Review

Mapping the Landscape of Proprioception Research in Gymnastics: A Bibliometric Analysis and Systematic Review

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Posted Date: 20 September 2023

doi: 10.20944/preprints202309.1277.v1

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Mapping the Landscape of Proprioception Research in Gymnastics: A Bibliometric Analysis and Systematic Review

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Abstract: Proprioception is an essential part of human movement and body awareness. It is the body's perception of its own spatial understanding, which helps us to accurately move our limbs and maintain balance. Purpose: This study aims to provide a comprehensive overview of the current state of knowledge and analyse bibliometric data about proprioception in gymnastics and acrobatics. Methodology: This article consisted of two phases: 1) a bibliometric review (based Web of Science) and 2) a systematic review (Web of Science, PubMed, and Scopus) of literature. "Gymnast*", "propriocep*", were utilized as search terms to find and choose published data. From a total of 164 studies, 30 were included for data extraction (n participants= 1432 of different age, sports, physical activities, and physical condition. Heterogeneity of studies design and assessment make it difficult to interpret the outcomes and the effect of proprioceptive interventions and comparations between samples. Proprioception is difficult to define in gymnastics considering the evidence references and the physiological considerations. Also, assessment tools used do not necessary evaluate proprioception globally considering the senses involved in gymnastics. Gymnastics training enhances joint awareness and force sense, improving proprioception and reducing injury risk. Proprioceptive exercises should be incorporated into gymnastics programs to enhance stability and precision in movements.

Keywords: body control; awareness; balance; training; assessment

1. Introduction

Proprioception is the body's sense of awareness of itself in space. Also understood as the sense that allows us to perceive the body´s parts in time and space. The proprioceptive system comprises receptors in the muscles, tendons, and joints that send information to the brain about the position and movement of the body. This information is used by the brain to control posture and movement and maintain balance and equilibrium [1–3].

There are several proposed tools, tests and means to assess proprioception [2]. Usually these assessments consider movement detection, reproduction, and discrimination [4]. Testing in proprioception could be classified as whether the test provokes a passive or active input or as argued, imposed (passive-centered in mechanoreceptors and peripheral mechanisms) or obtained (active considering central processing with cognitive factors) proprioception [1,4]. Some authors' questions have been raised about whether these traditional methods really succeed in examining higher-level proprioceptive ability as required in gymnastics [5]. Therefore, some global assessments have been proposed recently as imitation-based tests [3,6]. Despite all the questions raised recently around the way in which proprioception should be evaluated, a critical feature stands out, ecological validity [4].

 doi:10.20944/preprints202309.1277.v1

Proprioception is an important part of our ability to move and interact with the world. This ability is critical in sports, mostly in athletes and people who participate in activities that require high body control and rapid and precise actions, such as gymnastics and acrobatics. In these sports, athletes need to be able to control their bodies precisely to perform complicated maneuvers and avoid injuries while performing [7]. Aside from kinesthesia, the ability to regulate muscle contraction precisely is essential to acquire and master the complicated technique required for elite athletes to reach top level performance, particularly in sports characterized by multi-joint and multidimensional body actions [8].

Considering the gaps in knowledge concerning the study of proprioception in gymnastics and acrobatics and the interrogations about how proprioception should be evaluated; it is considered necessary to review how the evidence around proprioception in gymnastics is being evaluated and the dynamics of scientific publications in relation to this topic. This systematic reviewing is key to guide future interventions [9]. In this sense, a review of crucial source of theoretical findings as a format for recording research outcomes in sport science is needed [10]. The bibliometric analysis and systematic review methods lays the groundwork for future scientific investigation by providing a thorough understanding of the research trends and their state of development [11]. Researchers have published a variety of studies that have examined the role of proprioception and its evaluation in gymnastics, making it important to understand how to draw information from these studies and to define the current state of research and development in this area.

The bibliometric analysis is a process of assessing and forecasting the status and development trends in the study field using measuring techniques like mathematics and statistics. It uses quantitative approaches to examine the structure and development of various disciplines [12]. Scholars can learn about the state and trends of proprioception and gymnastics research through the examination of institutions, authors, and keywords in bibliometric analysis. When comparing studies from various countries and evaluating the benefits of author collaboration, quantitative analysis of the literature avoids researcher bias and has the added benefit of highlighting key study findings [13].

Considering the above, this study aimed to analyze the dynamics of bibliometric data and provide a complete up-to-date summary of the existing evidence related to proprioception and gymnastics. The outcomes of this review may guide future research lines and recommendations highlighting the evaluation methods, studies outcomes, and findings on this topic.

2. Materials and Methods

2.1. Bibliometric review

This bibliometric analysis was carried out in accordance with previously described procedures [12]. A unique toolset for bibliometric analysis was used considering performance analysis [14,15] (e.g., citation and publication metrics), considering science mapping [16] (e.g., co-citation, co-word, co-authorship). Consequently, the bibliometric analysis considered information such as authorship and co-authors network, year of publication, journals, affiliation, country, citations, and keywords.

The current paper employed a group of articles as a homogenous foundation for citation, including the main database of Web of Science (WoS), based on a search vector concerning the exploration of proprioception in gymnastics, and performed the search and extraction until May 2023. The keywords "gymnast*", "propriocep*, were used to search for and select published data. Furthermore, the papers chosen satisfied a set of inclusion and exclusion criteria: a. articles in the topic; b. available on WoS; c. years of publication until 2023. Excluding all manuscript related to technical notes, proceedings papers, editorial, abstract and reviews.

Following the abstract review, 53 studies were found. The set of articles obtained was analyzed using bibliometrics, a method previously used in the field of sports science for evaluating general bibliometric indicators, analyzing scientific production, mapping scientific knowledge, and identifying trends in terms of exponential growth. This approach ensures a sufficient volume of

documented scientific production that is of interest to the international scientific community and allows for meaningful analysis [17,18].

