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Review

Potential neurophysiological and biomechanical risk factors for sport-related back problems: A scoping review

Erika Zemková[a,b,*], Banafsheh Amiri[a], Henrieta Horníková[c], Ludmila Zapletalová[b]

[a] Department of Biological and Medical Sciences, Faculty of Physical Education and Sport, Comenius University in Bratislava, Slovakia
[b] Faculty of Health Sciences, University of Ss. Cyril and Methodius in Trnava, Slovakia
[c] Department of Track and Field and Sport Conditioning, Faculty of Physical Education and Sport, Comenius University in Bratislava, Slovakia

A R T I C L E I N F O

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A B S T R A C T

This scoping review aims (1) to map the literature dealing with neurophysiological and biomechanical aspects of back problems in athletes in order to identify valid risk-factors for their prevention, plus (2) to identify gaps in the existing research and propose suggestions for future studies. A literature search conducted with Scopus, Web of Science, MEDLINE and Cochrane Library was completed by Elsevier, SpringerLink and Google Scholar. The main neurophysiological risk factors identified leading to back problems in athletes are neuromuscular imbalance, increased muscle fatigability, muscle dysfunction and impaired motor control, whilst biomechanical risk factors include maladaptive spinal, spinopelvic and lower limb kinematics, side-to-side imbalances in axial strength and hip rotation range of motion, spinal overloading and deficits in movement pattern. However, most studies focused on back pain in the lumbar region, whereas less attention has been paid to thoracic and cervical spine problems. The range of sports where this topic has been studied is relatively small. There is a lack of research in sports in which the core muscles are highly involved in specific movements such as lifting weights or trunk rotations. A limited number of studies include female athletes and master athletes of both genders. In addition to chronic back pain patients, it is equally important to conduct research on healthy athletes with a predisposition to spine problems. Investigators should focus their empirical work on identifying modifiable risk factors, predict which athletes are at risk for back problems, and develop personalized sport-specific assessment tools and targeted prevention strategies for them.

This review was registered using the Open Science Framework Registries (https://osf.io/ha5n7).

1. Introduction

Low back pain (LBP) can be considered a global problem of the human population.[1,2] This disease affects the quality of life, and has become the leading cause of years lived with disability worldwide.[2–4] The most common causes associated with increased risk of LBP are strenuous activities, such as heavy lifting or manual handling in some occupations.[5] However, the LBP is also very common issue in athletes, in whose its incidence was reported to be 1%–30% depending on the specificity of their sport.[6] While leisure-time physical activities decrease the risk of chronic LBP,[7] strenuous exercises in most professional sports can cause serious spine problems.[8]

Systematic review by Wilson et al.[9] revealed the prevalence and risk factors for LBP in athletes, such as a previous episode of LBP, high training volume, periods of load increase and years of exposure. Specifically, strong association between previous and future LBP evidence was found.[8,10] For example, one-year incidence of LBP reccurrence was 33% and participants who reported more than two previous episodes of LBP had increased odds of future reccurrences.[10] Another risk factor is associated with amount of time at training and competition. Athletes have to endure a high training volume and perform many repetitive trunk motions.[11] These attributions lead to a great deal of mechanical strain, and, thus to stress on musculoskeletal system.[12,13] The amount of strain on the back depends also on the type of sport, athletes' competitive level, and training frequency.[12,13] Study by Malliaropoulos et al.[14] showed that running for more than six years and high competitive level increase the risk of LBP occurrence. A significant correlation between back pain prevalence and the number of weekly hours of practice was found in professional athletes who achieve higher training volume.[15,16]

* Corresponding author. Department of Biological and Medical Sciences, Faculty of Physical Education and Sport, Comenius University in Bratislava, Nábr. arm. gen. L. Svobodu 9, 814 69, Bratislava, Slovakia.
E-mail address: erika.zemkova@uniba.sk (E. Zemková).

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Abbreviations

BP	Back pain
LBP	Low back pain
CLBP	Chronic low back pain
NBP	Non-back pain
NLBP	Non-low back pain
HLBP	History of low back pain
LBI	Low back injury
sEMG	Surface electromyography
EO	External Oblique
IO	Internal Oblique
LD	Latissimus Dorsi
ES	Erector Spinae
RA	Rectus Abdominis
MRI	Magnetic Resonance Imagining
LM	Lumbar Multifidus
LDD	Lumbar interverbal disc degeneration
CF	Crunch factor
CoM	Center of Mass
ROM	Range of Motion
ITE	Isometric trunk extension
ITF	Isometric trunk flexion
DTFR	Dynamic trunk flexion-rotation
DEXA	Dual-energy X-ray absorptiometry
VAS	Visual Analogue Scale
Hp/Dap ratio	Compression deformities ratio
Hm/Hp ratio	Biconcave deformities ratio
Ha/Hp ratio	Anterior wedge vertebral deformities ratio
Ha	Anterior margin vertebral body height
Hp	Posterior margin vertebral body height
HM	Hallway between Ha and Hp
Dap	Anterior-posterior diameter of the vertebral body
AXIS	Critical appraisal tool for the assessment of quality of cross-sectional studies
TESTEX	Tool for the assessment of study quality and reporting in exercise
SF-36	Short form 36-Questionnaire
OCU Test	Questionnaire developed by Osaka City University
TSK	Tampa Scale for Kinesiofobia
SF-MPQ	Short Form of McGill Pain Questionnaire

With regards to neurophysiological risk factors for back problems, it is known that LBP causes clinical instability of the lumbar-pelvic spine.[17] It results in a loss of the normal pattern of spinal motion as the neural control system motion alters the timing of muscular contraction patterns and reflex responses.[18,19] One of the possible explanations for recurrent LBP in athletes could be that those who demonstrate neuromuscular control alternations to sudden trunk loading have an increased risk of sustaining a low back injury.[20] Other factors include impaired neuromuscular activation,[21] decreased in the size of the multifidus muscle,[22] muscle dysfunction,[21] and impaired motor control.[23] However, there is little evidence to support the association of these factors with sport-specific exercise loads, thus further experiments remain to be conducted.

The most common biomechanical risk factors for LBP occurrence in athletes are imbalance in hip rotation range of motion (ROM),[24] weakness of the core muscles,[25,26] and decreased lumbar ROM.[27] Regarding the hip rotation ROM, judo athletes with history of LBP exhibited deficits in hip rotation and greater asymmetry in rotation between limbs compared to athletes without LBP.[24] Further, insufficient strength of the deep core musculature and muscular compensations may increase muscular fatigue, leading to risk of developing LBP.[26] These sport-related back problems depend on the type of physical activity,[28,29] mostly in terms of movement biomechanics and specific athletic features.[15,29–31] The association with back pain indicators has been observed in sports involving repetitive or extreme loading of the spine (e.g., canoeing, rowing, weightlifting), and in those leading to impulsive landing or impact forces (e.g., gymnastics, volleyball, basketball, football).[29]

So, compared to the general population suffering from back pain due to a sedentary lifestyle,[32] athletes consistently transfer high repetitive forces through the spine during trunk rotations or lifting tasks. Therefore, they need a high functional capacity of the core musculature in order to compensate these sport-specific loads. If core strength and core stability is inadequate, athletes may be at a high risk of developing chronic back pain. In addition to reduced function of the core muscles, any kinetic chain faults may contribute to their back problems. Fatigue of the trunk muscles induced by excessive loading of the spine is one of the sources of back problems in athletes.[33] In particular, high training volume and repetitive motions are responsible for the high prevalence rates.[33] The most influential are physiological and biomechanical variations underlying the spine, though stress-related psychological factors should also be considered.[33] These factors have been usually analysed in relation to the causes and consequences of sport-specific exercises, however, little is known regarding to what extent they may be helpful in predicting athletes' spine problems. Therefore this scoping review aims (1) to analyze the literature investigating neurophysiological and biomechanical aspects of back problems in athletes in order to identify valid risk-factors for their prevention, plus (2) to identify gaps in the existing research and to propose suggestions for future studies.

2. Methods

Within the spectrum of sports injuries, such as those of ankle, knee and shoulders, spine problems are less common. Nonetheless, long-term excessive loading of the spine may change from mild to severe chronic back pain. Therefore, identifying modifiable risk factors is vital for successful athletic performance. This scoping review addressed one main question: Are there neurophysiological and/or biomechanical risk factors that would be able to predict and thereby prevent back problems in athletes?

2.1. Protocol and registration

This scoping review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines. The research team employed the frameworks by Arksey and O'Malle[34] and Levac et al.[35] to systematically locate pertinent literature and extract themes related to the research objective and identification of evidence gaps. The review was registered on March 16, 2023, using the Open Science Framework (OSF) Registries (https://osf.io/ha5n7).

2.2. Eligibility criteria

The inclusion criteria included research papers that described participants, study design itself, and the measures used to assess relevant outcomes. Articles published in years 2000–2022 were preferred. The literature search was limited to English language. Papers that failed to meet the eligibility criteria were excluded. Books, theses, case reports, and abstracts were excluded. Incomplete articles and studies that did not include original research were also excluded.

