive gender disparity remains evident in the literature—the vast majority of research focuses on the female population, leaving the injury and biomechanical profile of male skaters underexplored. This compels future researchers to conduct long-term, prospective cohort studies using uniform injury definitions (e.g., in accordance with the 2020 IOC consensus).

5. Conclusions

Based on the systematic literature review from 2020-2026 and the analysis of the historical evolution of figure skating, the following final conclusions were formulated:

1. **A paradigm shift in injury profiles:** Modern single figure skating, driven by the demands of the ISU Judging System, is characterized by a drastic predominance of overuse injuries (accounting for approximately 69% of all injuries) over acute injuries. There is an evident increase in the percentage of severe injury episodes (requiring more than 21 days of absence), with the foot and ankle, the knee extensor mechanism, and the lumbopelvic-hip complex (LPHC) being the predominant locations of pathology.

2. **The critical role of equipment pathomechanics and landing mechanics:** A significant portion of overuse injuries is a direct consequence of asymmetrical landings from multi-rotational jumps (generating forces of 4 to 5 times body weight) in an extremely rigid skating boot. The restriction of dorsiflexion in the ankle joint forces a compensatory, rapid absorption of impact forces by higher segments of the kinetic chain, which directly explains the growing incidence of patellofemoral pain syndrome (PFPS) and posterior column stress fractures of the spine (spondylolysis).

3. **The cumulative effect and early specialization:** The key predictor of lower spine injuries in young skaters is not a single training error, but rather chronological age, which proves the existence of the "cumulative effect". Widespread early sport specialization (over 8 months of specialized training per year) and the superimposition of thousands of asymmetrical loads on an immature skeleton ultimately exceed its regenerative capacity. The recent ISU decision to raise the senior age limit to 17 is a necessary and evidence-based systemic response to this exact threat (International Skating Union, 2022).

4. **Underestimation of extrinsic factors (RED-S and lack of monitoring):** Stress fractures and chronic injuries are strongly correlated with Relative Energy Deficiency in Sport (RED-S), manifested by intentional meal skipping, menstrual dysfunction, and deficiencies in vitamin D and iron, among others. The situation is exacerbated by the prevalent lack of objective training load monitoring among elite athletes (especially the systematic tracking of jump counts).

5. **The necessity for multidisciplinary interventions:** Reducing injury rates requires a shift away from the culture of ignoring pain towards proactive athlete health management. It is essential to implement strict jump limits, nutritional education regarding RED-S prevention, and modifications to off-ice physical training, with a particular emphasis on strengthening the pelvic stabilizing muscles (e.g., the gluteus medius).

Disclosure

In preparing this work, the author(s) used Gemini AI for the purpose of linguistic refinement, grammatical correction, and style enhancement. After using this tool/service, the author(s) have reviewed and edited the content as needed and accept full responsibility for the substantive content of the publication.

Supplementary Materials

Not applicable.

Author Contributions

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Aleksandra Białek; data curation, Mikołaj Czerniakowski; writing - rough preparation, Aleksandra Białek; writing - review and editing, Aleksandra Sadok; visualization, Zuzanna Gorczyca; supervision, Jakub Karczewski; project administration, Kamila Ryń. All authors have read and agreed with the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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