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Article

A systematic review and hot topic analysis of ballet injury research: CiteSpace visualization atlas

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Abstract: Objective: This study aims to analyze trends, hot topics, and influential research on ballet-related injuries between 2000 and 2023, providing insights for prevention and management strategies. **Methods:** Using the Web of Science Core Collection, 787 articles were identified with subject terms related to ballet injuries. CiteSpace software (version 6.2.R2) was employed to conduct visual analyses of trends, keyword co-occurrences, and co-citations. The dataset was analyzed across dimensions such as time, geography, authorship, institutions, and hot topics. **Results and Conclusions:** The publication volume of ballet injury research has steadily increased, with the United States, England, and Australia leading in output. Central topics include risk factors, musculoskeletal disorders, and injury prevention strategies. Key clusters revealed five prominent research directions: risk factors, proprioception, physical activity, jump-related injuries, and bone mineral density. Authors such as Wanke Eileen M., Steinberg Nili, and Ambegaonkar Jatin P. emerged as influential contributors. Institutions like the University of Wolverhampton and Goethe University Frankfurt displayed significant academic impact. The research objects of ballet injury research are mainly female ballet dancers. Research on the causes of ballet injuries mainly focuses on physical activities and incorrect training plans. The most studied part of ballet injuries is the ankle joint.

Keywords: dance injury; risk factors; Web search; neuromuscular injury; prevention

1. Introduction

Dancing is a high-injury risk activity [1,2], especially ballet, which has very high requirements for dancers in all aspects [3–5]. Among many types of dance, ballet practice is the basis for dancers to acquire dance techniques, such as modern dance and Latin dance. Ballet dancers are often described as artists or athletes [6] because they need to perform complex combinations of dance moves that require a high level of physical athleticism [7,8]. Most ballet dancers start training in early childhood, and the injuries they suffer may have an impact on their future health [2,9]. In addition, the special body shape and aesthetic requirements of ballet may lead to various health problems, such as musculoskeletal, metabolic and nutritional disorders [3,10]. Ballet includes a series of classic difficult movements, such as Arabesque, Fouette, Grande Cart, etc, these movements exceed the limitations of human anatomy and require long-term training to meet performance requirements, therefore dancers are at a relatively high risk of injury [11,12]. It is necessary to conduct targeted research on how to prevent sports injuries caused by ballet dancers during training. This study uses

CiteSpace visualization analysis software to conduct a comprehensive analysis of the research literature on ballet training injuries from 2000 to 2023, exploring the literature from multiple dimensions such as time, subject, hot spots, and content, to provide ideas and references for future research on ballet injuries. At the same time, it provides ballet dancers with relevant risk information about ballet injuries and will also provide ballet students and their parents with more knowledge about ballet injuries to minimize the incidence of ballet injuries.

2. Methods

2.1. Tools and sources

The obtained literature was analyzed by searching the Web of science™ core collection, and the core search terms were TS = (Ballet) and TS = (injury OR damage OR harm OR fracture OR sprain OR twist OR contusion OR bruise OR dislocation OR strain OR Joint dislocation) for subject search. The time span was 2000–2023, and the search time was 25 May 2024. The search process strictly adhered to the following criteria: only studies related to ballet injuries were included; the included studies had to be explicitly related to the topic of "ballet injuries", including keywords such as "Ballet", "Injury", "Risk Factor", etc. Duplicates were de-duplicated and excluded from the search process. Injury", 'Risk Factor', etc. Literature not directly related to the topic was excluded, and De-duplication was performed for duplicate literature. The search finally obtained 787 documents, and the retrieved documents were downloaded in "TXT" plain text format as research data.

2.2. Operation and analysis

This study uses CiteSpace [version number: 6.2.R2] software based on the JAVA platform to draw a visual knowledge graph [13]. Enter the new page of the software, set the parameters for the analysis of literature, select "Years per slice" as 1, "Time Slicing" as 2000–2023, Pathfinder as the cropping method, and select "Pruning sliced networks" and "Pruning the merged network" to streamline the network. Other settings remain unchanged. Select the function buttons such as Author, Institution, Keyword, and Reference for visual analysis.

3. Results and discussion

3.1. The time of publication of ballet injury articles

Using Excel to plot the number of papers published each year and make a linear prediction, we found that the number of papers has a linear exponential trend over time, with the formula $y = 2.763x - 1.913$, and $R^2 = 0.8049$, indicating that there is a strong linear relationship between the number of papers published and the year. As can be seen from **Figure 1**, the number of papers published in this research field is on the rise, Especially after 2015, there has been a significant acceleration in the growth of annual publications. This growth is closely related to the background of the continuous integration and development of dance medicine and sports science in recent years. On the one hand, the attention of professional dance companies and educational

institutions to the health and injury management of dancers has continued to rise, and researchers have paid more attention to providing a scientific basis for training safety and the career development of dancers; on the other hand, the advancement of technological means, such as biomechanics and medical imaging, has contributed to the rapid accumulation of academic results.

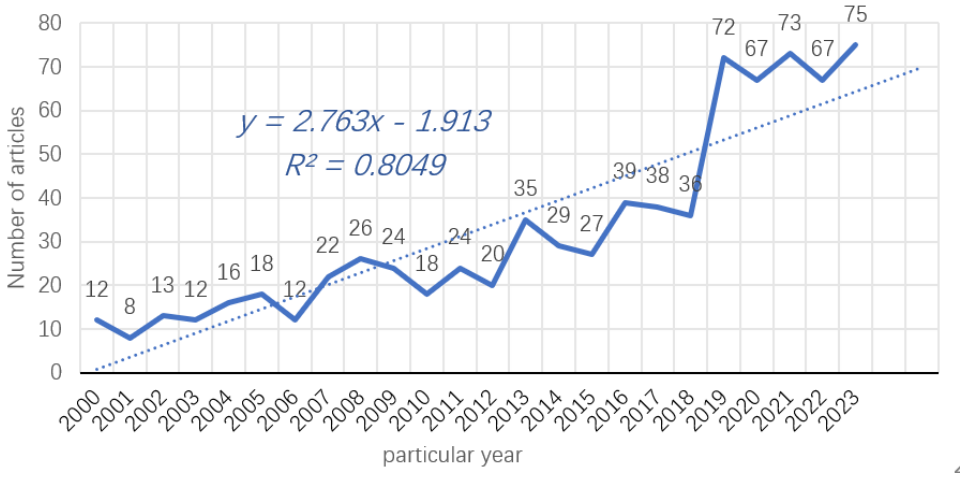

Figure 1. Trend chart of the number of articles per year.

3.2. The country (regions) of publication of ballet injury articles

Through Citespace software analysis, we obtained a knowledge graph of country (regions) distribution as shown in **Figure 2** and a list of the top 10 countries (regions) in terms of publication volume as shown in **Table 1**. The United States ranks first with 266 papers published, followed by the England with 127 papers and Australia with 88 papers published.

Table 1. Distribution of published papers on ballet injury research.