2.3. Information sources

A literature review was made to analyze existing research related to modifiable neurophysiological and biomechanical risk factors for the prevention of back problems in athletes. The search conducted with Scopus, Web of Science, MEDLINE and Cochrane Library was completed by Elsevier, SpringerLink and Google Scholar. Articles in peer-reviewed journals were analysed. However, references included in reviews were also manually searched to identify other relevant studies.

2.4. Searching, screening and assessing for eligibility

In the case of neurophysiological risk factors for back problems in athletes, the search strategy included suggested sports combined with these terms: "back pain" AND "physiological factors" AND "athletes" OR "sport" AND "back problems" OR "spine problems" AND "thoracic injuries" AND "cervical spine injuries/cervical injuries". Further search was performed using words from subheadings that specified "lumbar spine problems" AND "compression" AND "burst" AND "transverse or spinous process fractures" AND "lumbar injuries" AND "disc herniations" AND "avulsions" AND "spondylosis" AND "low back pain" AND "musculoskeletal pain" AND "lumbar disc degeneration" AND "lumbar contusions" AND "strains" AND "sprains" AND "fracture" AND "muscle spasms" AND "lumbar disk disorders" AND "sacral stress fractures" AND "posterior element overuse syndrome" AND "atypical (lumbar) Scheuermann" AND "vertebral body apophyseal avulsion fracture" AND "neurophysiological" AND "somatosensory evoked potentials" AND "transcranial magnetic stimulation" AND "electromyography" OR "EMG" AND "muscle activation pattern" AND "neuromuscular" AND "proprioceptive" AND "myoelectric manifestation" AND "muscle cramps" AND "muscle imbalances" AND "motor control" AND "altered neural transmission" AND "polyelectromyography". Altogether 273 papers were found through database searching. After an initial screening and assessing for eligibility, studies that did not meet the inclusion criteria were removed. Out of 93 articles, 24 that addressed the main question were included in this scoping review. Fig. 1 shows phases of the search process.

In the case of biomechanical risk factors for back problems in athletes, the search strategy included suggested sports combined with these terms: "sport" OR "athletes", AND "back problems" OR "spine problems", AND "back pain" OR "back injuries" OR "spine injuries" AND "biomechanics" OR "biomechanical factors" AND "movement patterns". Further search was performed using words from subheadings that specified the type of sport (e.g., tennis, ice-hockey, golf, track and field, gymnastics, cycling etc.). Altogether 120 papers were found through database searching. After an initial screening and assessing for eligibility, studies that did not meet the inclusion criteria were removed. Out of 46 articles, 15 that addressed the main question were included in this scoping review. Fig. 2 shows phases of the search process.

2.5. Data extraction

The search was focused on studies close to the main purpose of this review. The key inclusion criterion was that studies investigated neurophysiological and biomechanical factors in connection with risk of back problems in athletes, and/or identified variables that can predict the occurrence of back pain in athletes due to repeated overloading of their spine, and/or verified the effectiveness of various strategies for prevention of these problems. However, only a small number of studies was revealed using this approach. Therefore, the search was widened to studies dealing with neurophysiological and/or biomechanical variables associated with changes induced by exercise interventions. Athletes from individual and team sports with back problems were considered a target population. This helped us to identify gaps in the existing research and propose recommendations for further research on this topic. However, some concerns were about the risk factors for back problems in athletes, as in many cases they were not precisely described or directly investigated. There was a limited number of studies related to the athletic population in general. Main attention has been paid to back pain in athletes of certain sports. Relatively high differences in movement pattern and the training load among sports limited the comparison of

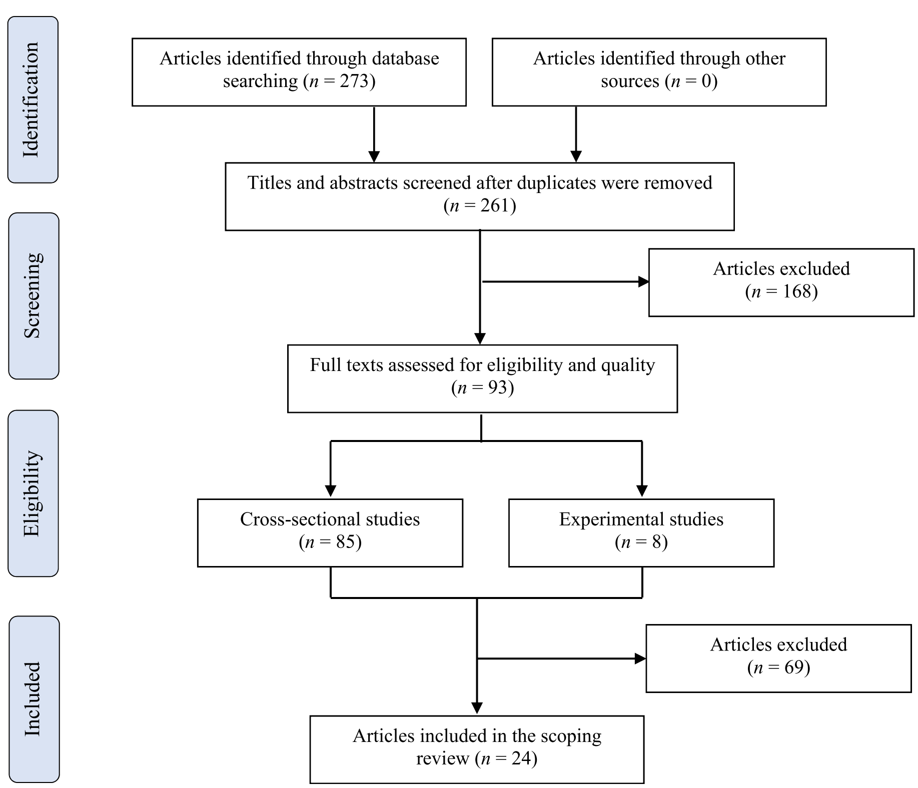

Fig. 1. Phases of the literature search process of neurophysiological risk factors for back problems in athletes.

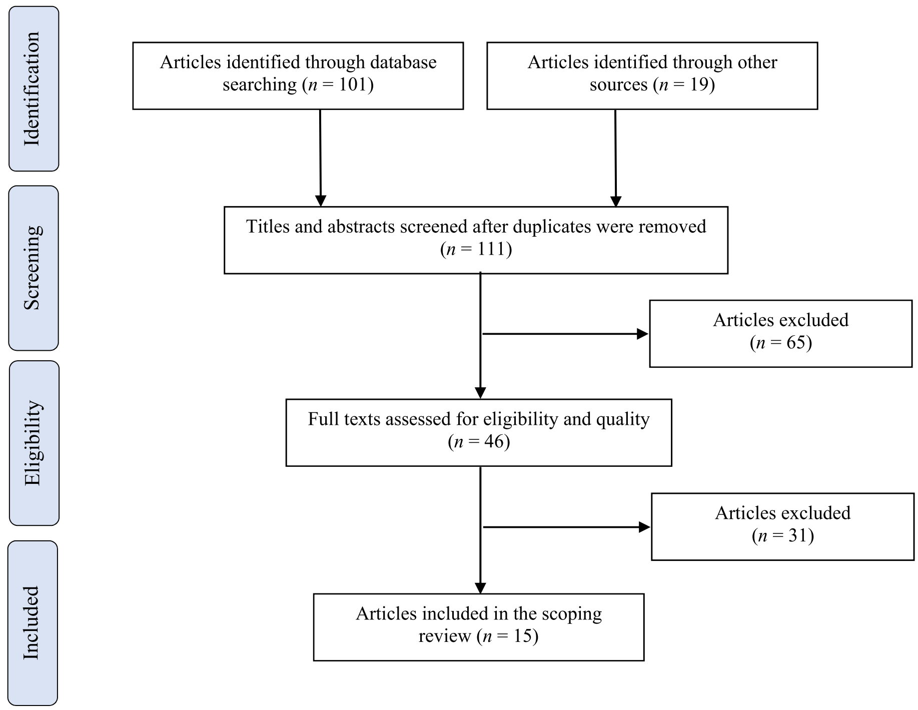

Fig. 2. Phases of the literature search process of biomechanical risk factors for back problems in athletes.

relevant risk factors for back problems in athletes and making general conclusions.

Data extraction process of selected articles involved using a standard Excel spreadsheet. Two authors were responsible for data extraction (BA, LZ), while another author (EZ) cross-checked the extracted data for accuracy. The extracted data included the publication details (study location, study design, year of publication), primary and secondary outcomes, participants characteristics (sample size, age, gender, sport specialization, back problems), methodology used, and main results related to neurophysiological and biomechanical risk factors for back problems in athletes.