As statistical analysis, the Bradford's law of concentrations was applied to academic publications, splitting into thirds of articles, avoiding the exponential diminishing performance by broadening the search of references in peripheral scientific journals to the topic under investigation (Urbizagastegui, 1996). After recognizing the most prolific group of authors and research subjects, Lotka's law about authors was used in isolation from other authors with a lesser number of publications based on the irregularly distributed scientific production among authors [20]. The h-index was applied to papers based on the most cited articles by the scientific community and the citations they obtained in other publications from the studied databases, defined as "n" documents cited "n" times or more [21,22]. Zipf's law was applied to words to discover the words with the highest frequency of usage in the collection of articles evaluated through empirical observation (author keywords, keywords plus, or key terms on titles or abstract) [23]. Visualizing spatiality and the processing of information, co-authorship, and co-occurrence, the VOS viewer Software was used to control employing fragmentation analysis with theme and time visualization results [24,25].

2.2. Systematic review

This systematic literature review will be based on the guidance outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) agreements [26]. This study included scientific articles publish until December 2022. The search for articles was carried out in the PubMed (MedLine), Web of Science (WoS) and Scopus (Elselvier) databases. The following keywords were used for the search: "gymnast*", "propriocep*¨ Boolean search combined words using AND/OR to achieve relevant results by focusing on those documents that contain the keywords. Before the formal search, a bibliometric analysis of the topic was carried out to better understand the commonly used terms and keywords that could help reduce resources, organize information, and identify individuals or entities interested in the topic, as well as relevant methods used on the topic. All references were collected and imported into an open-source research tool (Zotero, Fairfax, Virginia, USA) to be later organized in a spreadsheet (Excel, Microsoft, California, USA).

For the selection and inclusion of studies, inclusion and exclusion criteria were established by the authors in consensus and after the initial inquiry of potential articles described previously (Table 1).

Table 1. Criteria for inclusion and exclusion of documents.

Inclusion criteria
Original scientific articles
Participants who practice gymnastics
Published in English, Spanish or Portuguese
Full text available
Published since 1995 to date (June 2023)
Use at least one method to quantify proprioception
Use proprioception as a method of intervention
Include, in summary, title or keywords the selected descriptors
Exclusion criteria
Animal studies that do not involve humans
Manuscripts that cannot be referenced
Meta-analysis studies, reviews, editorials, opinion, perspectives, clinical cases and others
Documents not related to non-musculoskeletal diseases
Manuscripts that use acupuncture as treatment

The search and extraction of the articles will be carried out by two researchers independently (A.F-C. and D.R-V.), while the selection of the articles to be used will be carried out jointly by all the authors (advisory group and student). To discard low-quality and irrelevant evidence, specific

 doi:10.20944/preprints202309.1277.v1

exclusion criteria were followed, and the Cochrane Scale (high risk of bias) was used. Studies with scientific evidence classified as second level were included for the study areas of sports science and medicine [28]. Literature related to book chapters, abstracts, and articles with serious lack of information was excluded. Duplicates were identified and eliminated among the databases and essential data from the selected studies were collected. To judge the relevance of the article, the full text will be read to verify compliance with the proposed eligibility criteria. The PRISMA process flow can be analyzed in Figure 1. The information will be presented in a matrix in which each of the finally selected articles will be presented and containing the following information: authors, participant characteristics, study design, pain indicator used and results.

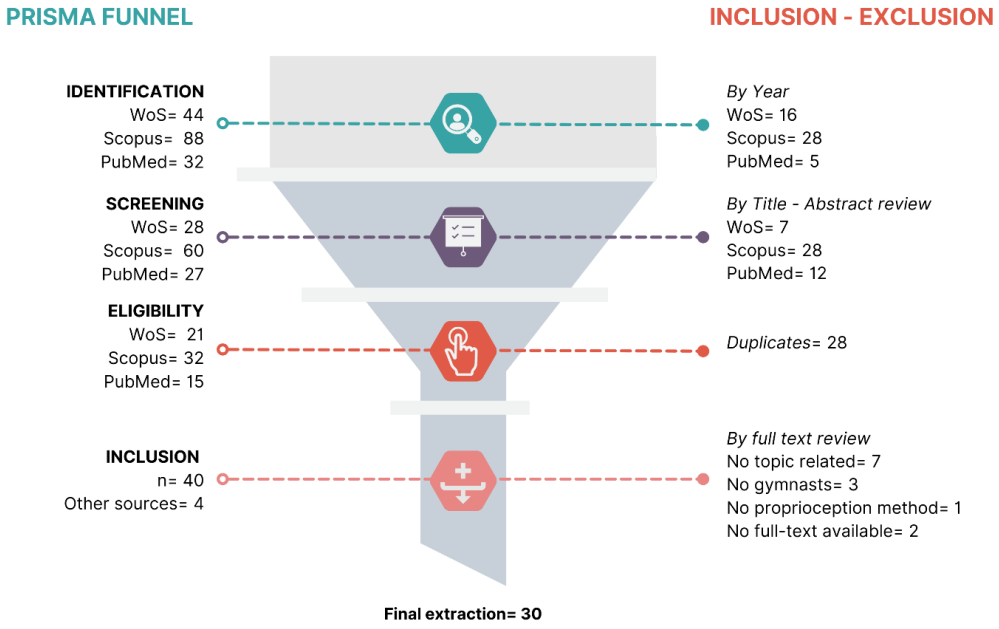

Figure 1. Flow of identification, selection, and discrimination of articles.

3. Results

3.1. Bibliometric review outcomes

The bibliometric data was analyzed based on organizations, countries, and authors. Each of these dimensions were explored based on number of publications and citations. A total of 38 out of 53 studies included after title, keywords, abstract review. There was found a found a gap in the number of publications between 1996 and 2002, and a ten-year interval 2002 and 2012. There is an exponential growth in the number of published papers in the last five year (70%, R2=0.0096).

The total of studies was published by 15 countries around the world, but with significant number of studies and collaborations made by North America and Europe. Figure 2., shows the number of publications and the collaboration between countries.