Ranking	Quantity	Country (region)
1	266	USA
2	127	ENGLAND
3	88	AUSTRALIA
4	48	CANADA
5	39	GERMANY
6	32	GREECE
7	31	ISRAEL
8	30	BRAZIL
9	25	SWITZERLAND
10	23	NETHERLANDS

Centrality means betweenness centrality, which is an indicator to measure the importance of a node in a network (in addition, common indicators to measure the importance of a node include degree centrality, closeness centrality, etc.). CiteSpace uses this indicator to discover and measure the importance of documents and uses purple circles to highlight such documents (or authors, journals, and institutions, etc.,

and the betweenness centrality of nodes with purple circles is not less than 0.1). Documents with high betweenness centrality are usually key hubs connecting two different fields, and are also called turning points in CiteSpace [14]. Through Citespace software analysis, we obtained a knowledge graph of centrality distribution as shown in **Figure 2** and a list of the top 10 centrality in terms of publication volume as shown in **Table 2**. Canada has the highest centrality, followed by the England and Greece. This distribution reflects the leadership of countries such as the United States, the United Kingdom, and Australia in the field of dance medicine and ballet injury research. Thanks to a strong research infrastructure, a diverse dance education system, and an emphasis on dance medicine. The United States has a number of research institutes and associations focused on dance medicine, such as the International Association for Dance Medicine and Science (IADMS), which plays an important role in advancing the prevention and treatment of dance injuries. Australian researchers have conducted an in-depth study of musculoskeletal injuries in professional ballet companies, shedding light on the health challenges dancers face in training and performance [15]. In addition, a team of researchers in the United Kingdom conducted an epidemiologic study of foot and ankle injuries in professional ballet dancers, providing valuable data to support the study [16].

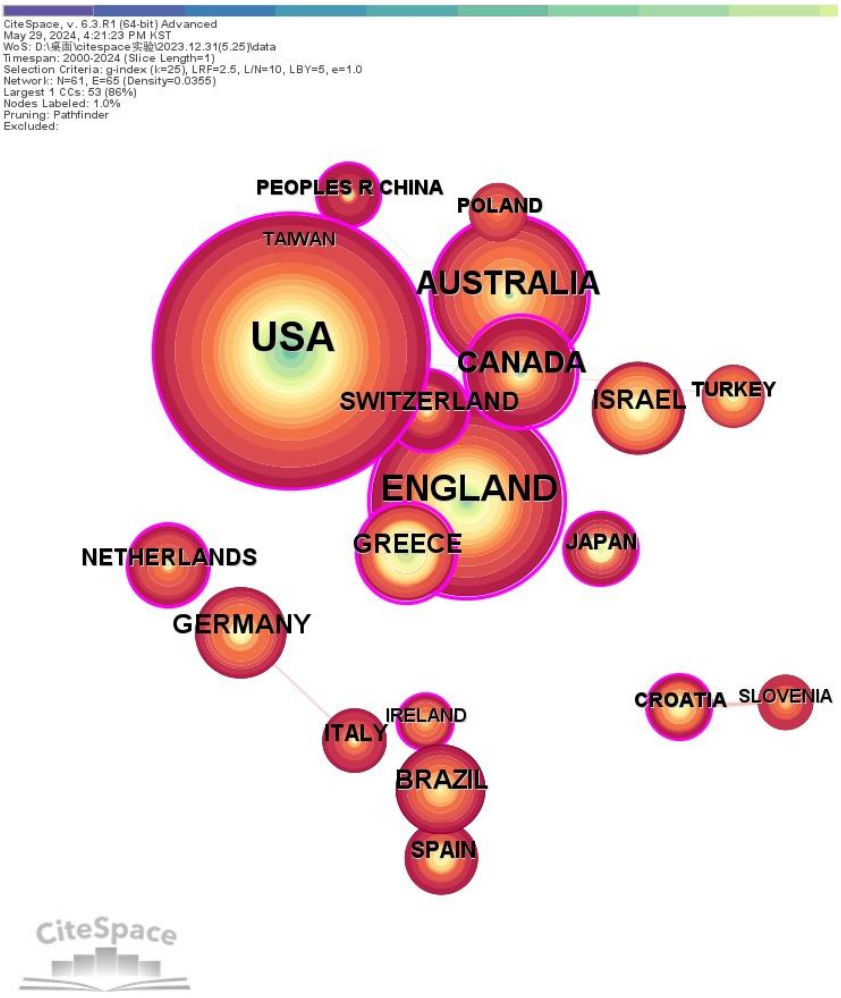

Figure 2. Country (region)/centrality knowledge graph.

Table 2. The centrality of published papers on ballet injury research.

Ranking	Centrality	Country (region)
1	0.79	CANADA
2	0.68	ENGLAND
3	0.47	GREECE
4	0.43	AUSTRALIA
5	0.39	QATAR
6	0.31	NORWAY
7	0.26	TUNISIA
8	0.23	SWITZERLAND
9	0.23	NETHERLANDS
10	0.22	USA

3.3. The author of publication of ballet injury articles

Select "Author" as the node type in the CiteSpace control panel, keeping all other settings unchanged. Next, generate the corresponding knowledge graph (**Figure 3**) and identify the top 10 authors with the highest number of publications (**Table 3**). The top three authors—Wanke Eileen M, Steinberg Nili, and Ambegaonkar Jatin P—each have published more than 15 articles. These prolific scholars have accumulated deep research on injury prevention, rehabilitation strategies, and training methods for professional dancers. Echoing existing studies, the work of scholars such as Wanke focuses more on the areas of dance injury prevention and health assessment of professional dancers; Steinberg et al. focuses on the interaction between growth and development and movement patterns of adolescent dancers; and Ambegaonkar's research has a wide range of research directions, including healthy quality of life of dancers and performing artists, and strategies for movement training and rehabilitation. The research ideas of the prolific group of authors are highly instructive to subsequent scholars. However, these authors are mainly concentrated in Europe and the United States, and dance medicine researchers from Asia and other emerging countries have not yet been fully integrated into this international academic network. With the increase of international academic exchanges, it is expected that the global coverage of dance medicine research will be broadened in the future.

Table 3. The author of published papers on ballet injury research.

Ranking	Quantity	Country (region)
1	20	Wanke, Eileen M
2	19	Steinberg, Nili
3	15	Ambegaonkar, Jatin P
4	14	Koutedakis, Yiannis
5	12	Wyon, Matthew
6	11	Bronner, Shaw
7	11	Wyon, Matthew A
8	9	Groneberg, David A
9	8	Shaw, Joseph W
10	8	Siev-ner, Itzhak

