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Scoping Review

Assessment Methods of Sport-Induced Neuromuscular Fatigue: A Scoping Review

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Background

Neuromuscular fatigue (NMF) has been defined as the exercise-induced performance decrease associated with muscular activity.

Purpose

The primary aim was to identify the available evidence regarding the testing tasks used to assess NMF in the lower limbs and to determine the most commonly used test in specific sports. The secondary aim was to group the tests found according to the type of sport.

Study Design

Scoping review.

Methods

A literature search was conducted in PubMed, ScienceDirect, SportDiscus, and Web of Science databases. Search terms were "neuromuscular fatigue" and ("test" or "tests" or "testing task" or "task"). Studies that analyzed healthy humans, voluntary contractions, and participants under 50 years old were included. Studies in which the main focus was not NMF, the lower limbs were not analyzed, the knee joint was not involved, the pre-post analysis of fatigue was not used, or there was no sport fatigue protocol between tests were excluded. The PRISMA-ScR guidelines were followed.

Results

A total of 97 studies were included. Most of these included males (68.0%) and professional athletes in their samples (46.4%) . The data most commonly studied for NMF were athletes from team sports (74.2%), specifically soccer (32.0%) and rugby (18.6%). Matches and trainings sessions were the fatiguing protocols (59.8%), whereas vertical jumps (82.5%), measured by force platforms (77.5%), was the test most commonly used. The most commonly evaluated parameters were jump height (75.0%) and peak power (41.3%). Tests varied different according to the sport, and vertical jumps (77.8%), and sprints (15.3%) were the tests most commonly used for the athletes in team sports. For

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athletes in individual sports, vertical jumps (72.0%) and isometric knee extension/knee flexion (24.0%) were most utilized.

Conclusions

Different fatigue protocols, test tasks, materials, and variables are used to assess NMF. Veritcal jump is the most commonly utilized test task for athletes of both team and individual sports. It appears necessary to choose the most appropriate test tasks according to each type of sport.

Level of evidence

Level 2b

INTRODUCTION

Neuromuscular fatigue (NMF) has been universally defined as the exercise-induced performance decrease associated with muscular activity.[1-6] This concept has been widely studied over the last century,[7-9] although scientific interest in fatigue has not increased until recent years.[10] Several tools and methods have been reported to assess NMF,[11] which have included different technological elements,[1,12] tasks and parameters,[6,13,14] and various sports.[15-17]

NMF has been considered multi-factorial,[4] due to a combination of central (processes inside the spinal cord and above) and peripheral (neuromuscular junction or muscle itself) mechanisms.[2,18,19] NMF may alter kinematic patterns,[20] decrease performance,[2] reduce the ability to absorb energy,[21] or increase the magnitude of muscle force fluctuations, resulting in decreased control of muscle forces.[22] These changes may lead to an increased injury risk because they are closely related to a reduction in muscle contractile properties.[1] Assessment of musculoskeletal tissue and its characteristics before and after exercise is crucial in the prevention of overuse injuries.[5] However, although several studies have found associations between fatigue and injury risk,[23,24] it would not be appropriate to conclude a direct causal relationship, as injuries are complex and multifactorial phenomena.[25]

Measures of neuromuscular function have been used to assess NMF status during or after sports activities because of their greater utility in monitoring low-frequency fatigue, in comparison with others indirect markers (ratings of perceived fatigue, or muscle soreness).[26] Low-frequency fatigue has been characterized by assessing tissue damage evoked by active lengthening of skeletal muscle during high-intensity activity.[26] Reduced performance has been observed as a decline in various muscle parameters including: maximal voluntary isometric contraction (MVIC), maximal shortening velocity, analysis of the curve of the force-velocity relationship, slowing of the time course of relaxation, and stretch-shortening cycle (SSC) alterations.[2,6,11,18,27-30] Performance decreases may be explained by different variables, such as the physical activity level, age, and gender.[31-36]