2.6. Quality assessment

The methodological quality of the studies was evaluated using two assessment tools. The first one was an appraisal tool for cross-sectional studies (AXIS tool).[36] The items in the AXIS tool are arranged to align with the standard sections of a study report including introduction, methods, results, discussion, and "other". It assesses study quality by using 20 items, out of which some have key (six items) or secondary importance (two items) to the specific subject matter plus there are additional questions to appraise these important items thoroughly (12 items). The key and secondary items are used to assign firm definitions of "high", "medium", or "low" quality of studies. Using the AXIS tool, 23 out of 24 cross-sectional and observational studies related to neurophysiological risk factors for back problems in athletes were assessed. Five studies scored high and 18 studies scored medium ratings on the quality scale. The second one was a study quality assessment tool for exercise training studies (TESTEX).[37] It evaluates study quality using 12 parameters with a maximum score of 15 points. The quality scores are presented as follows: almost perfect, substantial, moderate, fair, slight, and poor. Only one study was assessed by TESTEX. The score for this study was substantial (7 out of 15 points). Similarly, 15 studies related to biomechanical risk factors for back problems in athletes with a cross-sectional design were assessed using the AXIS tool. All of them scored medium ratings on the quality scale because of missing justification of sample size and representativeness of target population.

3. Results

3.1. Selection of sources of evidence

With regards to neurophysiological risk factors for back problems in athletes, the initial search produced 273 articles. After the removal of duplicates, we screened 261 titles and abstracts, resulting in the selection of 93 articles based on the inclusion and exclusion criteria. After the full-text screening, 69 articles were excluded. The reasons for exclusion were mainly that the studies did not answer the review question about neurophysiological risk factors for back problems in athletes. The final number of selected articles for this scoping review was 24. The studies included in this review were mainly of observational cross-sectional and observational cohort design, and one using an experimental design. The selection process is summarized in Fig. 1.

With regards to biomechanical risk factors for back problems in athletes, the initial search produced 120 articles. After removing duplicates, 111 titles and abstracts were screened. This resulted in the selection of 46 articles based on the inclusion and exclusion criteria. After the full-text screening, 31 articles were excluded, mainly because they did not answer the review question about biomechanical risk factors for back problems in athletes. The final number of selected articles for this scoping review was 15. The studies included in this review were of retrospective or prospective cross-sectional design. The selection process is summarized in Fig. 2.

3.2. A summary of studies related to neurophysiological risk factors for back problems in athletes

Table 1 provides an overview of eligible studies. Out of 24 studies, 17 were conducted on youth adults,[20–24,38–49] two studies on both young and adults,[50,51] and five were unclear.[52–56]

Regarding the gender, over a third of the selected studies were conducted on male athletes,[22,43,46,50,51,53,54] another third on both male and female athletes,[20,21,24,43,44,48] and none on female athletes.

All studies involved athletes participating in organized sports at different levels. This included tennis,[21,52] soccer,[39,46] hockey,[42]

Table 1
An overview of studies dealing with neurophysiological risk factors for back problems in athletes.

Authors (year)	Subjects	Spine problems	Neurophysiological risk factors	Variables evaluated	Main findings
Cholewicki et al. (2005)[20]	292 college athletes from 22 different sports with LBI (19.4 ± 1.1) years and without low back injury (19.3 ± 1.2) years	LBI	Delayed muscle reflex response	VAS: level of pain; Roland-Morris Disability Questionnaire; level of disability; A quick force release in three separate directions of isometric trunk exertions: to assess the trunk muscle response to sudden unloading; sEMG: RA, EO, IO, LD, ES (lumbar and thoracic)	The odds of sustaining LBI increase 2.8-fold when a history of LBI is present and increase by 3% with each ms of abdominal muscle shut-off latency; On average, this latency is 14 ms longer for athletes with LBI as compared to those who not sustain LBI.
Correia et al. (2016)[21]	35 tennis players (28 males, 7 females; [18.54 ± 3.0] years)	LBP	Muscle imbalance	McGill's tests: isometric trunk endurance using flexor, extensor, and side bridge tests; Nordic Musculoskeletal Questionnaire: LBP history; sEMG: bilaterally from rectus abdominis, external obliques, iliocostalis lumborum, and longissimus thoracis	There are differences in trunk muscles endurance time, fatigue, and activation in tennis players with and without LBP.
Rostami et al. (2015)[22]	14 professional competitive off-road cyclists with LBP (27.2 ± 4.74) years and 24 controls (27.8 ± 5.26) years	Lower back pain	The lower thickness of transversus abdominis and lumbar multifidus spinae muscles and decreased back endurance	Ultrasound: the thickness of transversus abdominis, internal oblique and external oblique along with the cross-sectional area of lumbar multifidus spinae muscles in hook-lying position on the examination table, and mounted on the bicycle; Back dynamometer: the back strength and endurance (maximal force, time of holding the bar at 50% of maximum strength)	There is lower thickness of transversus abdominis and cross-sectional area of lumbar multifidus spinae muscles in cyclists with LBP compared to controls in all positions; There is no significant difference in the isometric back muscle strength between groups; There is lower endurance in back dynamometry with 50% of maximum isometric back strength in subjects with LBP.
Roussel et al. (2013)[23]	40 pre-professionals' dancers (20.30 ± 2.40) years	Lower back pain	Motor control impairment	A clinical test battery consisting of an evaluation of lumbopelvic motor control, muscle extensibility, generalized joint hypermobility, and sacroiliac joint pain provocation tests; SF-36 questionnaire, TSK and a self-established medical questionnaire; The VAS – 100 mm for the assessment of pain severity	Lumbopelvic motor control is poorer in dancers with than without a history of LBP.
Almeida et al. (2012)[24]	42 judokas: 21 with HLBP (16.7 ± 2.9) years, and 21 without history of LBP (16.3 ± 2.0) years	Lower back pain	Deficits in hip rotation range of motion, and asymmetry between limbs	Computed photogrammetry: internal and external hip rotation range of motion in active and passive movement	A significant reduction in active internal rotation and active total rotation of the non-dominant limb is in the HLBP group; A significant reduction in internal rotation of the dominant and non-dominant limb, total rotation of the non-dominant limb, and total rotation is during a passive rotation in the HLBP group; A significant reduction in both active and passive internal rotation, and active and passive total rotation of the non-dominant limb is in the HLBP group.
Balius et al. (2011)[38]	17 asymptomatic elite handball players from the Spanish national handball team (mean age 24.76 years)	Ruptured rectus abdominis muscles	Asymmetric hypertrophy of the rectus abdominis muscle	Ultrasound, MRI: rectus abdominis thickness	The phenomenon of contralateral abdominal hypertrophy in handball players appears in the dominant arm.
Cejudo et al. (2021)[39]	94 (61 men and 33 women) competitive amateur soccer and basketball players (24.35 ± 4.76) years	Lower back pain	Sagittal pelvic tilt, sagittal spinal curves due to hamstring extensibility	Self-Administered Questionnaire: four major sections for collecting information on demographics, anthropometrics, sports experience, and detailed	The probability of low-hamstring extensibility influences on the pelvis is 77.4% in male players with restricted lumbosacral angle in maximum trunk forward

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Table 1 (*continued*)

Authors (year)	Subjects	Spine problems	Neurophysiological risk factors	Variables evaluated	Main findings
				questions on LBP (location, pain history, and severity); ROM-SPORT battery: assessment of hamstring extensibility; Goniometer and ISOMED Unlevel inclinometer: to assess sagittal pelvic tilt and spinal curves	flexion position, and 100% in recurrent LBP players; The probability of low-hamstring extensibility influences on the pelvis is 75% in female players with restricted lumbosacral angle in maximum trunk forward flexion position.
Cejudo et al. (2020)[40]	19 (8 males and 11 females) equestrian athletes (14.7 ± 1.9) years	Lower back pain	Having a body fat higher than 23%; and trunk lateral flexor endurance lower than 65 s	Mobile stadiometer, and Tanita-305 body fat analyzer: anthropometric traits (body mass, body height, body mass index and body fat percentage); ROM-SPORT battery: the maximum passive 9 hip and knee ROMs of the dominant and non-dominant limb; The field tests of ITF, ITE, DTFR and isometric side bridge endurance for dominant and non-dominant sides; Chronometer and metronome: trunk muscle (flexors, extensors, and lateral flexor) endurance	Two risk factors and cutoff values are identified as predictors of LBP in child equestrian athletes: having a body fat higher than 23% and trunk lateral flexor endurance lower than 65 s, while body fat being the strongest predictor.
Crewe et al. (2012)[41]	46 asymptomatic fast bowlers (13–18) years	Lumbar stress fractures and spondylolisthesis	Acute bone stress reactions of the lumbar pars interarticularis	MRI: to assess the lumbar spine and abnormalities of the pars interarticularis and intervertebral discs	There are acute bone stress reactions of the lumbar pars interarticularis revealed on MRI.
Fortin et al. (2019)[42]	32 hockey players (18 females, 14 males; [21.4 ± 1.4] years)	Lower back pain	Deficits in lumbar multifidus morphology	Ultrasound imaging: resting LM cross-sectional area bilaterally at the L5 level in prone and standing, LM thickness at rest and during contraction; DEXA: body composition; Self-reported questionnaire: LBP history	Lumbar multifidus morphology is associated with body composition measurements; Specific deficits in lumbar multifidus morphology is observed in hockey players with LBP; Lumbar multifidus function is not associated with echo intensity or LBP.
Hides et al. (2008)[43]	26 male elite cricketers (21.2 ± 2.0) years	Lower back pain	Impaired motor control, size, symmetry, and function of the trunk muscles	MRI: the cross-sectional areas of the quadratus lumborum, lumbar erector spinae plus multifidus and psoas muscles, the thickness of the internal oblique and transversus abdominis muscles, and the amount of lateral slide of the anterior abdominal fascia	There is asymmetric hypertrophy of the quadratus lumborum, and lumbar erector spinae plus multifidus muscles in cricketers with LBP; with larger quadratus lumborum, and lumbar erector spinae plus multifidus muscles in the dominant arm and internal oblique muscle on the side contralateral to the dominant arm; There is a reduced ability to draw in the abdominal wall and contract the transversus abdominis muscle independently of the other abdominal muscles in cricketers with LBP.
Koyama et al. (2013)[44]	104 (70 men and 34 women) Japanese collegiate gymnasts (19.7 ± 1.0) years	Lower back pain	Lumbar disc degeneration	OCU Test: presence of LBP; MRI: prevalence of abnormalities (disc bulging, disc protrusion, lumbar disc degeneration, limbus vertebra, Schmorl's nodes, High-Intensity Zone, modic change, spondylolisthesis)	The incidence of lumbar disc degeneration and limbus vertebra is significantly greater in gymnasts with than without LBP; After analyzing the concomitant environmental variables, only lumbar disc degeneration (odds ratio, 2.70; 95% confidence interval, 1.10–6.66) is a significant variable accounting for LBP.
Mueller et al. (2017)[45]	8 adolescent athletes (canoeing/rowing, triathlon, wrestling) with	Back pain	Trunk muscles activity changes	Bilateral 12-lead sEMG: to assess trunk muscle activity during drop jump. Ground contact time,	There are significantly higher sEMG amplitudes for subjects with BP in the ventral and