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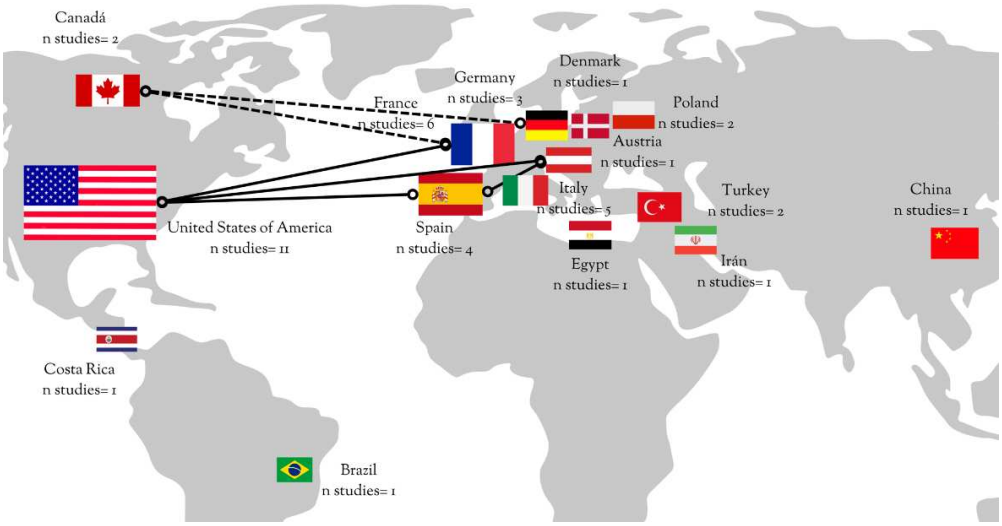

Figure 2. Number of publications and collaboration dynamic between countries/authors.

Besides, there were identified a total of 132 authors that were clustered in 33 groups. Clusters varied from one author to nine authors. The studies were published by 68 different institutions worldwide. From the analysis of keywords, a total of 239 were identified (221 with interaction), and proprioception and gymnastics were recognized as the strongest interacting with performance, expertise, balance, children, and flexibility.

3.2. Systematic review outcomes

3.2.1. Study Selection

A total of 164 potentially pertinent publications were found after an extensive search of electronic databases. 44 papers were chosen for full-text evaluation after duplicates were eliminated and inclusion and exclusion criteria were used. Finally, 30 studies were included in the systematic review since they matched the requirements (see Table 2.).

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Table 2. Systematic review study characteristics and outcomes.

#	Author	Year	Study aim	Participants characteristics / Interventions	Study Design	Propioception Assessment Method	Outcome Measures	Synthesis of Results	Research future direction
1	Niespodzi ´nski, et al.	2022	To evaluate the impact of long-term gymnastic training on joint position and force senses in boys and adults	n= 53♂ Groups: a.Gymnast (n= 15 adults + 13 boys) b.Control untrainned(n= 15 adults + 10 boys) Age: a.Boys Gymnast (11.07 ± 0.65) Control untrained (10.47 ± 0.73) B: Adults: Gymnast (20.20± 2.40) Control untrained (20.07 ± 0.80)	Observational cross-sectional study	Bilateral and unilateral: Reproduction of joint position sense reproduction of force sense	°Joint Elbow flexion 20% and 50% of MVC during elbow extension and flexion	↑ joint position sense in adults ↑ force sense in adults ↑ force sense in gymnast	Different joints and kinesthetic modalities
2	(Dallas et al., 2014)	2014	Study the immediate impacts of three warm-up methods (static stretching, proprioceptive neuromuscular facilitation, and stretching exercises on a vibration platform) on flexibility and jump performance in artistic gymnasts.	n= 18 ♂ ♀ gymnasts Age: 21.83±1.76 years	Counterbalanced crossover Experimental groups: Static Stretching Proprioceptive Neuromuscular Facilitation Stretching + Vibration	Sit and reach test Countermovement jump Squat jump	cm	↑cm (sit and reach) in proprioceptive neuromuscular facilitation group compared to other experimental groups after 15min	Study how jump performance can be affected by different stretching durations and the acute effects resulting from varying the frequency, amplitude, and/or vibration.

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				3 set of 15s stretching to mild discomfort (knee flexors and extensors and plantar flexors)				
3	(Busquets et al., 2018)	2018	Investigates sensory reweighting in standing posture adjustment among gymnasts and non gymnasts subjects	n= 81 ♂ Groups: a.Gymnast (n= 23 adults + 34 children) b.Non.gymnast(n= 13 adults + 12 children) Age: a.Children: Gymnast (9.3 ± 1.3) Non-gymnast (9.7 ± 1.1) B: Adults: Gymnast (16.3 ± 2.6) Non-gymnast (17.0 ± 0.3)	Vibrations 3 x 45 seg with eyes open and with eyes closed	Vibration	COP on baseline, perturbation phase and re-integration phase	↑ better control in trained children ↑ better values with eyes open than with eyes closed	Continue assessing gymnastics as a potential strategy for improving balance
4	(Li & Kang, 2022)	2022	Investigates the funtional and structural aspects of foot while identifying the causes of foot joint injuries in gymnasts	n= 20 ♂ Groups: a. Experimental n= 10 b. Control n= 10 Age: 22.05±1.20	Multivariate analysis of variance and sample T test Experimental group received proprioception recovery training Control group received normal functional recovery training	Ankle stability test Ankle propioception test	Overall statistic parameters Front and rear axial static parameters Left and right axial static parameters	Ankle recovery training improves stability for damage ankle joint Improved balance stability with proprioception training ↑ Experimental group had better results on the	long term training and follow up