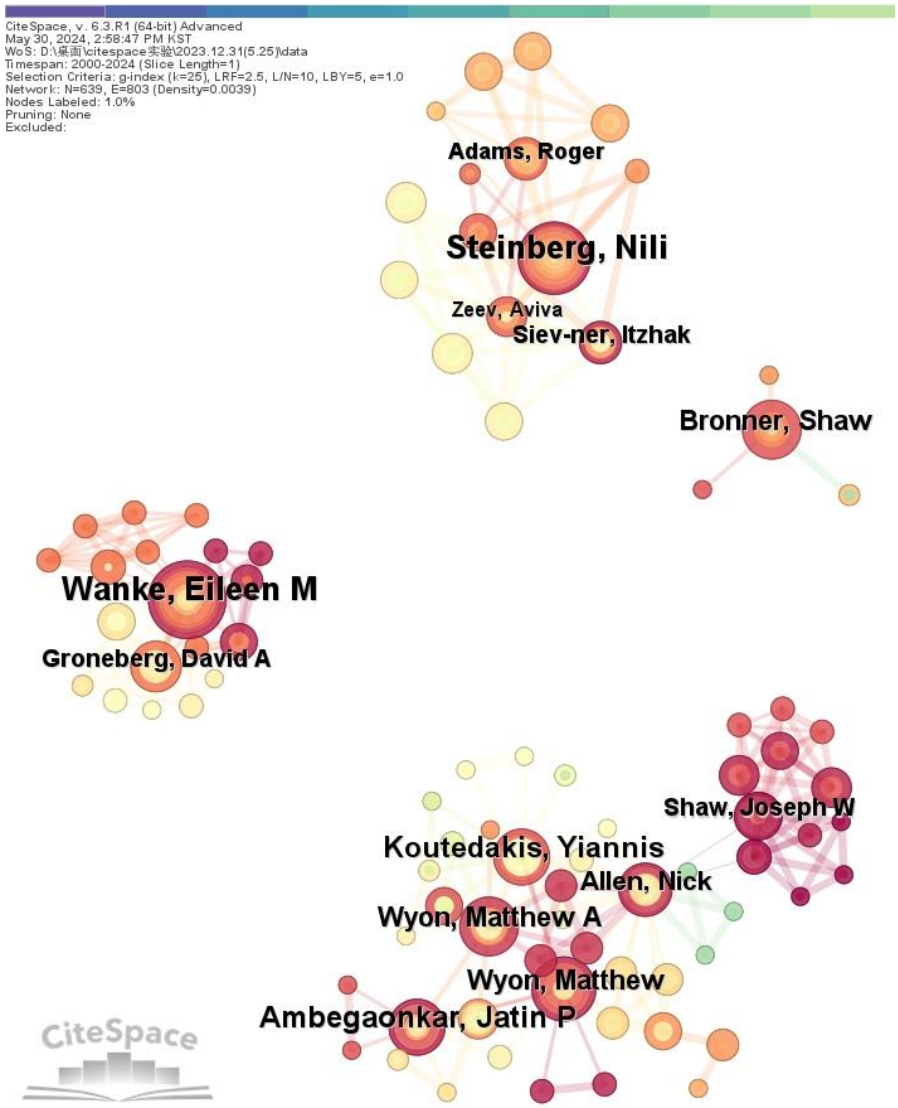

Figure 3. Author knowledge graph.

3.4. The institutions of publication of ballet injury articles

As shown in **Table 4** and **Figure 4**, the primary institutions publishing research on ballet injuries are universities. The University of Wolverhampton leads with the highest number of publications, followed by Goethe University Frankfurt and the University of Thessaly. Notably, the University of Wolverhampton also ranks first in centrality (**Table 5**), highlighting its leadership in both publication volume and academic influence, with the University of Thessaly and Harvard University following closely behind. Despite the centrality of these institutions in the research network, the global distribution of research remains uneven. The United States and European countries dominate the academic network of dance medicine.

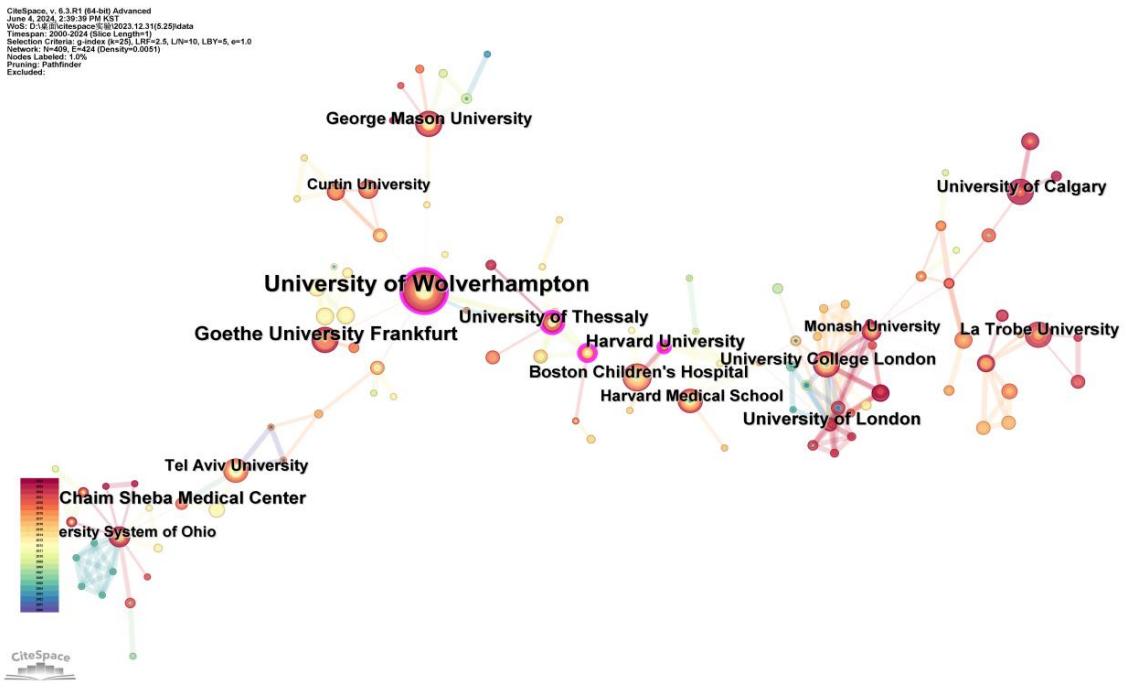

Figure 4. Institutions knowledge graph.

Table 4. Distribution of published papers on ballet injury research.

Ranking	Quantity	Institutions
1	52	University of Wolverhampton
2	27	Goethe University Frankfurt
3	20	University of Thessaly
4	18	Harvard University
5	17	Chaim Sheba Medical Center
6	17	University of London
7	16	Boston Children's Hospital
8	15	La Trobe University
9	15	University College London
10	15	George Mason University

Table 5. The centrality of published papers on ballet injury research.

Ranking	Centrality	Institutions
1	0.12	University of Wolverhampton
2	0.11	University of Thessaly
3	0.11	Harvard University
4	0.11	University of California System
5	0.1	Feinberg School of Medicine
6	0.07	Academic Medical Center Amsterdam
7	0.06	University of London
8	0.06	Monash University
9	0.06	University of Southern Denmark
10	0.05	Chaim Sheba Medical Center

3.5. Analysis of hot spots in ballet injury research

3.5.1. Keyword co-occurrence analysis of ballet injury research

Keyword co-occurrence analysis examines the relationships between keywords provided by authors and databases within a dataset. When using CiteSpace to perform this analysis, set the Node Type to "Keyword." After configuring the necessary parameters in the function settings, click "GO!" to generate the keyword co-occurrence network.

In this part of the analysis, we merged synonymous keywords, such as "ballet dancer" and "dancer," into a single term, "ballet dancer," and so on. After running the software, a knowledge graph of keyword co-occurrence in the field was generated (**Figure 5**). Using CiteSpace, we extracted the top 20 keywords in this research area and further organized the data in Excel to create a table of high-frequency keywords in the field (**Table 6**) and the ranking of centrality (**Table 7**). It is evident that, in addition to search terms like "ballet dancers" and "injury," the most frequently occurring term is "risk factor," followed by "stress fractures" and "pain". High-centrality keywords include "bone mineral density" "exercise" and "children". These keywords highlight the main concerns of ballet injury research. The frequent occurrence of the keyword "risk factor" suggests that researchers are not only focusing on the incidence of injuries, but are further attempting to quantify and identify specific causative factors for injuries in order to propose targeted preventative measures; the occurrence of "stress fractures" and "pain" appear to indicate that skeletal and muscular system health issues are key areas of research in dancer injuries. At the same time, the high frequency of "pain" reflects the importance of pain management after injury, which is a key factor in determining a dancer's ability to return to training and performance [17].