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Table 1 (*continued*)

Authors (year)	Subjects	Spine problems	Neurophysiological risk factors	Variables evaluated	Main findings
	back pain (BP) (15.9 ± 1.3) years, and 11 matched athletes without BP			maximum vertical jump force, jump time, and the jump performance index calculated for drop jumps	transverse muscles compared to those without BP identified by the muscle group analysis over the whole jumping cycle.
Noormohammadpour et al. (2019)[46]	30 male soccer players from the Premier League (17.4 ± 1.1) years	Lowew back pain	Muscle thickness changes	Musculoskeletal ultrasound imaging bilaterally: thicknesses of the external oblique, internal oblique, and transversus abdominis muscles	Subjects with a sports life history of LBP have significantly lower internal and external oblique muscle thickness bilaterally; They have significantly less hamstring flexibility than the non-LBP group on the dominant limb.
Ranson et al. (2010)[47]	28 members of the England and Wales Cricket Board Elite Fast Bowling Group (16–24) years	Stress fracture	Changes of bone stress	MRI: changes in the appearance of the lumbar spine	There is a strong correlation between signs of acute bone stress on either the season 1 or season 2 MRI scans and the later development of a stress fracture.
Shenoy et al. (2013)[48]	24 athletes from various sporting bodies (soccer, hockey, handball, basketball) with chronic LBP (24.26 ± 4.7) years and 25 asymptomatic athletes (25.13 ± 5.05) years	Lower back pain	A delay in onset latency to unexpected perturbations, and reduced long latency response amplitudes to perturbation	sEMG of superficial trunk muscles: rectus abdominis and erector spinae	The latency of onset is delayed in unexpected perturbations but there is no change in expected tasks; The mean root square amplitudes are significantly lower in both tasks for rectus abdominis and in the expected tasks for erector spinae.
Wilkerson et al. (2012)[49]	83 collegiate football players (20 ± 1.5) years	Core strains and sprains	Low back dysfunction and suboptimal endurance of the core musculature	Preparticipation administration of surveys to assess low back, knee, and ankle function; Biering-Sørenson test: posterior core muscle endurance; Side bridging test: lateral core muscle endurance; Flexor endurance test: anterior core muscle endurance	Football players with ≥ 2 of 3 potentially modifiable risk factors related to core function have two times greater risk for injury than those with < 2 factors.
Cole and Grimshaw (2008)[50]	12 male golfers with LBP, 18 asymptomatic golfers	Lower back pain	Neuromuscular deficiencies	SF-MPQ: to establish the severity of subject's condition; VAS: to rank the intensity of pain; sEMG: the myoelectric activity of the lumbar erector spinae and the external obliques	LBP golfers tend to reduce lumbar erector spinae muscle activity at the end of the backswing; Lumbar erector spinae and external obliques muscle activity is higher in the high handicap golfers with LBP than the asymptomatic ones.
Tak et al. (2020)[51]	62 judokas with LBP (n = 29) and without LBP (n = 33) (18–40) years	Lower back pain	Lower flexibility of the hip-spine complex	VAS: average pain for the past week in the LBP-group; A battery of flexibility tests: range of motion (passive and active rotations) of hips, lumbar spine (flexion-extension) and fingertip-to-floor distance	Lower hip internal rotation of the non-dominant leg (passive and active) and lower lumbar flexibility are significantly related to LBP in male adult judokas.
Balius et al. (2012)[52]	61 professional tennis players	Rectus abdominis muscle strain	Asymmetric hypertrophy of the rectus abdominis muscle	Ultrasound (with an 8- to 12-MHz linear multi-frequency transducer): to assess rectus abdominis thickness, and the degree of asymmetry between the different rectus abdominis slices	There is prevalence of rectus abdominis muscle lesions in professional tennis players (29.5%).
Cole and Grimshaw (2008)[53]	12 right-handed male golfers with history of LBP (46 ± 17.85) years, 15 right-handed male golfers with no history of LBP (39.60 ± 13.94) years	Lower back pain	Onset activity of erector spinae muscle	SF-MPQ: to establish the severity of subject's condition; VAS: to rank the intensity of pain; sEMG: the myoelectric activity of lumbar erector spinae muscles	Onsets of bilateral upper and lower lumbar erector spinae are earlier relative to the beginning of backswing in the LBP group.
Hides et al. (2010)[54]	26 young male elite cricketers	Lower back pain	Specific impairments in the motor control of the abdominal muscles	MRI, ultrasound imaging: changes in the cross-sectional area of the trunk, the thickness of the internal oblique and transversus abdominis muscles, and the shortening of the transversus abdominis muscle in response to an abdominal	There is improvements in the cross-sectional area of the trunk, the thickness of the internal oblique and transversus abdominis muscles, and the shortening of the transversus abdominis muscles in response to an abdominal drawing-in task

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Table 1 (*continued*)

Authors (year)	Subjects	Spine problems	Neurophysiological risk factors	Variables evaluated	Main findings
				drawing-in task; VAS: LBP at the time of testing	after completion of a 13-week cricket training camp.
Iwai et al. (2016)[55]	151 collegiate male combat sports athletes, including 50 wrestlers and 101 judokas	Lumbar intervertebral disc degeneration	Asymmetrical and relatively smaller cross-sectional areas of the trunk muscles	MRI and a comprehensive grading system of LDD (grades I–V): lumbar intervertebral discs from L1–2 to L5–S1	The cross-sectional areas of the left and right sides in trunk muscles are significantly asymmetrical, independent of the lumbar intervertebral disc degeneration, which is prevalent in the disc levels; The relative cross-sectional areas of trunk muscles to their body weight are significantly smaller in the lumbar than non-lumbar intervertebral disc degeneration group.
Iwamoto et al. (2004)[56]	171 high school and 742 college football players	Lower back pain	Spondylolysis, disc space narrowing, and spinal instability	6 radiographs of the lumbar spine with anteroposterior, right and left oblique, and lateral (neutral, flexion, and extension positions) views; Abnormalities assessed: spondylolysis, disc space narrowing, spinal instability, Schmorl's node, balloon disc, and spina bifida occulta	High school players with spondylolysis have a higher incidence of LBP (79.8%) than those with no abnormal radiographic results (37.1%); College players with spondylolysis, disc space narrowing, and spinal instability have a higher incidence of LBP (80.5%, 59.8%, and 53.5%, respectively) than those with no abnormal radiographs (32.1%); College players with spondylolysis have a higher incidence of LBP than those with disc space narrowing and spinal instability.
Myrer et al. (2014)[57]	12 Division I female collegiate volleyball players (19.3 ± 1.3) years	Back pain	Muscle atrophy	Ultrasound imaging (GE Logic e): transverse images of the multifidus muscle taken bilaterally at the 4th and 5th vertebral level	Lumbar multifidus in cross-sectional area at the 4th and 5th vertebral level is smaller in players with LBP.