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								overall stability index and left and right stability index of dynamic balance ability when standing with eyes and feet open	
5	(Lamoth et al., 2009)	2009	Investigate whether stochastic dynamical analysis of body sway acceleration signals can differentiate postural sway patterns among three distinct populations varying in their athletic skill level	n= 34 Groups: Physical education n= 11 (♂= 8, ♀=4) Gymnastics n= 11 (♂= 4, ♀=18)	Repeated measures ANOVAs	Stood in a two-legged tandem stance Experimental conditions: standing with eyes open Standing with eyes closed Standing on foam	mediolateral (ML) and anterioposterior (AP) variability (RMS), mean power frequency (MPF), long-range correlations (a), regularity (SEn) and local stability (lmax)	↑ more fluctuation on foam stance. ↑ more automatic and efficient postural control in gymnastics	Investigate the effectiveness of automated and simplified accelerometric systems
6	(Mendez-Rebolledo et al., 2021)	2021	comparative effectiveness of Star Excursion Balance Test (SEBT) and neuromuscular (NM) training versus conventional artistic gymnastics training (CONV) for enhancing balance control	n= 33 ♀ Age: 11–12 years n= 8 13-15 years n= 21 16-17 years n=4 Groups: Conventional artistic training 11–12 years n= 3 13-15 years n= 2 16-17 years n=3 Star Excursion Balance Test (SEBT) 11–12 years n= 2 13-15 years n= 8 16-17 years	Repeated measures ANOVAs	Y-Balance Test	Dominant lower limb and non-dominant lower limb (anterior, posteromedial, posterolateral, total index)	↑ significant improvement in balance control with neuromuscular training	Balance plataforms or test batteries that specificallt assess balance control. More investigation of various training methods and other factors that could impact balance control.

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				n=1 Neuromuscular training 11–12 years n= 3 13-15 years n= 7 16-17 years n=1					
7	(Bressel et al., 2007)	2007		n= 34 ♀ Groups: Soccer n= 11 Basketball n= 11 Gymnastics n= 12	Repeated measures ANOVAs	Balance Error Scoring System (BESS)	Balance error scoring system static balance (error) Star Excursion Balance Test Dynamic balance (Σ% of leg length	↑ static and dynamic balance in gymnasts than basketball players	Investigate impact of different sports in specific components of balance to discern which sensorimotor systems are more influenced.
8	(Danion et al., 2000)	2000	Investigate the impact of vision removal on gymnasts during the execution of basic movements	n= 16 Groups: Gymnasts n= 8 (♂= 3, ♀=5) Age: 18-25 years Control n= 8 (♂= 4, ♀=4) Age: 19±24 years	Two-way analyses of variance	1.Walk a straight line with full vision, 2. blindfolded, 3. wheelchair in a straight line and 4. wheelchair pushed by another person.	Mean absolute veering	↑ gymnast performed better during suppresion of vision Gymnasts demonstrated using proprioception, indicating ability to pick up crucial information this via	Determine whether propioception is acquired through gymnastics training or is an inherent aptitude necessary for achieving highest proficiency in the sport.
9	(Rizzato et al., 2021)	2021	Investigate the effect of different gymnastic balls on center of pressure related parameters and	n= 11 ♂ Age: 22 ± 1.09 years	Cross-sectional design Test three diferente types of gymnastic	Postural balance control through a computerized platform	Area95 Unit path	65 cm ovoid shape ball minimized multidirectional displacements	Investigate how shapes and sizes can produce different stimuli.

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			the response of core stabilization muscles.		balls (diameter: 53 cm, 65 cm and 65 cm ovoid shape) Perform three tasks: bipedal seated, unipedal seated and dynamic exercise		Core muscle activation (EMG)	during postural tasks COP related parameters are more sensitive in assessing destabilization.	
10	(Guillou et al., 2007)	2007	Examine if proprioceptive input for motor control of the left and right supporting leg (SL) can be improved through symmetrical or asymmetrical equilibrium training.	n= 36 ♂ Groups: Dancers: n= 7. Gymnasts n= 9 Soccer players n= 10 Untrained n= 10 Age: Dancers: 18 ± 0.8 years Gymnasts: 19.1 ± 3.6 years Soccer players: 17.1 ± 1.1 years Untrained: 21.4 ± 5 years	Two factor ANOVA unrepeated between participants factor according to physical activity and a two factor ANOVA repeated within participants factor according to supporting leg	Unipedal experimental task on a moveable seesaw platform	Correlations with height Pivot displacement length Spectral analysis Low requency band analysis High frecuency band analysis	↑ experts showed better stability performance compared with untrained participant Lateral body balance component is important to regulate dynamic conditions Height and weight were found to have no direct impact on balance	Analyses of head-trunk and trunk-inferior limb coordination and sensori-motor interactions
11	(Asseman & Gahéry, 2005)	2005	Investigate how variations in head position and vision condition impact stability during handstand	n= 3 ♂, 2 ♀ gymnasts	Upright posture Handstand posture on 4 different head positions: 55º dorsiflexion, 90º, 0º and ventroflexion 55º. Five different situations 3x with	Handstand balance	Head and foot marker variance Duration of handstand Center of pressure surface	Vision significantly affected gymnasts' performance Handstand duration was shorter with eyes closed Vision alone was not enough to	Not reported

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				eyes closed and 3x eyes opened.			explain the differences in performance and postural stability according to head position.	
12	(Lamb et al., 2014)	2014	Evaluate the effect of proprioceptive training on the postural balance of rhythmic gymnastics athletes	n= 7 ♀ artistic gymnasts Age: 14 ± 1,5 years	Before and after intervention assessment of postural balance in 3 diferent conditions: bipedal with open eyes, unipedal right and unipedal left.	Postural balance with bipedal and unipedal support	Center of pressure (COP) displacement area and the average velocity of COP oscillation in both the anteroposterior (A/P) and medial-lateral (M/L) planes.	↑ possible improvement in postural stability due to proprioception training	Develop intervention protocols for postural balance training tailored to specific sports modalities in athletes
13	(Dallas & Dallas, 2016)	2016	Investigate the impact of fatigue on postural control in female participants.	n= 7 ♀ Age: 21 ± 4.6 years	Counter balanced across six different conditions: double-leg stance, foam surface, single-leg stance, tandem stance with both legs. Tested before and after fatigue exercises.	Postural control using the Balance Error Scoring System (BESS)	Error on 6x different conditions	Fatigue decreased postural stability	Not reported
14	(Aydin et al., 2002)	2002	Investigate the ankle joint position sense patterns in gymnasts and non-gymnasts	n= 40♀ 20 gymnasts Age: 14.3 ± 1.5 years 20 non-gymnasts Age: 13.6 ± 2.3 years	Participants blindfolded performed both tests, beginning with the passive test. ON active test, the subjects wore a headset too.	Active angle-reproduction test and passive angle-reproduction test	Average errors score for both tests. Maximum plantar flexion Maximum inversion	↑ gymnasts had better proprioceptive abilities Conditioning could develop enhanced neurosensory pathways that improve joint position	Identifying and categorizing postural or movement impairments, particularly in relation to their underlying causes.