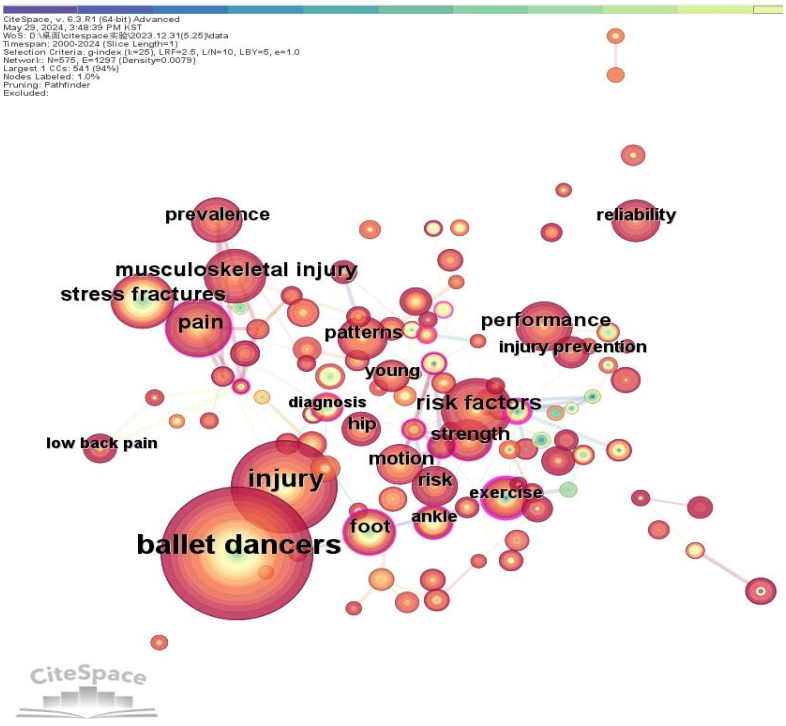

Figure 5. Keyword co-occurrence analysis knowledge graph.

Table 6. The top 20 statistics of high-frequency keywords for ballet injuries.

Ranking	Quantity	Keyword
1	445	Ballet dancers
2	238	Injury
3	97	risk factors
4	90	Stress fractures
5	85	Pain
6	74	musculoskeletal injury
7	65	Foot
8	59	Performance
9	58	Prevalence
10	49	Strength
11	49	Patterns
12	48	Motion
13	46	Risk
14	43	Hip
15	36	Reliability
16	34	Exercise
17	28	Ankle
18	27	Young
19	25	Injury prevention
20	23	low back pain

Table 7. The top 20 statistics of centrality keywords for ballet injuries.

Ranking	Centrality	Keyword
1	0.25	Bone mineral density
2	0.21	Exercise
3	0.18	Children
4	0.16	Diagnosis
5	0.15	Biomechanics
6	0.14	Ankle
7	0.14	Anterior cruciate ligament
8	0.13	Back pain
9	0.12	Classification
10	0.11	Strength
11	0.11	Lower extremity
12	0.11	Articular mobility
13	0.1	Pain
14	0.1	Foot

Table 7. (*Continued*).

Ranking	Centrality	Keyword
15	0.1	Delayed menarche
16	0.09	Adolescents
17	0.08	Flexibility
18	0.08	Bone density
19	0.08	Laxity
20	0.07	Stress fractures

3.5.2. Keyword cluster analysis of ballet injury research

The Log-Likelihood Ratio (LLR) method is a statistical approach used to evaluate the significance of the association or difference between two events or two sets of data. In fields such as text analysis and data mining, the LLR method is commonly applied to keyword extraction, word frequency analysis, and co-occurrence analysis of terms. In visualization tools like CiteSpace, LLR is used to identify keywords or terms with significant characteristics in a specific research area. By calculating the log-likelihood ratio of keywords, it can determine which keywords appear more frequently than would be expected by chance, thereby identifying research hot topic or key concepts. The higher the LLR value, the stronger the association between the two events or keywords.

Table 8. Main clusters and keywords of ballet injury research.

Cluster labels	Number of nodes	Clipping value	Label	Keywords
#0	99	0.685	Risk factors	musculoskeletal disorder, ballet dancing, lumbar flexion, total days, injury, muscle strength, young, motion, ankle range, dance, body composition, bone density, induced osteoporosis, MR imaging, single leg heel rise test, jump
#1	39	0.743	proprioception	performance, balance, rehearsal, players, injury risk, postural control, risk factors, movement, variability, ankle, impingement syndrome, ankle sprain, single leg heel rise test, profile, supple-mentation, posterior cruciate ligament injury, plyometric
#2	39	0.933	physical activity	exercise, injury, life style, cells, validity, sports, imaging, injuries, bone mineral density, exercise, bone density, ballet, female athlete triad, genetic damage, wrestling, inflammation
#3	33	0.983	jump	performance stress, classical ballet, students, association, eating disorders, life stress, model, athletic injury, trait anxiety, coping skills, beighton hypermobility score, occupational stress
#4	36	0.900	bone mineral content	ballet dancers, fatigue, density, geometry, strength, stress fracture, bone mineral density, sex steroids, parathyroid hormone, bone markers, density, bone density, induced osteoporosis, midfoot, rat model, nonunion, forefoot

Using the LLR method to cluster keywords, five research directions in ballet injury studies were identified: #0 Risk factors, #1 proprioception, #2 physical activity, #3 jump, and #4 bone mineral content (as shown in **Table 8**). The keyword clustering analysis reflects the hot topics in the field of ballet injury research, which is of great significance for revealing the development of the discipline and its future directions. From **Table 8**, information such as the number of nodes and silhouette values for each cluster can be observed. The number of nodes is directly proportional to the research

intensity of the cluster, while the silhouette value is closely related to the importance of the cluster. The higher the value, the more focused the research theme. The overall clustering effect of ballet injury research is quite good, with a high level of reliability (average silhouette value = 0.8488 > 0.6).

Ballet, as a highly technical dance art, carries a significant risk of injury beneath its graceful movements [18–20]. In the pursuit of technical perfection and artistic expression, dancers often overlook the strain placed on their bodies [21,22]. In recent years, with the advancement of scientific research, ballet-related injuries have become a prominent topic in dance medicine and sports science [11,23–26].

The risk factors for ballet injuries are complex and diverse, encompassing various dimensions such as body structure, training intensity, and psychological state [27,28]. According to clustering data analysis, risk factors (Cluster Label 0) are among the most prominent themes in ballet injury research [9,29]. These factors include musculoskeletal disorders [30], lumbar flexion movements [31], injury frequency [20], and muscle strength [32], among others. Young dancers, in particular, are more susceptible to injuries due to incomplete physical development [33]. Due to the incomplete development of the body, the bones, cartilage and tendons are not yet fully mature, when faced with high intensity or movements exceeding the physiological range of the joints, it is easier to produce an unbalanced distribution of stress, which may lead to stress fracture, cartilage injuries or ligament strains. In addition, inconsistent development of various parts of the body can also lead to insufficient muscle strength and joint stability. For example, incomplete formation of the foot arch can easily lead to repeated sprains or plantar fasciitis in the ankle area, while the curvature of the lumbar spine has not yet been finalized, which is prone to disc-related problems during repeated large-scale backward tilting or flexion movements. Additionally, ankle mobility, body structure, and bone density are critical factors affecting ballet dancers' health [34,35]. In the design of specific training programs, it is necessary to reasonably control the total amount and intensity of training according to the age, skill level and individual differences of the dancers; if the training program is not properly designed, too high a training load and too short a fatigue recovery time may cause musculoskeletal disorders and joint problems, which may significantly increase the risk of injury. Therefore, early identification and intervention targeting these risk factors are essential [36]. It is important to emphasize that risk factors do not exist independently, but are closely intertwined with the other four research directions. In training and performance, if dancers have insufficient proprioception (#1) to accurately perceive joint mobility and body loading, this can exacerbate uneven stress distribution during high-intensity or over-range maneuvers, amplifying the impact of risk factors on injury [37]. Similarly, when the frequency of physical activity (#2) or jump training (#3) is too high and recovery from fatigue is inadequate [38], can also constrain each other through cumulative mechanical loading and declining bone health (#4), creating multiple risk stacks.