The most common approach for measuring NMF is to assess fatigue pre- and post-exercise in some manner.[11] This method performs pre-exercise measurements to determine a baseline and compares it to an assessment performed when the task has been completed to evaluate the recovery of contractile function.[18] Neuromuscular function (to assess NMF) may be evaluated using varied measures and methods such as strength analysis using the MVIC[37,38] through measurements during a single joint exercise, time to task failure using a sustained strength measure,[39,40] muscle activation with electromyography (EMG),[41,42] power assessment through vertical jumps[43-45] or using a whole-body force measurement such as the Isometric Mid-Thigh Pull test (IMTP),[46,47] assessing speed using sprint tests,[19,48] and endurance analysis through intermittent tests.[49,50] There is a need to specify the characteristics of each of the potential tests because they may present some differences such as the duration and intensity, the type of contraction (isometric vs dynamic), type of task (intermittent vs continuous), and the joints involved (single-joint vs whole-body exercise).[51] Assessment of NMF may have some inaccuracies due to errors in study design[52] or the lack of the similarity of the fatiguing task compared to the sport analyzed.[6] Because NMF has been studied in several sports, such as basketball,[53] cricket,[54] cycling,[17] handball,[55] judo,[56] mixed martial arts,[57] Muay Thai,[58] soccer,[59] running,[60] tennis,[47] and triathlon[61]; is important to explore the most specific tests according to each type of sport. This distinction is based on the sport-specific movement patterns and maneuvers, the aerobic or anaerobic energy system required according to the characteristics of each sport, and several neuromuscular factors, such as the stretch-shortening cycle (SSC) or the force-time demands in the actions.[1,62] These factors could be influenced by the interaction with teammates, the presence of opposing players, the use of implements, or the possibility of contact with opposing players.[63,64]

Therefore, the primary aim of this scoping review was to identify the available evidence regarding the testing tasks used to assess NMF in lower limbs and to describe the most commonly used test in specific sports. The secondary aim was to group the tests found according to the type of sport.

METHODS

PROTOCOL

This scoping review was performed following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-analysis Protocols for Scoping Review (PRISMA-ScR).[65]

Table 1. General characteristics extracted from the included articles.

Variable	Description (Levels)
References	Format citation of the authors
Year	Year of publication of the article
Country	Country of the data of the article
Number (participants)	Total of participants of the study
Gender of participants	Gender of participants of the study *(Male, Female, Both)*
Age (participants)	Age of participants of the study
Level	Level of participants of the study *(Professional, Semi-professional, Amateur and Recreational)*
Sport	Sport analyzed in the study
Study design	Design of the study *(Longitudinal, Cross-sectional and Mixed)*
Aim	Principal aim of the study

SEARCH STRATEGY

A literature search was conducted using Pubmed, ScienceDirect, SportDiscus and Web of Science databases using the same Boolean terms and key words: ("neuromuscular fatigue") AND ("test" OR "tests" OR "testing task" OR "task"); the last search was performed in October 2024.

ELIGIBILITY CRITERIA

Taking into account the characteristics of sports studied, journal articles were included if: (1) it was an original article, (2) the sample only included humans, (3) participants were healthy, (4) participants performed voluntary contractions, and (5) participants were less than 50 years old; and were excluded if: (1) the main focus of the study was not NMF, (2) the lower limbs were not analyzed, (3) the knee joint was not involved, (4) pre-post analysis of fatigue was not used and (5) there was no sport fatigue protocol between tests (Figure 1).

IDENTIFICATION OF THE STUDIES

Three of all authors participated in the evidence screening and data charting process. After identification and exclusion of duplicate articles, a screening of titles, abstracts, and keywords was completed in duplicate for all remaining articles. Reviewers voted yes, no, or maybe for each article. Each maybe vote was considered a yes vote. The discrepancies were resolved through majority group consensus. All included full-text articles were also subjected to a duplicate data charting process by the same three authors. The discrepancies were resolved through majority group consensus.

DATA EXTRACTION

The variables extracted from the selected studies were grouped into two categories: general characteristics of the studies (Table 1), and characteristics of fatigue protocols and test tasks (Table 2). The variable of level of participants (professionals, semi-professionals, amateurs, and recreational) has been provided by Thuany et al.[66] (Table 1).

The main aim was addressed by reporting the most commonly used methods and test tasks for to assessment of NMF. The secondary aim was addressed by reporting the types of sports according to a combination of definitions provided by Delleli et al.,[67] Frisch et al.,[64] and Land.[68] This scoping review categorized the different sports as team sports, individual sports, implement sports, and combat sports.

RESULTS

Figure 1 presents the PRISMA-ScR flowchart to summarize all the stages of the selection process regarding assessment methods of sport-induced NMF. The 16 articles from other sources were found by checking the reference list of the included studies read in full text. Corresponding authors of some articles (n = 4) were eventually contacted by e-mail to request full text document.