BP - Back pain, LBP - Low back pain, CLBP - Chronic low back pain, NBP - Non-back pain, NLBP - Non-low back pain, HLBP - History of low back pain, LBI - Low back injury, sEMG - Surface electromyography, EO - External Oblique, IO - Internal Oblique, LD - Latissimus Dorsi, ES - Erector Spinae, RA - Rectus Abdominis, MRI - Magnetic Resonance Imaging, LM - Lumbar Multifidus, LDD - Lumbar interverbal disc degeneration, CF - Crunch factor, CoM - Center of Mass, ROM - Range of Motion, ITE - Isometric trunk extension, ITF - Isometric trunk flexion, DTFR - Dynamic trunk flexion-rotation, DEXA - Dual-energy X-ray absorptiometry, VAS - Visual Analogue Scale, Hp/Dap ratio - Compression deformities ratio, Hm/Hp ratio - Biconcave deformities ratio, Ha/Hp ratio - Anterior wedge vertebral deformities ratio, Ha - Anterior margin vertebral body height, Hp - Posterior margin vertebral body height, HM - Hallway between Ha and Hp, Dap - Anterior-posterior diameter of the vertebral body, SF-36 - Short form 36-Questionnaire, OCU Test - Questionnaire developed by Osaka City University, TSK - Tampa Scale for Kinesiofobia, SF-MPQ - Short Form of McGill Pain Questionnaire.

football,[49,56] cricket,[43,47,54] bowling,[41] cycling,[22] handball,[38] dancing,[23] golf,[53] gymnastics,[44] basketball,[39] equestrian sport,[40] wrestling and judo,[24,51,55] and a combination of various sporting bodies.[20,48]

Retrospective or combined concurrent assessments of back problems with neurophysiological risk factors were performed in six studies,[41,43,44,52,55,56] retrospective with prospective data collection in three studies,[20,38,47] simultaneous assessment of spine condition with measurement of neurophysiological risk factors in 13 studies,[21–24,39,40,42,46,48–51,53] and assessment of the effect of specific exercise training on neurophysiological risk factors in elite athletes with back problems in one study,[54] whilst the other study was conducted on athletes with back problems during their sport-specific activities.[45]

The majority of studies focused on LBP patients and investigated neurophysiological risk factors for LBP in athletes (18 out of 24 studies). The most common risk factor was neuromuscular imbalance (10 out of 18 studies) including impaired neuromuscular activation, decreased muscle size, and increased muscle fatigability. An association between reduced trunk muscle activity and LBP was reported in athletes from 22 different sports,[20] further in tennis players,[21] golfers,[50,53] canoeists/rowers, triathletes, wrestlers,[45] soccer, hockey, handball, and basketball players.[48] Four studies evaluated muscle size risk factors in athletes with LBP in sports like cycling,[22] hockey,[42] soccer,[46] and cricket.[43] Six out of 18 studies related to LBP reported that athletes who had muscle dysfunction were at increased risk of LBP.[21,22,39,40,43,51] The association between reduced trunk muscle function and LBP was reported in tennis, cricket, soccer, and basketball.[21,43,48] Motor control impairment was significantly associated with LBP prevalence in cricketers[43,54] and dancers.[23] The LBP was also associated with deficits in hip rotation ROM,[24] an asymmetry between limbs,[24] spondylolysis, disc space narrowing, spinal instability,[56] lumbar disc degeneration,[44] and high body fat (higher than 23%).[40]

Furthermore, back problems include core strains and sprains,[49] stress fractures,[47] lumbar stress fractures,[41] spondylolisthesis,[41] lumbar intervertebral disc degeneration,[55] rectus abdominis muscle strain,[52] and ruptured rectus abdominis muscles.[38] Further risk factors include changes in muscle size,[38,52,55,57] bone stress,[41,47] and muscle dysfunction.[49] Target population in these studies were athletes from handball, tennis, cricket, football, volleyball, wrestling, and judo. The majority of studies included in this chapter used surface electromyography (sEMG), Magnetic Resonance Imaging (MRI), and functional tests for their investigations.

3.3. A summary of studies related to biomechanical risk factors for back problems in athletes

The overview of eligible studies is presented in Table 2. Out of 15 selected studies, seven were conducted on adults,[26,58–63] seven on youth,[24,64–69] and one study on both young and adult athletes.[70]

Regarding the gender, more than 70% of studies were conducted on male athletes and controls,[24,26,58,59,61–63,65,68,69] five on both male and female athletes,[45,60,65,66,70] and none on female athletes.

Regarding the sport, with the exception of one study,[60] all participants were engaged in organized sports at different levels in clubs or institutions.[26,58] This included tennis,[67,68] golf,[58,61] cycling,[59] rowing,[65] soccer,[69] judo,[24] diving,[66] softball,[63] and a combination of various sports.[26,45,62,70]

The influence of biomechanical factors on declared or medically confirmed LBP was investigated in nine studies,[24,58–60,63–66,69] the association between declared LBP and medically confirmed LBP degeneration in two studies,[67,68] the role of compensation in the damage of spinal structures in one study,[26] and the relationship between biomechanical factors and damage of spinal structures (spondylolysis, intervertebral disc angles, Faran ratio, lumbar body index etc.) in three studies.[61,62,70]

Retrospective or combined concurrent assessment of back problems with biomechanical risk factors was carried out in eight studies,[24,58,60–62,64–66] retrospective together with prospective assessment of back problems in one study,[63] and simultaneous assessment of spine condition with measurement of biomechanical risk factors in four studies.[59,67–69] Two studies conducted on healthy athletes simulated biomechanical deficits[26] or loading during sport-specific activities, such as athletic sprint and shooting in soccer.[70]

Regarding the methods used for the assessment of spine problems, standardized questionnaires were used in six studies,[24,58,60,61,64,65] non-standardized questionnaires in combination with laboratory or medical examination in four studies,[62,63,67,68] and medical or physiotherapeutical examinations in three studies.[59,66,69]

4. Discussion

There is some overlap in the mechanical factors that contribute to LBP across various sports. While each sport has its unique demands and characteristics, there are common issues such as repetitive trunk movements, increased loading, asymmetry, muscle imbalances, or prolonged flexed posture that can contribute to LBP in athletes. Addressing this overlap is a complex challenge because multiple sports may share similar risk factors. Therefore, it might not be practical to address each sport's LBP issues in isolation. Instead, the mechanical causes of LBP in athletes could be more clearly categorized based on typical movements in the above mentioned sports. For instance.

a) Sports with repetitive trunk rotational movements (e.g., dancing)

Multifactorial causes of LBP include repetitive movements, joint hypermobility, technique-related issues, muscle imbalances, and altered motor control. These factors lead to increased stress on the spine and lower extremities.[23]

b) Sports with repetitive asymmetric movements and/or high mechanical loading (e.g., golf, cricket, tennis, hockey)

Altered muscle activation patterns in golf can affect swing technique, with early activation of the erector spinae muscles potentially reducing swing stability.[50]

Bowling techniques in cricket involve rotations and side flexion, which contribute to repetitive and asymmetric movements. These actions lead to muscle imbalances and adaptations due to the repetitive one-sided nature of the sport. To maintain stability, cricketers may employ potential compensatory mechanisms.[43,54]

Tennis players often exhibit asymmetrical musculoskeletal adaptations, particularly in their dominant arms, as a result of the unilateral demands of this sport. The rapid speed of trunk movements and the substantial loads on the spine during serves and strokes emphasize the challenges this asymmetry, which can pose to a player's physical well-being.[21]

Hockey places substantial stress on the spine, pelvis, and lower limbs. Specific movements in this sport pose a challenge to the lumbar muscles, especially in forward-flexed positions that increase demands on these muscles. In addition, side-to-side muscle asymmetry can affect spinal stability, making it essential to address the unique mechanical demands that hockey places on athletes.[42] Repetitive mechanical loading places a significant strain on the lumbar spine. The presence of skeletal abnormalities renders the spine more susceptible to injury, further increasing stress and strain on the lumbar region during physical activities.[56]

c) Sports with repetitive trunk movements and increased loading on the back (e.g., judo, gymnastics)

In judo, where repetitive and asymmetric movements are common, athletes often perform fundamental hip rotations, placing significant stress on the hip joint. Athletes with LBP often display limited hip ROM, leading to potential compensation through increased lumbar mobility.[24,51]

Gymnastics engages athletes in repetitive hyperextension and rotational movements. High-impact landings during floor routines and dismounts further intensify the physical demands. Beginning gymnastics at a young age exposes athletes to considerable stress during their developmental years, often resulting in repetitive microtrauma and extreme postures that place significant strain on the lower back.[44]

d) Sports with repetitive compressive forces on the back (e.g., equestrian sport)

Repetitive compressive forces on the lumbo-pelvic-hip complex, especially affecting individuals with a sagittal spinal morphotype, can result in deviations from healthy spinal alignment. The asymmetric posture increases the strain to the back and core muscles, emphasizing the crucial role of trunk muscle endurance and stability in maintaining proper posture. In addition, the impact of landing forces during jumps can intensify stress on the spine and musculature.[40]

e) Sports with a prolonged flexed posture (e.g., cycling)

Cycling poses challenges with bike setup, which affects posture and stress on the lunbar region. The flexion-relaxation phenomenon puts stress on the spine, which underlines the need for strong core muscles. Proper technique and posture are vital to the health of the lumbar region, and the risk of back pain is related to the frequency and duration of cycling.[22]

f) Other sports (e.g., football, basketball)

Both football and basketball, characterized by repetitive movements, share a common concern regarding hamstring extensibility and its impact on the alignment of the spine, pelvis, and legs. Limited hamstring extensibility can disrupt normal alignment and movement patterns in athletes, resulting in alterations to lumbar curvature and pelvic position.[39]

4.1. Neurophysiological risk factors for back problems in athletes

Based on the frequency of studies, neuromuscular imbalance and muscle dysfunction were identified as primary risk factors contributing to

Table 2
An overview of studies dealing with biomechanical risk factors for back problems in athletes.