Proprioception is essential for ballet dancers' movement control and injury prevention. Data indicates (Cluster Label 1) that proprioception is closely linked to dancers' performance, balance abilities, and injury risk [39,40]. Studies show that specific training can enhance dancers' proprioception, thereby reducing injury occurrence [41,42]. In particular, proprioceptive training for the ankle joint has proven

effective in preventing landing impact injuries and ankle sprains [43,44]. Proprioceptive ability is also correlated with overall stability and postural control, which are critical in dance performance [8,45,46]. Research suggests that proprioception deficits may contribute to increased injury susceptibility, making targeted training vital for injury prevention [47,48]. Therefore, proprioceptive training should be an integral part of the ballet training system. It is important to note that proprioceptive deficits not only increase injury risk alone, but also interact with training intensity and movement technique. If dancers are fatigued (related to the theme of "risk factors"), their self-perception of physical activity is reduced and they are more susceptible to joint sprains or postural errors during high-impact maneuvers such as jumping and landing, which can further affect the maintenance of bone density or bone mass (#4).

Cluster Label 2 reveals that physical activity is another key factor influencing ballet dancers' health. Studies have shown that high-intensity dance training and performances can lead to fatigue, which is considered one of the primary causes of dance injuries [5,22]. While injury causes are multifaceted, injuries seem more common when dancers are fatigued. For instance, ballet dancers often experience fatigue toward the end of training sessions or performances [18,49]. Studies suggest that when fatigue affects the ankle muscles, delayed muscle response time and reduced muscle strength can lead to greater postural sway, thereby increasing the likelihood of ankle injuries [50,51]. Moderate training activity can enhance dancers' physical fitness and reduce injury risk [29,52]. However, excessive physical activity may cause fatigue and training injuries, increasing the risk of inflammation and stress fractures [18,53]. Therefore, developing a reasonable training plan and balancing the dancer's physical activity and recovery time is crucial to maintaining the dancer's health. Inappropriate physical activity (too much frequency or intensity, not enough rest) can lead to fatigue or injury, and can also affect overall health by weakening proprioception, exacerbating bone mineral loss, and other pathways.

Jumping is a core skill in ballet but also a high-risk area for sports injuries (Cluster Label 3). Jumping requires complex motion coordination, including lower limb muscle explosiveness, joint stability, and functional arch support. Prolonged jump training can exert excessive stress on joints and soft tissues, increasing the risk of knee and ankle injuries [54,55]. Studies reveal that performance pressure and trait anxiety may reduce coordination, making dancers more prone to injuries [56,57], at the same time, anxiety also impairs on-stage decision-making, leading to technical errors [58]. Therefore, scientific training plans, stress management, and physical fitness monitoring for ballet dancers play a key role in reducing jump-related injuries. In jump-related injuries, proprioception plays an important "protective" role. When dancers have good body perception, even in high-impact movements, they can reduce stress concentration; on the contrary, if the proprioception is insufficient or the amount of physical activity does not match the fatigue state, then it is easy to superimpose risk factors, leading to deviations in the landing posture and further increasing the burden on the skeletal system. increase the burden on the skeletal system.

From cluster label 4, Bone mineral content in ballet dancers is closely related to training intensity, nutritional status, and hormonal levels. Changes in bone mineral density not only reflect the skeletal health of the dancer, but are also closely linked to

the mechanism of injury (risk factor #0). High-intensity training can result in bone mineral loss, particularly among adolescents and female dancers [3,35]. Low bone density may lead to stress fractures, especially under prolonged training and inadequate recovery [59]. Additionally, hormonal imbalances, such as reduced sex steroids, further compromise bone strength [60]. Monitoring bone markers allows for a dynamic assessment of dancers' bone health, providing insights into early signs of bone demineralization [61]. Nutritional supplementation, such as calcium and vitamin D, is considered an effective approach to improve bone mineral content [62]. Regular bone density screenings and tailored training plans that balance physical load and recovery help prevent bone loss and reduce the risk of fractures [63,64].

3.6. Co-citation analysis of literature on ballet injuries

The citation of a literature is a key indicator of the quality of an academic paper. The number of citations shows the influence of a literature and the degree of attention it has received. We used CiteSpace software to analyze the co-citation map of literature with 761 nodes and 3716 links (**Figure 6**). The rankings of the citation frequencies are Kenny SJ, Ekegren CL, and Smith TO (**Table 9**). The contents of the literature involved are the incidence, main types, and severity of injuries of ballet dancers. At the same time, combined with Burst analysis (**Figure 7**), the citation frequencies of literature in the areas of risk factors for dance injuries, fatigue and psychological factors caused by physical activities, and knee and ankle injuries caused by jumping increased. We predict that in the future, the research hot topic of ballet injuries will mainly focus on the above directions.