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15	(Kochanowicz et al., 2018)	2018	Investigate the effects of gymnastic training on static and dynamic postural control in individuals aged 8-25 years	n= 105 ♂ Age: 8-10 years: Gymnasts n= 21 Non-gymnasts n= 21 12-14 years: Gymnasts n= 15 Non-gymnasts n= 20 18-25 years: Gymnasts n= 12 Non-gymnasts n= 16	ANOVA with repeated measurements (age and group), (eyes open – eyes closed) Body balance trials x3 times each with one minute interval	Static postural control in upright standing position with eyes open and closed. Dynamic postural control with visual feedback	Center of pressure (COP)	↑ significant differences in surface area between the non-training group and gymnasts, and also among different age groups ↓ lower surface area in eyes open condition Gymnast achieved better results than non-gymnasts in all age categories	incorporating more complex and sport-specific postural tasks to investigate postural control
16	(Niespodziński et al., 2022b)	2022	Investigate differences in joint position sense and force sense, and evaluate the impact of gymnastic training in these senses	n= 53 ♂ Age: 9-11 years: Gymnasts n= 13 Non-gymnasts n= 10 18-25 years:	Observational cross-sectional	Joint position sense test Force sense test	Absolute error (AE) and constant error (CE),	↑ gym nasts obtained better results propioception improves with age	different joints and kinesthetic modalities to gain more insight into the development of proprioception

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				Gymnasts n= 15 Non-gymnasts n= 15					
17	(Busquets et al., 2021)	2021	investigate the effects of sensory information alteration on postural movements performance and control during bipedal standing in different proprioceptive and visual conditions	n= 77 ♂♀ 7 - 14 years: Gymnasts n= 31 Non-gymnasts n= 11 +15 years: Gymnasts n= 22 Non-gymnasts n= 13	Stand barefoot and two visual conditions of three 45 s trials were performed during the session: eyes open (EO) and eyes closed (EC).	Balance standing with stimulated with two vibrators	Principal postural movement components (PP-rSDT 1-4) 2. Principal velocities (PV-rSDT 1-4) 3. Principal accelerations (PA-rSDT a1-2) 4. Sensory information contribution variables (PV-rSDT 1-4) 5. Trunk rotation velocity 6. AP hip flexion/extension velocity 7. AP ankle strategy (PA-rSDT)	Age effect on postural control Gymnastic experience effect on postural control	Investigate the effects of sensory information alteration on postural movements performance and control in different populations
18	(Schmidt et al., 2017)	2017	Investigate the prevalence of generalized joint hypermobility (GJH) and its association with adverse health outcomes in elite adolescent athletes participating in ballet, teamgym gymnastics, and team handball.	n= 132 36♂ 96♀ Ballet dancers n= 22 Gymnasts n=53 Handball players n=53	Cross-sectional Beighton score, self-reported injury questionnaire, and four static motor performance tests with eyes open and eyes closed.	Static motor performance tests	General joint hypermobility Center of Pressure Path	Generalized joint hypermobility (GJH) was higher in ballet dancers and gymnasts compared to team handball players.	Assess injury and including a more diverse sample of sports and age groups.
19	(Dalichau & Scheele, 2000)	2000	The study aimed to investigate whether the criteria of sport and back	n= 128 ♂ 28 hockey players	Cross-sectional study	Angle reproduction ability	Angle 10º, 15 º and 30 º	↑ position sense was greater in two-legged stance	Examining other sports with larger sample sizes to

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			pain influence the expression of position sense as a component of proprioception.	8 hockey players with lumbar pain 25 gymnasts 9 gymnasts with lumbar pain 41 tennis players 14 tennis players with lumbar pain 34 non-athletes 11 non-athletes with lumbar pain	Reproduce the angle position with visual reference and with eyes closed			Criteria of sports and lower back pain can influence the position sense as a component of proprioception	identify the loading profiles that can lead to the modification of proprioceptive abilities.
20	(Han et al., 2015)	2015	Investigate the relationship between proprioceptive ability, competition level achieved, and years of sport-specific training among elite athletes from five different sports	n=54♂ 46♀ Age: Gymnasts n= 20 Swimming n= 20 Sports dancing n= 20 Badminton n= 20 Football n= 20 Control group n= 20	Cross-sectional study	Proprioceptive acuity at the ankle, knee, spine, shoulder, and finger joints using an active movement extent discrimination test.	Proprioceptive acuity scores	↑ level of competitive success achieved by elite athletes was significantly related to their proprioceptive acuity. ↓	Investigate the mechanisms underlying the development of proprioceptive ability and the relationship between proprioception and other factors that contribute to athletic performance, such as strength, power, and endurance.
21	(Laßberg et al., 2020)	2020	Investigate the characteristics of the vestibulo-ocular reflex (VOR) in high-level	n=37♂ Gymnasts n=17 Age:	Cross-sectional and longitudinal design that includes a group of high-level gymnasts (Gym)	Multiaxial vestibular stimulation device	VOR mean values, standard deviation and coefficient of variance	↓ VOR gain level is not affected by practicing gymnastics	Not reported

			gymnasts compared to non-athletes	10-16 years old Non-athlete n=19 Age: 11-16 years old Top level gymnasts n=9 Age: 17-25 years old	compared to an age-matched control group of non-athletes (NA) who were tested twice over a period of three years Comparison of the data from the cross-sectional and longitudinal design (Gym and NA) with data from top-level gymnasts (TopGym) to give further insight into tendencies of additional relationships between the group's level of performance and individual VOR characteristics.				
22	(Ye & Qian, 2016)	2016	Develop a practical method for the evaluation of lower-limb proprioception during target-reaching stand-to-squat movements for trampoline gymnasts.	n= 37 19 ♂ 18♀ Age: 17.9 ±37 years Exercise experience: 8.27 ± 2.63 years	Two sessions, Day 1 and Day 2, to ensure the reliability and repeatability of the measurement.	Stand-to-squat movements	Matching rates, gender and rank, sports experience	Presented method demonstrated excellent reliability and was appropriate for use when evaluating lower-limb proprioception	Not reported
23	(Niespodziński et al., 2018)	2018	Compare the accuracy of joint position sense (JPS) and force sense (FS) in gymnasts and non-athletes	n= 41 participants Age: Gymnasts 20.54 ± 3.51 years Non-athletes	Cross-sectional design JPS and FS evaluation at the elbow joint	Joint position sense	Joint position sense (JPS) and force sense (FS) accuracy Muscle strength (MS)	↑ gymnasts had greater accuracy in joint position sense (JPS) and force sense (FS)	Investigate the contribution of Golgi tendon organs to force sense accuracy.