Authors (year)	Subjects	Spine problems	Biomechanical risk factors	Variables evaluated	Main findings
Almeida et al. (2012)[24]	42 judo athletes: 21 with HLBP (16.7 ± 2.9) years, and 21 without history of LBP (16.3 ± 2.0) years	Lower back pain	Deficits in hip rotation range of motion, and asymmetry between limbs	Internal and external rotation of lower limbs in prone position (maximal reach)	There are significant reductions in active internal rotation, active total rotation of the non-dominant limb and active total rotation in the HLBP than NLBP group; There are significant reductions in internal rotation of dominant and non-dominant limb, total rotation of the non-dominant limb and total rotation during passive rotation; There are significant reductions in active and passive internal rotation, and active and passive total rotation of non-dominant limb in the HLBP group.
Raabe and Chaudhari (2017)[26]	8 (6 females and 2 males) healthy participants (22.37 ± 3.93) years; athletic activities (2.4 ± 2.1) times per week	Lower back pain risk	Weakness of deep core muscles that causes changes in compressive and shear spinal loads	Deep core muscles (quadratus lumborum, psoas major, multifidus, deep fascicles of the erector spinae)	Superficial longissimus thoracis is a significant compensator for 4 out of 5 weakness conditions; Deep erector spinae require the largest compensations (45% ± 10%) when weakened individually.
Lindsay et al. (2006)[58]	40 healthy non-golfing controls, 32 healthy elite golfers, 7 elite golfers with lower back pain	Lower back pain	Side-to-side imbalances in axial strength and rotation	Bilateral trunk rotation strength and endurance: axial rotation torque, peak torque, and work	There are no significant differences in peak torque within or between groups; Endurance in non-dominant direction (the follow-through) is significantly lower in golfers with LBP than healthy groups. There is no significant difference in endurance between healthy elite golfers and non-golfing controls.
Van Hoof et al. (2012)[59]	8 cyclists with non-specific CLBP; 9 cyclists with NLBP	Non-specific chronic low back pain; Flexion pattern' disorders	Maladaptive lumbar kinematics	Pain over 2 h of cycling, saddle angle, total lumbo-pelvic flexion	There is an increase of pain over 2 h of cycling in CLBP group, and significant increase of lower lumbar flexed posture compared to NLBP group; There is no change in difference of kinematic variation between groups over time; CLBP group has slightly more posteriorly tilted saddle angle.
Chimenti et al. (2013)[60]	Recreational athletes (male/female) playing rotation-related sports (tennis, golf, racquetball); 52 with LBP and 25 with NLBP	Lower back pain history	Knee flexion and hip lateral rotation	Knee flexion, hip lateral rotation; Activity level during sport, work, and non-sport leisure activities	There are no differences between groups in knee flexion and hip lateral rotation; There is a greater difference between sport activities and majority of daily functions (work and non-sport leisure) in people with than without LBP.
Cole and Grimshaw (2014)[61]	12 male golfers with lower back pain, 15 male golfers without lower back pain	Spinal degenerations-lower back pain	CF: measure of LB injury risk based on lateral flexion and axial trunk rotation	Axial angular trunk velocity, lateral flexion angle	Average peak CF value does not differ significantly between the LBP and NLBP golfers; Timing of peak CF is not significantly different between the LBP and NLBP golfers; Golfers with higher CF present concomitant increase in both variables.
Rozan et al. (2016)[62]	12 cricket, 12 field hockey and 10 basketball national players with and without symptoms of lumbar pain; ([23 ± 3] years, [22 ± 3] years, and [20 ± 2] years, respectively)	Degenerative changes of lumbar spine	Sport specific physical loadings	Geometric variables: intervertebral disc angles, Farfan ratio, lumbar body index, Hp/Dap ratio, Hm/Hp ratio, and Ha/Hp ratio	There are significant differences in intervertebral disc angle at the L2/3, L3/4 and L4/5 level; lumbar index at the L2 level, and biconcave deformity at the L1 and L2 levels in relation to the anterior wedge deformity at L2 among all groups.
Senington et al. (2020)[63]	35 elite male fast bowlers (14 seniors, 8 with lower back pain, and 21 juniors, 8 with lower back pain)	Lower back pain	Spinal kinematics	Tibial and sacral impacts during fast bowling	There are no significant differences in spinal kinematics and impacts between senior and junior bowlers with and without LBP history; There is a greater rotation during wind-up and faster time-to-peak tibial impacts in non-LBP history bowlers;

(*continued on next page*)

Table 2 (*continued*)

Authors (year)	Subjects	Spine problems	Biomechanical risk factors	Variables evaluated	Main findings
					There are lower tibial impacts and greater lumbar extension during delivery in seniors with LBP.
Mueller et al. (2017)[64]	1 559 (945 males and 614 females) adolescent athletes (13.2 ± 1.6) years of different sports; 113 athletes with back pain	Back pain	Postural control, jumping performance, trunk strength	Center of pressure displacement, jump height, peak force, contact time, peak torque of the trunk; Co-variables: body height and weight, age, gender, training volume	There are no differences between BP and NBP groups, except for significant difference in the trunk strength; There are no differences between BP and NBP groups when co-variables (body height and weight, age, gender and training volume) are included.
Ng et al. (2015)[65]	10 male/12 female rowers between 14 and 17 years, 4 males/6 females with LBP	Lower back pain	Spino-pelvic kinematics	Time in flexion during rowing; range of lumbar spine flexion	There is a gradual increase in level of LBP in LBP group; LBP rowers spent significantly longer time in flexion during drive phase than non-LBP rowers; LBP rowers spent more time during the drive phase near end range of lumbar spine flexion (above 90% of full flexion).
Narita et al. (2012)[66]	83 (42 men and 41 women) elite Japan junior divers ([14.5 ± 1.6] years and [14.3 ± 1.8] years, respectively)	Lower back pain	Core muscle strength and endurance, flexibility, dynamic power, diving specific movement and postures	Core muscle strength and endurance, flexibility, dynamic power of lower limbs, shoulder rotation width, handstand posture	There is significant association between LBP and shoulder rotation width and age in male divers; There is higher shoulder rotation width in the pain than the no-pain group; There is a lack of flexibility in the pain group signed as a risk factor for LBP.
Campbell et al. (2013)[67]	20 male adolescent tennis players; 7 with LBP history and confirmed L4/L5 injury; 13 controls of matched age, height, mass, and performance	Lower back pain; confirmed L4/L5 injury	Regional upper and lower lumbar, pelvis, trunk and lower limb kinematics during the flat and kick serves	Upper and lower lumbar mobility in all planes, lateral pelvic tilt; Lower limb kinematics: knee and hip extension angels; knee and hip extensional velocity; serve kinematics	Pain group significantly reduces lower lumbar mobility in every plane of motion, has less right lower lumbar and pelvis/shoulder rotation, greater right pelvic tilt, earlier peak right knee extension velocity during the serve drive phase; There is a greater lower lumbar and pelvis left rotation, upper lumbar left lateral flexion, and anterior pelvis tilt during the forward-swing phase.
Campbell et al. (2014)[68]	20 male adolescent tennis players; 7 with history of lower back pain and confirmed L4/L5 injury; 13 controls matched for age, height, body mass, and performance	Lower back pain with confirmed L4/L5 injury and spondylolysis	Lumbar region mechanism during flat and kick serves	Serve kinematics: racket velocity, ball position at impact; Body kinematics and kinetics: peak angular displacement and velocity, and peak forces and moments of lumbar region	There is no significant difference in racquet velocity and ball position at impact between LBP groups or serve types; There is significantly greater (mean difference of 1.5 $N{\cdot}kg^{-1}$) peak left lateral force in the LBP than the control group; Flat serve is associated with significantly greater flexion moments (mean difference of 2.7 $N{\cdot}kg^{-1}$) than the kick serve.
Tojima et al. (2018)[69]	42 adolescent soccer players (13.9 ± 0.6) years; 22 in the lower back pain group, and 20 in the non-lower back pain group	Lower back pain	Lumbar extension and rotation: a shift of the CoM of the whole body	Foot contact, toe off, maximum hip extension, maximum knee flexion, ball impact, maximum hip flexion	NBP group compared with LBP group: lateral shift in CoM that increases the duration of kick motion, affects posterior positioning of supported foot and restricts the lateral bending of lumbar spine; There are no differences in lumbar extension, and posterior positioning of the supported foot.
Goto et al. (2018)[70]	17 male soccer players with NLBP	Lumbar spondylolysis	Kinematic and kinetic parameters: hyperextension and rotation of the trunk	Ground reaction force, kinematics (thorax, spine, pelvis, hip, knee, and ankle angles), and kinetics (hip moments)	Hip extension angle, spine rotation angle, and hip flexion moment are similar in dash and shoot during the maximum hip extension phase; Pelvic rotation angle is significantly greater in kicking than in the running conditions.