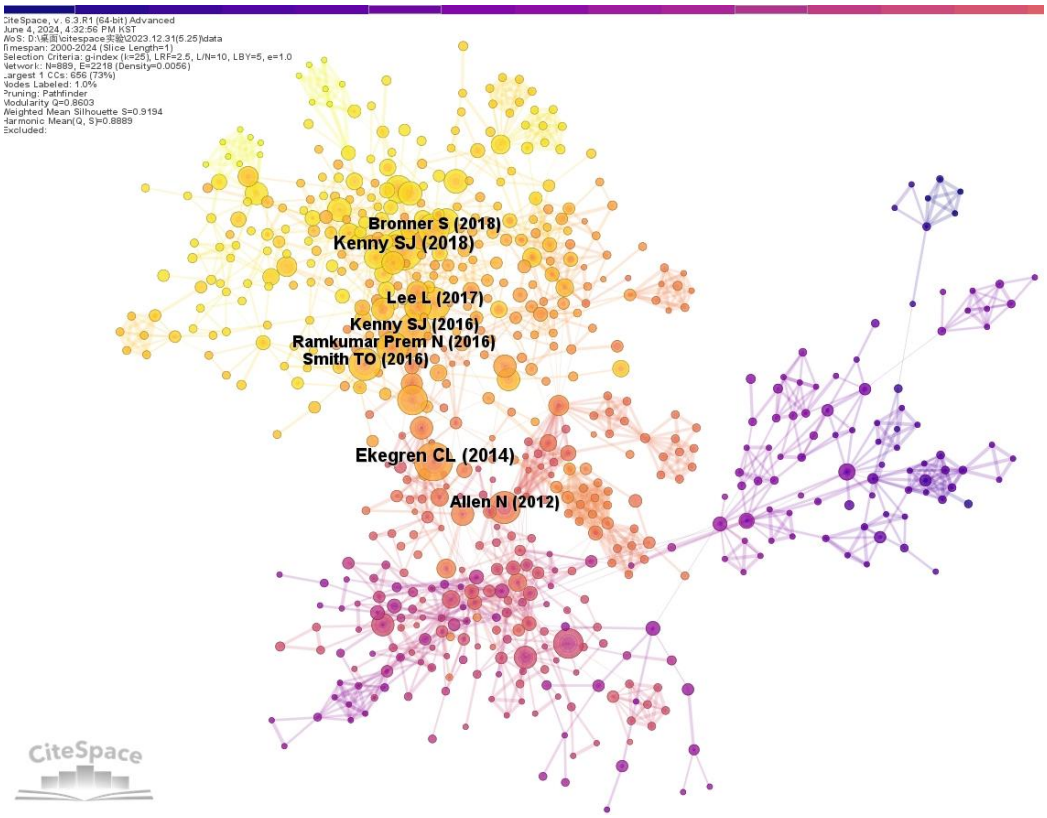

Figure 6. Co-citation knowledge graph of ballet injury literature.

Table 9. Top 3 most-cited authors in ballet injury research.

Rank	Citations	Year	Author	Title
1	53	2018	Kenny SJ	The Influence of Injury Definition on Injury Burden in Preprofessional Ballet and Contemporary Dancers
2	46	2014	Ekegren CL	Injuries in pre-professional ballet dancers: Incidence, characteristics and consequences
3	37	2016	Smith TO	Prevalence and profile of musculoskeletal injuries in ballet dancers: A systematic review and meta-analysis

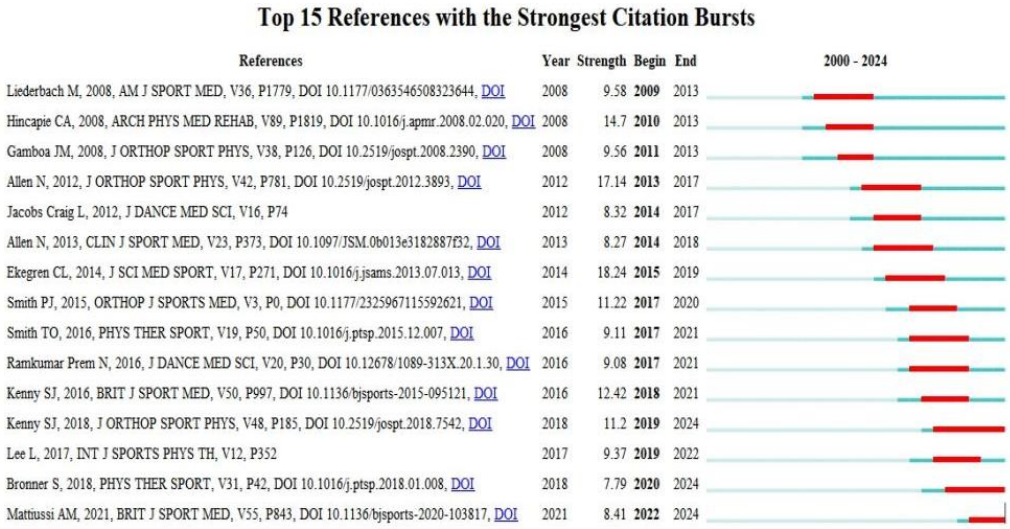

Figure 7. Top 15 references with the strongest citation bursts.

3.7. Current status, hotspots and future directions of ballet injury research

This study systematically combed the ballet injury literature from multiple dimensions, such as time trend, geographical distribution, authors and institutions, keyword co-occurrence, cluster analysis, and co-citation, and the results revealed the rapid development of the field in recent years and its increasingly prominent research hotspots. In view of these findings, their significance and implications need to be discussed in depth from the following perspectives.

First, ballet injury research has shown continuous growth at the temporal level, indicating that dance medicine and exercise science are gaining wider attention. In terms of geographic distribution, the high productivity and centrality of the United States, the United Kingdom, and Australia reflect both their investment in dance medicine and health research; however, the centralized nature of this research landscape may have led to insufficient attention being paid to the injury characteristics and protection needs of dancers in other regions. Through increased international collaboration and cross-regional research, not only can data sources be broadened to enhance the comprehensiveness of research, but also incorporate the characteristics of different training systems to provide more scientific and adaptive injury prevention strategies for diverse populations. Such collaborations can help break the limitations of a single cultural background for the health and professional development of dancers, as well as promote the globalization of ballet medical research.

Second, the authors and publishers analysis shows the influence of the core group

and key units in the field of ballet injury. The clustering of the core group of authors helps to drive cross-disciplinary and in-depth cooperation, leading to better intervention and management systems. However, this "core-periphery" pattern may also hinder the participation of new research teams, resulting in a relative concentration of knowledge dissemination and innovation in the field of dance medicine. In the future, a multidisciplinary platform can be established to encourage emerging research groups to work with the core team to explore the latest technologies and methods in ballet injury prevention, further promoting the academic prosperity and practical application of the field.

Keyword co-occurrence and clustering analyses highlighted that the themes of risk factors, proprioception, physical activity, jumping, and bone mineral content have become the focus of ballet injury research, and that they do not exist independently, but are intertwined and synergistic. For both adolescent and professional dancers, inappropriate training programs (high intensity, lack of recovery) and psychological stresses often amplify joint and bone loads through fatigue and decreased proprioception, while bone mineral loss accelerates the development of injuries under prolonged, high-load conditions, creating a "compounded" risk. This complex association reveals that it is difficult to prevent or minimize injuries with a single intervention, and it is necessary to integrate sports medicine, psychology, nutrition, and rehabilitation to form a comprehensive preventive strategy in order to protect the physical and mental health of dancers more effectively.

Finally, the co-citation analysis reflects the evolution of the core literature and basic theories in this field, which provides theoretical support for the related research, and also indicates the remaining deficiencies of the current research and the direction of future extension. The high frequency of citation of key findings indicates that these findings have been widely recognized at the practical level; however, more longitudinal follow-up and larger sample sizes are needed to test the stability and feasibility of the interventions in different populations, cultures, and periods of training and prevention. Only through continuous revision and improvement on a broader and more diversified basis can ballet injury research truly protect the health and professional development of dancers.

4. Conclusions

This study used CiteSpace software to analyze 787 articles on ballet injuries from 2000 to 2023, presenting the research hot topic and development trends in the field of ballet injuries. The research in this field is mainly reflected in the following points: a: There are many articles published worldwide from 2000 to 2023, and the attention will continue to increase; b: Research institutions on ballet injuries are mainly concentrated in Europe and America; c: The research objects of ballet injury research are mainly female ballet dancers, which may be related to the fact that injuries in female dancers are more prominent; d: Research on the causes of ballet injuries mainly focuses on physical activities and incorrect training plans; d: The most studied part of ballet injuries is the ankle joint.