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				19.84 ± 0.93					
24	(Han et al., 2014)	2014	Investigate the relationship between ankle proprioception and sport attainment, as well as to determine the predictors of sport attainment	n= 120 Athletes; n=100 ♂♀ Age: 20.5 ± 1.0 Non-athletes: n=20 ♂♀ Age: 20.6 ± 0.6	Correlational observational study	Judgement of ankle inversion movements	Ankle movement discrimination scores	Ankle proprioceptive ability is significantly correlated with competition level, but there is no significant relationship between ankle proprioception and years of sport-specific training for the five sports tested Athletes had significantly better ankle movement discrimination scores than healthy controls	Investigate the role of sport-specific training in maintaining a high level of ankle proprioceptive ability
25	(Vuillerme et al., 2001)	2001	Investigate whether the process of reweighting sensory information could be modified with expertise in sports requiring fine postural control	n= 14 ♂ Gymnasts: n= 7 Age: 21.1 ± 1.3 Non-gymnasts: n= 7 Age: 22.6 ± 2.1	Repeated-measures design, where each participant was tested under four different experimental conditions: Vision and no vision with normal proprioception condition, vision and no vision with perturbed proprioception	Postural behavior	Center of pressure (COP)	Process of reweighting sensory information can be significantly improved through specific training such as gymnastics	Not reported

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26	(Janin & Dupui, 2009)	2009	Examine the effects of medial arch support on center of pressure (CoP) and pressure distribution in bilateral standing	n= 13 ♀ Age: 8 years ± 9 months	Each participant was tested under three different experimental conditions: control condition (no stimulation), stimulation with the arch support of the left foot, and stimulation with the arch support of the right foot.	Postural behavior	Center of pressure (COP)	Unilateral placement of an arch support produced a mechanical increase of pressure underneath the supported foot, as well as an ipsilateral shift in the center of pressure (CoP)	Potential applications of medial arch stimulation for facilitating increased weight bearing in one of the lower extremities
27	(Lephart et al., 1996)	1996	Evaluate knee kinesthetic ability in gymnasts and non-gymnasts	n= 45 ♀ Gymnasts: n= 15 Non-gymnasts: n= 30 Mean age: 19.3 years	Cross-sectional study	Knee kinesthetic ability which was evaluated using a Passive Torsional Device (PTD)	Knee kinesthesia	Extensive training has a positive influence on knee kinesthesia	implications of training in increased kinesthesia, its effect on improved performanceand its reflex protective mechanism
28	(Kochanowicz et al., 2018)	2018	Analyze the peak torque and muscle activity of agonists/antagonists of the arms in non-trained individuals and gymnasts	n=67 ♂ Gymnasts: n= 32 Non-gymnasts: n=35 Age categories: 8-9 years n=40 18 – 25 years n=27	Cross-sectional study	Peak torque	Peak torque and muscle activity of agonists/antagonists	↑ gymnasts had higher peak torque values than non-trained individuals in both age categories	Not reported

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29	(Kochanowicz et al., 2019)	2019	Examine neuromuscular and torque kinetic changes after 10 months of explosive strength training (EST) on isometric explosive force (EF) and explosive endurance (EE)	n=30 ♂ Gymnasts: n=15 Age: 9.02 ± 0.41 Non-gymnasts: n=15 Age: 8.76 ± 0.51	Pre-post intervention design with a comparison group	Maximal voluntary contractions (MVC) for explosive force and explosive endurance	Neuromuscular and torque kinetic changes	After 10 months of explosive strength training (EST), prepubertal gymnasts showed significant improvements in neuromuscular and torque kinetic changes in isometric explosive force (EF) and explosive endurance (EE) compared to their untrained counterparts	Effects of specific strength training, such as high-intensity resistance training, on explosive muscle strength in prepubertal children
30	(Tikiz & Altun, 2022)	2022	Investigate the development of target joint position sense (JPS) and force sense (FS) in young gymnasts at different age groups and compare the effect of external load on position sense	n=17 ♂ 21 ♀ Age 12-14=6♂ 7 ♀ Age 15-17 =7 ♂ 5 ♀ Age 18 and over=8 ♂ 5 ♀	Cross-sectional study	Joint position sense (JPS) and force sense (FS)	Error scores	Older gymnasts demonstrated greater accuracy in JPS and FS in comparison to younger gymnasts	Investigate the effect of different types of external loads on joint position sense and force sense in gymnasts.

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3.2.2. Study Characteristics

The studies that are considered were completed between 1996 and 2022. Ten studies were released between 1996 and 2009, while 20 studies were found between 2014 and 2022. There was a gap on publications of five years between 2009 and 2014.

3.2.3. Participant Characteristics / interventions

Studies included sample sizes ranging from five to 132 participants (a total of 1432 participants). From a total of 1432 participants included in this review, 783 were men, 393 women, and 256 participants with no information of sex distribution (four studies). Selected research included a wide range of participants by age (e.g., adults, children), sports (e.g., gymnastics, soccer, basketball, sport dancing, swimming, handball, tennis, badminton, football, hockey), physical activities (e.g., dancing, ballet dancing, physical education students) and physical condition (e.g., trained, untrained, top-level gymnastics).