The evolution in the number of articles published per year is shown in Figure 2. Among the 97 articles selected, 86 (88.6%) of them were published since 2012, with 2022 being the year with most articles published with 13 (13.4%).

The general characteristics of the studies are shown in Table 3, in which it can been observed that sport-related NMF has been investigated in several countries. Of the total of 97 selected articles, 20 (20.6%) were studied in Australia, 15 (15.5%) in United Kingdom and 13 (13.4%) in Spain. Most of the studies included used longitudinal design (n = 48; 49.5%), included male athletes (n = 66; 68.0%), and focused on professional athletes (n = 45, 46.4%). Some studies (n = 5) included more than one sports level. The sport with the highest representation in the present review was soccer (n = 31; 32.0%), followed by rugby (n = 18; 18.6%) and running (n = 16; 16.5%). Some articles included more than one sport (total number of included sports is 107).

Although each sport is shown in Table 3, a further differentiation into a) team sports, b) individual sports, c) implement sports and d) combat sports[64,67,68] is reported in Figure 3. Team sports was the most common type of sports found in this research (n = 72; 74.2%).

Regarding the fatiguing protocol, most protocols involved a sport specific stimulus such as training or compe-

Table 2. Characteristics of the fatigue assessment extracted from the included studies.

Variable	Description
References	Format citation of the authors
Fatigue protocol	Characteristics of fatigue protocol
Test task	Characteristics of tasks for assessment neuromuscular fatigue
Pre-test	Moment of the tests before fatigue protocol *(Minutes, Hours, Days)*
Post-test	Moment of the tests after fatigue protocol *(Minutes, Hours, Days)*
Material	Materials used for the tests
Variables analyzed	Variables in which the test task focuses