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References

1. Liederbach M, Hagins M, Gamboa JM, et al. Assessing and Reporting Dancer Capacities, Risk Factors, and Injuries. Journal of Dance Medicine & Science. 2012; 16(4): 139-153. doi: 10.1177/1089313x1201600401
2. Jacobs CL, Hincapié CA, Cassidy JD. Musculoskeletal Injuries and Pain in Dancers a Systematic Review Update. Journal of Dance Medicine & Science. 2012; 16(2): 74-84. doi: 10.1177/1089313x1201600204
3. Burckhardt P, Wynn E, Krieg MA, et al. The Effects of Nutrition, Puberty and Dancing on Bone Density in Adolescent Ballet Dancers. Journal of Dance Medicine & Science. 2011; 15(2): 51-60. doi: 10.1177/1089313x1101500201
4. Roberts KJ, Nelson NG, McKenzie L. Dance-Related Injuries in Children and Adolescents Treated in US Emergency Departments in 1991−2007. Journal of Physical Activity and Health. 2013; 10(2): 143-150. doi: 10.1123/jpah.10.2.143
5. McEldowney KM, Hopper LS, Etlin-Stein H, et al. Fatigue Effects on Quadriceps and Hamstrings Activation in Dancers Performing Drop Landings. Journal of Dance Medicine & Science. 2013; 17(3): 109-114. doi: 10.12678/1089-313x.17.3.109
6. Gamboa JM, Roberts LA, Maring J, et al. Injury Patterns in Elite Preprofessional Ballet Dancers and the Utility of Screening Programs to Identify Risk Characteristics. Journal of Orthopaedic & Sports Physical Therapy. 2008; 38(3): 126-136. doi: 10.2519/jospt.2008.2390
7. Solomon R, et al. The cost of injuries in a professional ballet company: anatomy of a season. Medical Problems of Performing Artists; 1995.
8. Hu F, Qiu X, Wu X, et al. Effects of dance sports exercise on vestibular function and balance of children with sensorineural hearing loss; a randomized quasi-experimental trial. Frontiers in Pediatrics. 2024; 12. doi: 10.3389/fped.2024.1426343
9. Kenny SJ, Palacios-Derflingher L, Shi Q, et al. Association Between Previous Injury and Risk Factors for Future Injury in Preprofessional Ballet and Contemporary Dancers. Clinical Journal of Sport Medicine. 2019; 29(3): 209-217. doi: 10.1097/jsm.0000000000000513
10. Allen N, Nevill A, Brooks J, et al. Ballet Injuries: Injury Incidence and Severity Over 1 Year. Journal of Orthopaedic & Sports Physical Therapy. 2012; 42(9): 781-A1. doi: 10.2519/jospt.2012.3893
11. Luke AC, Kinney SA, D'Hemecourt PA, et al. Determinants of Injuries in Young Dancers. Medical Problems of Performing Artists. 2002; 17(3): 105-112. doi: 10.21091/mppa.2002.3016
12. Hamilton WG, Hamilton LH, Marshall P, et al. A profile of the musculoskeletal characteristics of elite professional ballet dancers. The American Journal of Sports Medicine. 1992; 20(3): 267-273. doi: 10.1177/036354659202000306
13. Chen Y, et al. The methodology function of CiteSpace mapping knowledge domains. Studies in Science of Science; 2015.
14. Chen C. CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. Journal of the American Society for Information Science and Technology. 2005; 57(3): 359-377. doi: 10.1002/asi.20317
15. Drysdale L, Gomes Z, Toohey L, et al. Musculoskeletal Injury in an Australian Professional Ballet Company, 2018-2021: 953 Medical-Attention and 706 Time-Loss Injuries Over 4 Years. Journal of Orthopaedic & Sports Physical Therapy. 2023; 53(11): 712-722. doi: 10.2519/jospt.2023.11858
16. Katakura M, Kedgley AE, Shaw JW, et al. Epidemiological Characteristics of Foot and Ankle Injuries in 2 Professional Ballet Companies: A 3-Season Cohort Study of 588 Medical Attention Injuries and 255 Time-Loss Injuries. Orthopaedic Journal of Sports Medicine. 2023; 11(2). doi: 10.1177/23259671221134131
17. Pollard-Smith T, Thomson OP. Professional ballet dancers' experience of injury and osteopathic treatment in the UK: A qualitative study. Journal of Bodywork and Movement Therapies. 2017; 21(1): 148-156. doi: 10.1016/j.jbmt.2016.06.009
18. Bowerman EA, Whatman C, Harris N, et al. A Review of the Risk Factors for Lower Extremity Overuse Injuries in Young

Elite Female Ballet Dancers. Journal of Dance Medicine & Science. 2015; 19(2): 51-56. doi: 10.12678/1089-313x.19.2.51
19. Allen N, Nevill AM, Brooks JHM, et al. The Effect of a Comprehensive Injury Audit Program on Injury Incidence in Ballet. Clinical Journal of Sport Medicine. 2013; 23(5): 373-378. doi: 10.1097/jsm.0b013e3182887f32
20. Ekegren CL, Quested R, Brodrick A. Injuries in pre-professional ballet dancers: Incidence, characteristics and consequences. Journal of Science and Medicine in Sport. 2014; 17(3): 271-275. doi: 10.1016/j.jsams.2013.07.013
21. Jeffries AC, Wallace L, Coutts AJ, et al. Injury, Illness, and Training Load in a Professional Contemporary Dance Company: A Prospective Study. Journal of Athletic Training. 2020; 55(9): 967-976. doi: 10.4085/1062-6050-477-19
22. Kozai AC, Twitchett E, Morgan S, et al. Workload Intensity and Rest Periods in Professional Ballet: Connotations for Injury. International Journal of Sports Medicine. 2020; 41(06): 373-379. doi: 10.1055/a-1083-6539
23. Hincapié CA, Morton EJ, Cassidy JD. Musculoskeletal Injuries and Pain in Dancers: A Systematic Review. Archives of Physical Medicine and Rehabilitation. 2008; 89(9): 1819-1829.e6. doi: 10.1016/j.apmr.2008.02.020
24. Steinberg N, Siev-Ner I, Peleg S, et al. Injuries in Female Dancers Aged 8 to 16 Years. Journal of Athletic Training. 2013; 48(1): 118-123. doi: 10.4085/1062-6050-48.1.06
25. Bronner S, Bauer NG. Risk factors for musculoskeletal injury in elite pre-professional modern dancers: A prospective cohort prognostic study. Physical Therapy in Sport. 2018; 31: 42-51. doi: 10.1016/j.ptsp.2018.01.008
26. Biernacki JL, Stracciolini A, Fraser J, Micheli LJ, Sugimoto D. Risk Factors for Lower-Extremity Injuries in Female Ballet Dancers: A Systematic Review. Clinical Journal of Sport Medicine. 2021; 31(2): e64-e79. doi: 10.1097/jsm.0000000000000707
27. Kenny SJ, Whittaker JL, Emery CA. Risk factors for musculoskeletal injury in preprofessional dancers: a systematic review. British Journal of Sports Medicine. 2015; 50(16): 997-1003. doi: 10.1136/bjsports-2015-095121
28. Mainwaring LM, Finney C. Psychological Risk Factors and Outcomes of Dance Injury: A Systematic Review. Journal of Dance Medicine & Science. 2017; 21(3): 87-96. doi: 10.12678/1089-313x.21.3.87
29. Russell J. Preventing dance injuries: current perspectives. Open Access Journal of Sports Medicine. 2013. doi: 10.2147/oajsm.s36529
30. Smith TO, Davies L, de Medici A, et al. Prevalence and profile of musculoskeletal injuries in ballet dancers: A systematic review and meta-analysis. Physical Therapy in Sport. 2016; 19: 50-56. doi: 10.1016/j.ptsp.2015.12.007
31. Gottschlich LM, Young CC. Spine Injuries in Dancers. Current Sports Medicine Reports. 2011; 10(1): 40-44. doi: 10.1249/jsr.0b013e318205e08b
32. Moita JP, Nunes A, Esteves J, et al. The Relationship Between Muscular Strength and Dance Injuries: A Systematic Review. Medical Problems of Performing Artists. 2017; 32(1): 40-50. doi: 10.21091/mppa.2017.1002
33. Sobrino FJ, Guillén P. Overuse Injuries in Professional Ballet: Influence of Age and Years of Professional Practice. Orthopaedic Journal of Sports Medicine. 2017; 5(6). doi: 10.1177/2325967117712704
34. Wiesler ER, Hunter DM, Martin DF, et al. Ankle Flexibility and Injury Patterns in Dancers. The American Journal of Sports Medicine. 1996; 24(6): 754-757. doi: 10.1177/036354659602400609
35. Amorim T, Wyon M, Maia J, et al. Prevalence of Low Bone Mineral Density in Female Dancers. Sports Medicine. 2014; 45(2): 257-268. doi: 10.1007/s40279-014-0268-5
36. Critchley ML, Bonfield S, Ferber R, et al. Relationships Between Common Preseason Screening Measures and Dance-Related Injuries in Preprofessional Ballet Dancers. Journal of Orthopaedic & Sports Physical Therapy. 2023; 53(11): 703-711. doi: 10.2519/jospt.2023.11835
37. Leanderson J, Eriksson E, Nilsson C, et al. Proprioception in Classical Ballet Dancers. The American Journal of Sports Medicine. 1996; 24(3): 370-374. doi: 10.1177/036354659602400320
38. Verschueren J, Tassignon B, De Pauw K, et al. Does Acute Fatigue Negatively Affect Intrinsic Risk Factors of the Lower Extremity Injury Risk Profile? A Systematic and Critical Review. Sports Medicine. 2019; 50(4): 767-784. doi: 10.1007/s40279-019-01235-1
39. Batson G. Upate on Proprioception. Journal of Dance Medicine & Science. 2009; 13(2): 35-41. doi: 10.1177/1089313x0901300201
40. Fredyk A, Bara A, Brachman A, et al. Keep an eye on the balance—the influence of experimental training on postural stability in ballet dancers. Research in Dance Education. 2022; 25(2): 176-188. doi: 10.1080/14647893.2022.2078295
41. Ljubojević A, et al. Effects of Proprioceptive Training on Balance Skills Among Sport Dance Dancers. Facta Universitatis: Series Physical Education & Sport; 2012.