HLBP - History of low back pain, LBP - Low back pain, NLBP – Non-low back pain, BP - Back pain, NBP – Non-back pain, CLBP - Chronic low back pain, Hp/Dap ratio - Compression deformities ratio, Hm/Hp ratio - Biconcave deformities ratio, Ha/Hp ratio - Anterior wedge vertebral deformities ratio, Ha - Anterior margin vertebral body height, Hp - Posterior margin vertebral body height, HM - Halfway between Ha and Hp, Dap - Anterior-posterior diameter of the vertebral body, CF - Crunch factor, L4/L5 - Lumbar vertebrae 4/5, CoM - Center of Mass.

spine injuries and back pain in athletes.[20,21,40,43,45,46,48,50,53,57] Furthermore, motor control impairment,[23,43,54] deficits in hip rotation ROM,[24] and asymmetry between limbs in athletes[24] are considered to be factors that increase the risk of spine injuries. However, most of the studies focused on LBP in patients and the risk factors associated with LBP, whereas studies related to the thoracic and cervical spine were rare. The findings including neurophysiological risk factors for back problems in athletes can be summarized as follows.

a) Neuromuscular imbalance and increased muscle fatigability

Impaired neuromuscular activation, muscle size, and increased muscle fatigability have been pointed out as risk factors for the prevalence of back problems.[20–22,38,42,45,46,48,50,53] As shown in Table 1, differences in trunk muscle fatigue and the activation profile have been demonstrated among tennis players with symptoms of LBP compared to players without LBP.[21] Chronic LBP athletes from various sporting bodies (soccer, hockey, handball, basketball) have exhibited a delay in onset latency to unexpected perturbations and reduced long latency response amplitudes to perturbation.[48] Moreover, the delayed muscle reflex response has been shown as a neurophysiological risk factor that significantly increases the odds of sustaining a low back injury.[20] On the other hand, LBP golfers have been reported to activate their erector spinae muscles before beginning the backswing, which is significantly earlier than golfers without LBP.[50] A delay in erector spinae muscle activation during the backswing in LBP golfers compared to golfers without LBP was reported, although this delay did not reach statistical significance.[53] The differences in erector spinae muscle activity may indicate that LBP golfers rotate their trunk with greater velocity.[53] This phenomenon could be a factor influencing the development of LBP. The higher activation of the ventral and transverse muscles during drop jumps has been reported in athletes (canoeing/rowing, triathlon, wrestling) with back pain compared to those without back pain.[45] All studies analysed in this review used sEMG recordings for investigation of neuromuscular activations.

The asymmetric movements of the athletes' trunk in sports like tennis, hockey, handball, basketball, golf, canoeing/rowing, and wrestling is a crucial cause of muscle imbalances. Changes in the antagonist-agonist ratio of superficial trunk muscles in chronic LBP individuals alter neuromuscular control and increase muscle fatigability.[48] These athletes are at an increased risk for spine problems, especially LBP and re-injury due to neuromuscular imbalance in either the dominant or non-dominant side. For instance, a greater muscle volume of the left (nondominant) rectus abdominis in tennis players has been found,[21] which may confirm this explanation. Therefore, it is important to address these problems with one-sided overloading of the core muscles and the activation of distinct muscles in asymmetric sports to help minimize the impact of neuromuscular imbalance on increasing risk of back pain.

Imaging was used in four studies to explore the relationship between LBP and muscle size.[22] Among them, three studies focused on the lumbar multifidus muscle. A smaller cross-sectional area of lumbar multifidus spinae muscles, and a lower thickness of transversus abdominis muscles was found in cyclists with LBP compared to controls.[22] Specific deficits in lumbar multifidus morphology have been revealed in hockey players with LBP.[42] The lumbar multifidus morphology was strongly associated with body composition measurements. A larger multifidus and quadratus lumborum plus lumbar erector spinae muscles in the dominant arm and internal oblique muscle on the side contralateral to the dominant arm has been reported.[43] The contraction capacity (muscle thickness) of trunk muscles associated with LBP was also reduced in cricketers.[43] Furthermore, lower internal and external oblique muscle thickness bilaterally has been shown as a significant risk factor for LBP in young soccer players.[46]

The lumbar multifidus muscle changes are most likely a response/adaptation to the specific physical demands of sports. Cyclists and hockey players spend most of their time in the field with their hips, knees, and spine flexed. Holding a forward flexed position (in comparison with an upright position) may lead to a deactivation of the multifidus muscles.[71] The authors found that cyclists experience a decrease in co-contraction of their lumbar multifidus muscles. An altered trunk and/or lower limb movements may also be responsible for changes in the lumbar multifidus muscle in hockey players with LBP.

b) Muscle dysfunction

An association between reduced trunk muscle function and LBP was found in tennis players,[21] male elite cricketers,[43] and child equestrian athletes.[40] A minimal endurance time of abdominal muscles has been revealed in tennis players suffering from LBP.[21] Low endurance in trunk lateral flexors has also been reported in child equestrian athletes.[40] A reduced ability to draw in the abdominal wall and contract the transversus abdominis muscle independently of the other abdominal muscles has been introduced as a risk factor for LBP in elite cricketers.[43]

c) Impaired motor control

The relationship between motor control impairment and LBP in athletes has been investigated in three studies.[23,43,54] These studies provided some evidence of impaired motor control in dancers and elite cricketers with LBP.

d) Other neuromuscular risk factors

Low back dysfunction and suboptimal endurance of the core musculature appear to be important modifiable injury risk factors for core strains and sprains injuries in football players that can be identified by preparticipation screening.[49] Regular lumbar magnetic resonance scans of asymptomatic elite fast bowlers showed changes in bone stress as a risk factor for a stress fracture.[41,47] Asymmetrical and relatively small cross-sectional areas of the trunk muscles have been found to be a risk factor for lumbar intervertebral disc degeneration in combat sports athletes.[55] Asymmetric hypertrophy of the rectus abdominis muscle appears to constitute a risk factor for strain and rupture of rectus abdominal muscle in professional tennis players and elite handball players.[38,52] Deficits in hip rotation ROM and asymmetry between limbs also increase the risk of LBP in judo athletes.[24]

However, research evaluating possible neurophysiological risk factors for cervical spine problems in athletes is currently limited. This is despite the fact that cervical spine injuries occur in many sports.[72] Although injuries of the neck are rare, they are potentially the most severe. Therefore, main risk factors for cervical injuries should be investigated to reduce their incidence in athletes.

4.2. Biomechanical risk factors for back problems in athletes

Identifying key biomechanical risk factors for back problems in athletes is a broad and a complex issue. This is evident in both the methods used for their assessment, as well as kinematic and kinetic patterns of sport-specific movements.

Using the kinematic and/or kinetic analysis, biomechanical risk factors for back pain and spine degeneration in athletes have been studied in association with a) repetitive unilateral lumbar extensions and trunk rotations in sports like baseball, cricket, golf, tennis and soccer, b) repetitive loading in a flexed posture in sports such as rowing and cycling, c) abrupt rotational movements of the hips and lumbopelvic region in combat sports, d) repetitive rotational movements and high impact forces caused by landings in diving, and e) repetitive gait cycles in running.

While retrospective analyses displayed non-significant differences in spinal kinematic, and tibial and sacral impacts during fast bowling between LBP and non-LBP cricketers, prospective analysis showed large effect sizes for lumbar extension during bowling.[63] Furthermore, trunk rotation endurance in the non-dominant direction (follow-through) in

LBP golfers was the factor that differentiated them from the group of healthy golfers and healthy non-golf controls. However, non-significant differences in bilateral trunk rotation strength[58] indicate that trunk rotation endurance is more important risk factor for LBP than trunk rotation strength alone. Other study has shown no differences in axial angular trunk velocity and lateral flexion angle between the LBP and non-LBP golfers.[61] The crunch factor (measure of LBP injury risk factor based on lateral flexion and axial trunk rotation) was not suitable to explain and predict the golf specific LBP. Thus, the increased magnitude of crunch factor cannot be attributed to an increased axial or angular trunk velocity or lateral flexion, but rather to concomitant increase of both variables. In addition to the repeated performance of the golf swing,[73] also improper golf swing technique is responsible for the development of LBP.[74] Therefore, further research is needed to investigate the effectiveness of specific swing modifications for reducing LBP in golf.[75]

Similarly, improper tennis serve techniques could cause LBP. Analysis of the body kinematics during serving revealed reduced lumbar, pelvis and pelvis/shoulder right rotation with the pelvis tilted laterally more to the right, and earlier right knee extension velocity during the drive phase in the LBP group compared to non-LBP group of players.[67] Furthermore, a greater peak of left lateral flexion forces that occurs simultaneously with peak vertical force, extension and right lateral rotation were found in LBP tennis players.[68] The flat serve was associated with significantly greater flexion moments than the kick serve.[68] These factors were marked as a possible reason for LBP in tennis players.[68]

Lateral flexion and extension and the lumbar rotation is typical also for shooting in soccer. However, unlike tennis and golf, shooting is a matter of the lower limbs. Therefore, it is impossible to expect the same causes of spine problems. Young soccer players with LBP showed a lateral shift in the center of body mass (CoM) and larger rotation of the lumbar spine compared to non-LBP players.[69] A large distance between the supporting foot and the ball, and a lateral shift in CoM with excessive lumbar rotation could stress the lumbar spine.[69] The posterior positioning of the support foot can be affected in those with LBP and restrict their lumbar spine from bending laterally.[69] In practice, more attention should be paid to the lumbar spine rotation and the CoM shift during kick motion in soccer players.