3.2.4. Study Design

The design and interventions varied across the included studies. Those participants of sports others than gymnastics and untrained sample served usually as control or comparative groups depending on study´s aim. Most studies (n= 21) were comparative by age, physical ability, training level and sport. A total of four studies used a control group and five selected a one group cross-sectional design.

3.2.5. Proprioception Assessment

The studies used a range of measures to assess proprioception, including balance tasks (n= 14), joint position sense and reproduction tests (n= 8), force sense and reproduction tests (n= 5), center of pressure (n= 5), spatial-temporal orientation tests (n= 1). Balance tasks varied using different settings and conditions as: unipedal or bipedal balance, static or dynamic tasks, visual feedback or blind folded. Some studies also employed vibration and vestibular stimulation devices (n= 3).

3.2.6. Outcome Measures

The outcome variables assessed in this study encompassed various aspects of motor control, balance, and proprioception. The proprioceptive tasks and assessment gave information regarding perturbation and re-integration phases and anterior, posterior, and mediolateral variability, regularity, veering data, change of direction, frequency, degrees, velocity, coefficient of variance, standard deviation, and other outcomes. Other assessments used scoring, and rankings based on indexes and grading systems.

3.3. Synthesis of Results

The comprehensive review produced several important conclusions about proprioception in different demographics and sports. In comparison to baseline, adults had better joint position sensation and force sense, suggesting the possibility of proprioceptive augmentation with aging. Gymnasts demonstrated superior force sensing skills, demonstrating the beneficial effects of force perception training. Children who had received training exhibited superior motor control, and when tasks were performed with the eyes open as opposed to closed, better results were obtained.

Ankle recovery exercises were observed to increase stability in those with damaged ankle joints, demonstrating the potential therapeutic benefits of proprioceptive interventions. Proprioception training also led to an increase in balance stability, with the experimental group outperforming control groups in terms of both overall stability indices and dynamic balancing skills.

Gymnasts demonstrated more automatic and effective posture control, and they performed better when it came to blocking their vision while performing activities. The assessment of instability was found to be more sensitive to center of pressure-related characteristics. In comparison to

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untrained participants, experts demonstrated greater stability performance, highlighting the need of proprioception competence.

Additionally, vision had a major impact on gymnasts' performance, with eyes closed resulting in a shorter handstand duration. The variations in performance and postural stability based on head position, however, were not entirely explained by vision by itself. While fatigue was found to reduce stability, proprioception training showed potential benefits for postural stability. Across all age categories, gymnasts consistently demonstrated superior proprioceptive skills over non-gymnasts. Ballet dancers and gymnasts had higher rates of joint hypermobility, and proprioceptive acuity was positively correlated with competition success.

In terms of assessment procedures, gymnasts outperformed non-trained individuals in joint position sense and force sense. Ankle proprioceptive capacity was related to competition level but not to years of sport-specific training. Athletes outperformed healthy controls in ankle movement discrimination, showing the impact of sport-specific training on discrimination abilities. Gymnastics training improved sensory reweighting, but unilateral installation of an arch support altered the center of pressure and increased pressure underneath the supported foot.

3.4. Research Future Directions

Despite the high-quality findings, some gaps and potential study directions were noted. To begin, there was significant variation in the designs, individuals, and types of proprioceptive assessment and tasks used, making comparing study outcomes difficult. Future research should look at the effects of different joints and kinesthetic modalities on proprioception to gain a better knowledge of how it develops. Exploring the impact of different stretching durations, acute factors, and balance-specific training protocols can also help to maximize performance and improve training techniques.

More research should be done to determine the long-term effects of gymnastics training on balance and to examine more diverse populations to uncover sport-specific variables. The creation of automated systems and customized balance platforms can give effective instruments for evaluating balance control. Investigating the relationship between proprioception and other elements that influence athletic performance, as well as the mechanisms underlying proprioceptive ability, can help to develop training strategies and improve athletic outcomes.

4. Discussion

This systematic review's findings provide important insights into the role of proprioception in various demographics and sports. The analysis of bibliometric data focused on exploring organizations, countries, and authors in terms of their publications and citations. Interestingly, there was a noticeable gap in publications during the years 1996 to 2002 and a ten-year interval from 2002 to 2012. When examining the geographical distribution of these studies, it was found that a total of 15 countries across the world contributed to the research. Notably, North America and Europe stood out with a substantial number of studies and collaborations. This finding suggests that there is limited interaction beyond these regions, emphasizing the importance of expanding knowledge and fostering collaborations with researchers and institutions from other parts of the world. By doing so, it would be possible to enhance the global reach and impact of research in this field.

Based on the systematic review outcomes, gymnasts' superior force sense abilities demonstrate the positive influence of gymnastics training on force perception, emphasizing the sport's special benefits proprioceptive capabilities [29–32]. Proprioception is important for injury prevention in gymnastics and other acrobatic disciplines, in addition to its function in optimal performance [33]. This sense assists athletes in precisely gauging their body's position and movement, allowing them to make required adjustments to lessen their risk of falls or other accidents. Proprioception may help athletes in performing motions using proper technique, lowering the chance of overuse injuries and other common concerns. Balance and coordination training and fitness drills can improve proprioception and reduce injury risk in these high-impact sports [34].

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Furthermore, proprioception is important in gymnastics and acrobatic disciplines since these sports involve exact control and awareness of one's body in space. It is required in artistic gymnastics to execute perfect landings, modify body position mid-air, and maintain equilibrium on diverse apparatus. Overall, proprioception is an important part of gymnastic and acrobatic performance because it allows athletes to control their movements precisely and execute skills with grace and precision [35,36]. Consenquently, proprioception involves both central and peripheral aspects. Proprioception is based on the neural input accumulated by mechanoreceptors at the peripheral level (articular, muscle, and skin) [4,5]. The central nervous system then analyzes this information to establish the body's location and motion. We would be unable to manage various movements accurately without proprioception [4,5].

The proprioceptive neuromuscular facilitation group's improved sit-and-reach flexibility after a brief intervention period shows the viability of targeted proprioceptive training approaches for improving flexibility [37]. Children who had received proprioceptive training had greater motor control, which may have long-term advantages for movement coordination [29]. Furthermore, performing tasks with open eyes produced greater results than doing so with closed eyes, highlighting the critical function that visual feedback plays in proprioceptive processing [38].