42. Lin CW, You YL, Chen YA, et al. Effect of Integrated Training on Balance and Ankle Reposition Sense in Ballet Dancers. International Journal of Environmental Research and Public Health. 2021; 18(23): 12751. doi: 10.3390/ijerph182312751
43. Vilar PL, Kovačič T, Gerževič M. Injury prevention and physiotherapy procedures for ankle injuries in ballet dancers. Annales Kinesiologiae. 2023; 13(2): 93-113. doi: 10.35469/ak.2022.349
44. Verhagen E, van der Beek A, Twisk J, et al. The Effect of a Proprioceptive Balance Board Training Program for the Prevention of Ankle Sprains. The American Journal of Sports Medicine. 2004; 32(6): 1385-1393. doi: 10.1177/0363546503262177
45. Li H, Qiu X, Yang Z, et al. Effects of Cha-Cha Dance Training on the Balance Ability of the Healthy Elderly. International Journal of Environmental Research and Public Health. 2022; 19(20): 13535. doi: 10.3390/ijerph192013535
46. Rein S, Fabian T, Zwipp H, et al. Postural control and functional ankle stability in professional and amateur dancers. Clinical Neurophysiology. 2011; 122(8): 1602-1610. doi: 10.1016/j.clinph.2011.01.004
47. Schmitt H, Kuni B, Sabo D. Influence of Professional Dance Training on Peak Torque and Proprioception at the Ankle. Clinical Journal of Sport Medicine. 2005; 15(5): 331-339. doi: 10.1097/01.jsm.0000181437.41268.56
48. Schiftan GS, Ross LA, Hahne AJ. The effectiveness of proprioceptive training in preventing ankle sprains in sporting populations: A systematic review and meta-analysis. Journal of Science and Medicine in Sport. 2015; 18(3): 238-244. doi: 10.1016/j.jsams.2014.04.005
49. Jarvis DN, Abergel RE. What Do We Know About How Acute Physical Fatigue Affects Movement in Dancers?: A Systematic Review of the Literature. Medical Problems of Performing Artists. 2019; 34(3): 161-168. doi: 10.21091/mppa.2019.3022
50. Gribble PA, et al. The effects of fatigue and chronic ankle instability on dynamic postural control. Journal of athletic training. 2004.
51. Barbieri FA, Penedo T, Simieli L, et al. Effects of Ankle Muscle Fatigue and Visual Behavior on Postural Sway in Young Adults. Frontiers in Physiology. 2019; 10. doi: 10.3389/fphys.2019.00643
52. Berardi G. Finding Balance. Routledge. 2013. doi: 10.4324/9780203446003
53. Blevins P, et al. Overtraining and recovery in dance: A case study approach. In Australian Society for Performing Arts Healthcare 2017 Symposium (ASPAH); 2017.
54. MacSweeney NDH, Shaw JW, Simkin GP, et al. Jumping Asymmetries and Risk of Injuries in Preprofessional Ballet. The American Journal of Sports Medicine. 2024; 52(2): 492-502. doi: 10.1177/03635465231218258
55. Mattiussi AM. Injury, Strength, and Jumping in Professional Ballet. St Mary's University; 2024.
56. De Wet JS. Recovery-stress states and training load of professional ballet dancers during a rehearsal and performance phase of a ballet year. Stellenbosch: Stellenbosch University; 2020.
57. De Wet JS, Africa E, Venter R. Recovery-Stress States of Professional Ballet Dancers During Different Phases of a Ballet Season. Journal of Dance Medicine & Science. 2022; 26(1): 7-14. doi: 10.12678/1089-313x.031522b
58. Fryer AM. The Cascading Effect: Mitigating the Effects of Choking under Pressure in Dancers. The Florida State University; 2018.
59. Hewett EM, and Tufano JJ. Bone health in female ballet dancers: a review. Eur J Sport Study. 2015.
60. Carson JA, Manolagas SC. Effects of sex steroids on bones and muscles: Similarities, parallels, and putative interactions in health and disease. Bone. 2015; 80: 67-78. doi: 10.1016/j.bone.2015.04.015
61. Alekel DL. Contributions of physical activity, body composition, age, and nutritional factors to total and regional bone mass in premenopausal aerobic dancers and walkers. University of Illinois at Urbana-Champaign; 1993.
62. Cianferotti L, Bifolco G, Caffarelli C, et al. Nutrition, Vitamin D, and Calcium in Elderly Patients before and after a Hip Fracture and Their Impact on the Musculoskeletal System: A Narrative Review. Nutrients. 2024; 16(11): 1773. doi: 10.3390/nu16111773
63. Skelton DA, Mavroeidi A. Which strength and balance activities are safe and efficacious for individuals with specific challenges (osteoporosis, vertebral fractures, frailty, dementia)?: A Narrative review. Journal of Frailty, Sarcopenia and Falls. 2018; 03(02): 85-104. doi: 10.22540/jfsf-03-085
64. Hoover C. An Analysis of Strength Training Implementation in Ballet. Honors Program of Liberty University; 2024.