Intervertebral disk angles and ratios, and vertebral body size and shape identified as predictive risk factors for LBP or injury in basketball, field hockey and cricket players demonstrated significant differences between these three groups in the intervertebral disc angles at the L2/3, L3/4 and L4/5 levels, the lumbar vertebral body shape and size, the lumbar index at the L2 level, the biconcave deformity at the L1 and L2 levels, and in relation to the anterior wedge deformity at the L2 level. Greater signs of disc degeneration were found in cricketers than in other players. The most biconcave and anterior wedge deformities were found in field hockey players.[62] Specific physiological loading in these sports contributes to the development of degenerative changes in the lumbar spine and is considered as a main risk factor for LBP.[62]

With regards to cycling, various position of the body, including the flexion of lumbar spine, are used to achieve proper aerodynamics and to increase speed. A flexed spinal position adopted by cyclists inverts the physiological intervertebral angels and changes the areas of spinal loading.[76] A significant increase of lower lumbar flexed posture was found in the chronic LBP group compared to the non-LBP group of cyclists together with more posteriorly tilted saddle and increased LBP.[59] The maladaptive motor control pattern at lower lumbar spine during cycling can be associated with chronic LBP and its increase during cycling.

Similar movement pattern with lumbar spine flexed may be seen in rowing. Rowers are in the flexed posture for 70% of the stroke cycle. Flexion range reaches to 55% of maximum range of spinal flexion. The magnitude of the forces on the lumbar spine is also very high. Compressive loads reach to 3 919 N for men and to 3 330 N for women. The combination of flexion with compressive loading has been identified as a main reason for spine injuries.[77] Also, differences in regional lumbar kinematics, such as less excursion of the upper and lower lumbar spine into extension during the driving phase, greater variability of upper and lower lumbar angles, positioning of the upper lumbar spine later toward the end of flexion, and longer flexion time in the upper lumbar spine can be considered as risk factors for LBP.[65] Greater flexion strains can lead not only to LBP but also to other spine deformations. Additionally, the low hip-trunk ratio score, foot force asymmetries, late hill engagement, and poor force profiles also increase the risk of injury.[78]

The group of sports with abrupt rotational movements of the hips and lumbopelvic region is represented by judo. Judokas with a history of back pain exhibit deficits in hip rotation and greater rotational asymmetry between limbs, whereas those without back pain do not.[24] Both maximum trunk extension and flexion have a significant influence on the developing of back pain.[45] Age, training load and gender has greater relevance than strength deficits or postural control.[45]

Repetitive rotational movements in the air and high impact forces in the final phase (when entering the water) are typical for diving. LBP is frequently reported symptom in divers.[66] Extracted flexibility of the shoulder joint has been identified as one of the risk factors for chronic LBP in diving. Elite junior divers with insufficient flexibility in the shoulder joint compensate the water entry posture by increasing the angle of extension or by moving the thorax.[66]

How much influence could repetitive running cycles have on the pathological mechanism of lumbar spondylolysis in track and field athletes was shown in the study that compared dash and jog with two kicking actions - pass and shoot.[70] The dash can lead to spondylolysis in runners because of the repeated mechanical stress at the pars interarticularis of the lumbar spine, which is similar to that caused by shoot.[70] Motion analysis revealed that the spinopelvic angles in dash are kinematically and kinetically similar to kinematic in shoot during the maximum hip extension phase in soccer players.[70]

Potential strategies to compensate for weakness of the deep core muscles during running and to identify accompanying changes in compressive and shear loading of the spine were investigated in kinematically-driven running simulations.[26] It has been hypothesized that the increased load on the spine over numerous gait cycles during running may result in damage to spinal structures.[26] Insufficient strength of the deep core muscles increased the possibility of developing LBP in runners. The authors demonstrated that with their complete weakness, peak anterior shear loading on all lumbar vertebrae increased up to 19%, whereas compressive spinal loading on the upper lumbar vertebrae increased up to 15% and on the lower lumbar vertebrae decreased up to 8%. Compensation for weakness of the deep core musculature during running increases muscular fatigue and may lead to spine injuries.[26]

4.3. *Gaps in current studies investigating risk factors for back problems in athletes and proposals for future research*

Regarding the neurophysiological risk factors, the following gaps in the literature were identified and recommendations were formulated.

(i) Despite the fact that the prevalence of low back problems in some sports such as archery, aviation, badminton, bobsleigh, diving, luge, modern pentathlon, taekwondo, underwater rugby, and waterpolo is very high,[9] there is a lack of studies investigating the neurophysiological risk factors of LBP in the above mentioned sports.

(ii) There is a lack of studies related to the thoracic area. Although thoracic injuries are not common in athletes, their potential severity and life-threatening consequences highlight the importance of identifying and assessing any risk factors that could increase their likelihood. Since the thoracic spine is the least mobile region of the spine, it heavily relies on the surrounding muscles for support and stability. Core muscles imbalance can put extra strain on the thoracic spine. This can potentially increase the risk of injury or pain in the thoracic region. Therefore, further research is needed to better understand the mechanisms of these injuries and to develop more effective prevention strategies to reduce their occurrence.

(iii) Despite the fact that cervical spine injuries occur in many sports,[72] there is little research on them.

(iv) Regarding the age of participants, there is a lack of studies with master athletes.

(v) Most neurophysiological risk factors have been usually analysed in relation to the causes and consequences of sport-specific exercises. However, long-term investigations should be carried out to explore their role in the prediction of spine problems in athletes.

Regarding the biomechanical risk factors, the following gaps in the literature were identified and recommendations were formulated.

(i) There is an imbalance in research within sports. For instance, tennis, golf, cycling and rowing are often investigated in the context of a high incidence of back pain. Further research should be focused on analysis of biomechanical factors which could serve as predictors of spine problems in many other sports with high demands on strength and stability of the core musculature. It should be also aimed at sports in which back problems (back pain and degenerative changes of the spine) are among the most serious overuse injuries.

(ii) Most attention is being paid to pain or degenerative changes of the lumbar spine, whereas other spine regions (thoracic and cervical) are often neglected. Studies related to the thoracic spine have been carried out in gymnastics, for example, but they are of an older date. Research related to the cervical spine has been primarily focused on acute accidental injuries, mostly in contact sports such as ice hockey, rugby, and so on. These injuries also occur in diving, mainly in recreationally physically active individuals due to poor jumping technique, low water, etc.

(iii) Medical research has been usually conducted on patients with spinal deformities and back pain, but not on healthy athletes with a predisposition to spine problems.

(iv) Most research is carried out in laboratories, where athletes perform under different conditions than they are used to in practice. If possible, research should be carried out in the natural environment of training and competition using sport equipment and gear (shoes, helmets, bicycles, boats, etc.).

(v) More research should be focused on female athletes and investigations related to gender differences in risk factors for spine problems in athletes.

(vi) There is a relatively high diversity of research in terms of selection of participants and methodology used within particular sports, which does not allow us to made more specific conclusions. The influence of variables such as age, gender and training conditions should be taken into account when processing the data.

5. Conclusions

The main neurophysiological risk factors identified leading to back problems in athletes are neuromuscular imbalance, increased muscle fatigability, muscle dysfunction and impaired motor control, whilst biomechanical risk factors include maladaptive spinal, spinopelvic and lower limb kinematics, side-to-side imbalances in axial strength and hip rotation range of motion, spinal overloading and deficits in movement pattern. However, most studies focused on back pain in the lumbar region whereas less attention has been paid to thoracic and cervical spine injuries. Additionally, the range of sports where this topic has been studied so far is relatively small. Therefore, more research should be carried out in physical activities with high demands on strength and stability of the core. Furthermore, including more female athletes in research would allow us to compare between-gender differences in the risk factors for back problems. Further research on master athletes is also needed to assess changes in back pain indicators with increasing age. In addition to chronic back pain patients, it is equally important to conduct research on healthy athletes with a predisposition to back problems. Investigators should focus their empirical work on identifying modifiable risk factors (neurophysiological and/or biomechanical), predict which athletes are at risk for back problems, and develop personalized sport-specific assessment tools and targeted prevention strategies for them. This could help to avoid future serious spine disorders and contribute to a healthier back for athletes.

Availability of data and materials

The data within this study are secondary data and available through the relevant sources referenced.

Authors' contributions

Erika Zemková: Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization. **Banafsheh Amiri:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation. **Henrieta Horníková:** Writing – review & editing, Writing – original draft, Investigation. **Ludmila Zapletalová:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation.

Submission statement

The article has not been published previously, it is not under consideration for publication elsewhere, its publication is approved by all authors, and if accepted, it will not be published elsewhere including electronically in the same form, in English or in any other language, without the written consent of the copyright-holder.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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