The benefits of ankle rehabilitation exercises on stability in people with damaged ankle joints support the use of proprioceptive therapies in rehabilitation. The experimental group outperformed the control group in both static and dynamic balance tests, demonstrating that proprioception training can also improve balance stability. Gymnasts' automatic and effective postural control demonstrates the benefits of specific training on proprioceptive abilities and emphasizes the use of proprioception in tasks requiring the suppression of vision [39–41].

The sensitivity of COP-related indicators to destabilization strengthens their utility in assessing postural control. Experts outperformed untrained participants in terms of stability performance, highlighting the importance of experience and sustained training in proprioceptive development. The role of vision on gymnast performance, on the other hand, implies that proprioception alone may not explain for all differences in performance and postural stability, highlighting the intricate interplay of sensory modalities [42–44]. The observed shift in center of pressure and pressure distribution beneath the supported foot as a result of unilateral installation of an arch support illustrates the possible significance of external stimuli in changing proprioceptive input. These findings help us understand how external variables can alter proprioception and postural control. Overall, the findings of this comprehensive review highlight the importance of proprioception in a variety of contexts, from athletic performance to injury healing, and highlight the potential benefits of focused proprioceptive training programs.

Gymnasts' consistently higher proprioceptive abilities across different age groups highlight the impact of gymnastics training on proprioceptive skills across the lifetime. Joint hypermobility was shown to be more common in ballet dancers and gymnasts, implying a possible link between joint hypermobility and participation in activities that require high levels of proprioception [33]. Furthermore, the positive relationship between competitive success and proprioceptive acuity emphasizes the significance of proprioceptive talents in obtaining peak athletic performance [33,45].

Researchers now have legitimate instruments for testing lower-limb proprioception thanks to the dependable measurement methodologies identified in this systematic study. Gymnasts outperformed non-trained persons in joint position awareness and force sense accuracy, highlighting the impact of sport-specific training on proprioceptive ability. The relationship between ankle proprioceptive ability and competition level suggests that proprioceptive skills may help athletes perform better, and athletes' superior ankle movement discrimination scores support the impact of sport-specific training on discrimination abilities [33,34,45].

Considering the helpful information gathered from this systematic review, there are some areas that require additional research. Future research should look at the long-term impact of proprioceptive training and its applicability to other functional activities and sports. Furthermore, the impact of various training methods, intensities, and durations on proprioceptive outcomes should be investigated in order to optimize training regimens.

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More research is needed to understand the underlying mechanisms of proprioceptive development and its link to other characteristics impacting athletic performance, such as strength, power, and endurance. By filling these knowledge gaps, we can gain a better understanding of proprioception and its consequences for human performance.

Future research directions

This bibliometric analysis and systematic review provide a complete evaluation of the body of research on proprioception in gymnastics. Building on this foundation, some future research directions can be identified. First, more longitudinal research on the long-term effects of gymnastics training on proprioceptive abilities are needed. By studying gymnasts over time, researchers can better understand the course of proprioceptive development and identify critical opportunities for intervention. To improve training methods and performance, it would also be good to research how specific training regimens, like as strength and conditioning programs, affect gymnasts' proprioceptive abilities.

Future research should investigate how different aspects of gymnastics training, such as apparatus-specific abilities and training intensities, affect proprioceptive performance. By studying how different training modalities affect proprioception, researchers can create training regimens to improve certain proprioceptive qualities vital in gymnastics. Furthermore, studies on the efficacy of proprioceptive training approaches, such as balance training regimens or sensory integration exercises, may provide coaches and gymnastics practitioners with helpful information. Evaluating the efficiency of various intervention strategies and selecting the most efficient methods for proprioceptive development will be critical in improving gymnast performance and lowering the risk of injury.

In general, proprioception research in gymnastics should focus on longitudinal studies, studying specific training modalities, and analyzing the efficacy of proprioceptive training regimens. By bridging these study gaps, we can learn more about proprioceptive systems in gymnastics and offer evidence-based training recommendations.

Limitations

There are a few limitations to this systematic study that should be mentioned. To begin, the review may be biased toward published studies, thereby ignoring unpublished or non-English language research. Second, the heterogeneity of the included research, such as differences in methodology, sample sizes, and outcome measures, makes direct comparison difficult. Furthermore, the emphasis on cross-sectional and intervention research limits the ability to measure long-term improvements in proprioceptive capacities. Furthermore, because the research focused solely on gymnastics, the findings may be limited in their generalizability to other sports or groups. Future study should focus on overcoming these constraints to gain a more complete knowledge of proprioception in gymnastics and beyond.

5. Conclusions

The results show that gymnasts consistently have better joint position awareness and force sense than non-gymnasts, showing the unique benefits of gymnastics training in improving proprioception. Proprioceptive training interventions have been shown to improve gymnasts' stability, balance control, and postural stability, implying the importance of incorporating targeted proprioceptive exercises into gymnastics training regimens to reduce the risk of ankle joint injuries. Proprioception and vision interact, with visual cues and head position influencing gymnast performance. However, the findings highlight proprioception's unique role to performing precise movements and maintaining postural stability, underlining the need of focusing on proprioceptive development in gymnastics training programs.

Author Contributions: Conceptualization, A.F-C., J.M-J., D.R-V and K.L.; methodology, A.F-C., and D.R-V; software, A.F-C., and D.R-V.; validation, A.F-C., J.M-J. and K.L.; formal analysis, A.F-C., and D.R-V; investigation, A.F-C., and D.R-V; resources, A.F-C., J.M-J. and K.L.; data curation, A.F-C.; writing—original draft

preparation, A.F-C., and D.R-V.; writing—review and editing, A.F-C., J.M-J., D.R-V and K.L.; visualization, A.F-C.; supervision, J.M-J., D.R-V and K.L.; project administration, J.M-J., D.R-V and K.L.; funding acquisition, J.M-J., D.R-V and K.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors report none.

Conflicts of Interest: The authors declare no conflict of interest.

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