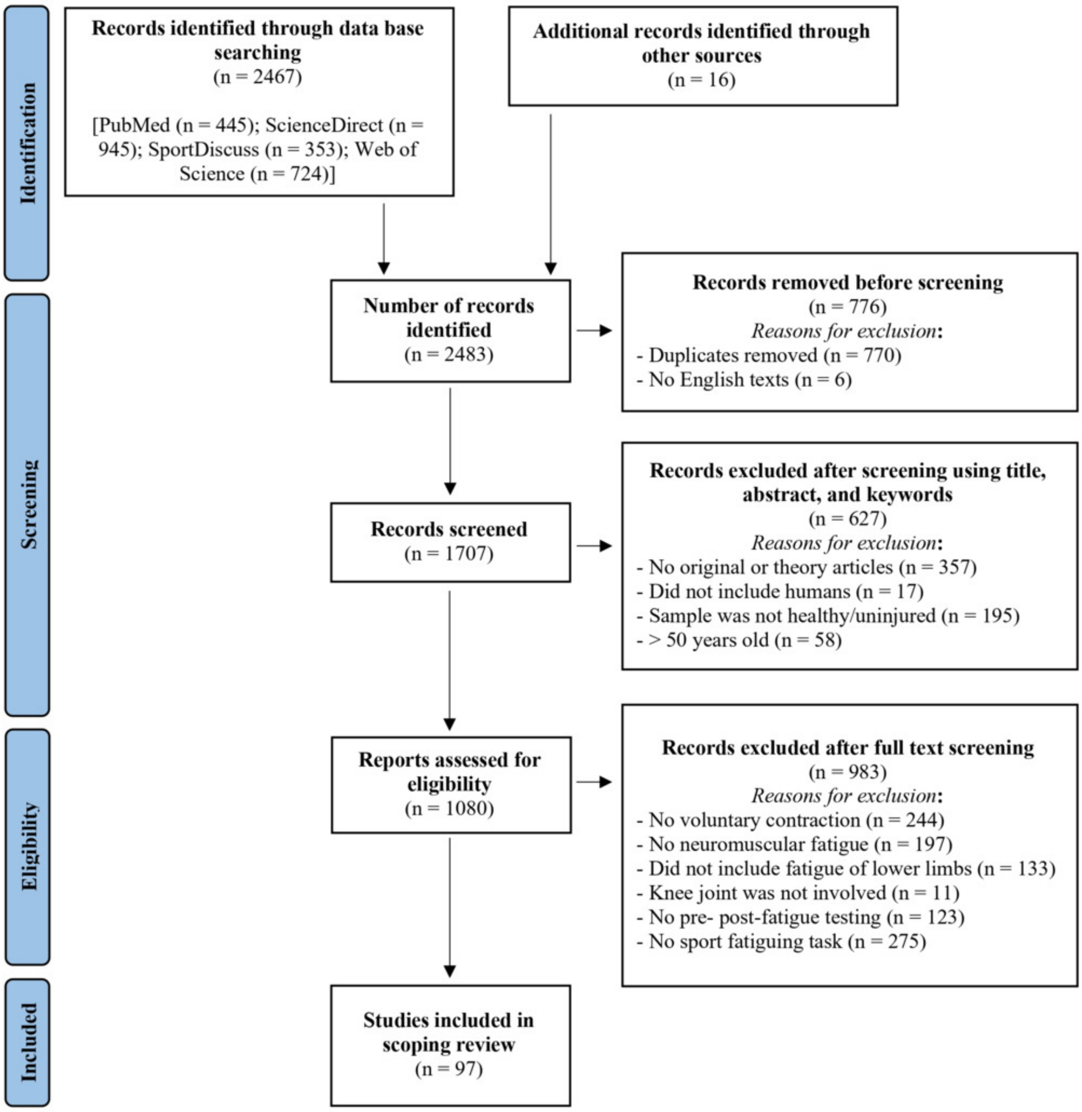

Figure 1. PRISMA-ScR flow diagram for search strategy, and study selection process.

tition (n = 58; 59.8%), followed by endurance run test (n = 13; 13.4%) or sprint test (n = 11; 11.3%). (Table 4).

Figure 4 shows the tests tasks used in the different articles. Many studies used more than one test task (n = 36; 37.1%), accounting for a total of 131 test tasks that were used. The vertical jumps tests were the main test task used (n = 80; 82.5%), following by isometric knee extension (KE)/knee flexion (KF) test (n = 13; 13.4%) and a sprint test (n = 12; 12.4%).

In Table 5 shows the tests tasks used in the different studies according to the type of sport. Two studies included more than one type of sports. Regarding the team sports, vertical jumps (n = 56; 77.8%), running sprints (n = 11; 15.3%) and isometric KE/KF (n = 7; 9.7%) were the most

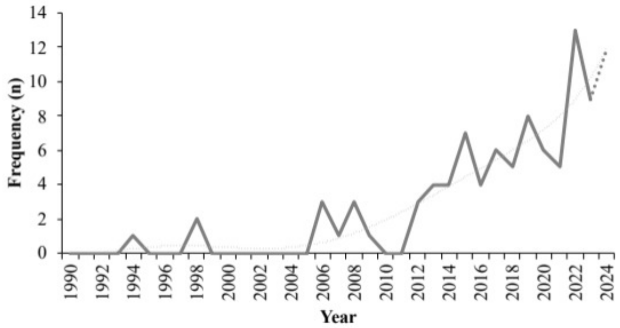

Figure 2. Evolution of articles published in each year.

The year 2024 is represented with a dotted line because data were collected until October 2024.

commonly used tests. For individual sports, vertical jumps (n = 18; 72.0%), isometric KE/KF (n = 6; 24.0%) and EMG (n = 3; 12.0%) were the most commonly used tests. Based on the present inclusion criteria, a low number of studies in implement sports and combat sports were found.

Materials used and variables are reported according to the tests used (Appendix 1). For vertical jump tests, force platforms (n = 62; 77.5%) were the most commonly used materials. Further, jump height (n = 60; 75.0%), peak power (n = 33; 41.3%), flight time, and peak velocity (n = 17; 21.3%) were the most commonly used variables. For the assessment of the maximum strength through isometric KE/KF test, the computerized dynamometer (n = 11; 84.6%) and the strain gauge (n = 4; 30.8%) were the most commonly used materials, while peak torque (n = 5; 38.5%), rate of torque development (RTD) (n = 3; 23.1%), and MVIC (n = 3; 23.1%) were the most commonly assessed variables. Regarding sprints, the most used material was photocells (n = 11; 91.7%) and the most commonly used variable was speed (n = 12; 100%).

DISCUSSION

The main findings of this scoping review indicate that vertical jumps were the most used tests in all types of sports to evaluate NMF of the lower limb muscles. The most commonly used materials were force platforms to assess the variables of jump height, peak power, flight time, MVIC, and peak velocity. Parameters of peak torque and MVIC were also analyzed using isometric KE/KF and isokinetic KE/KF tests with data gathered by dynamometers or strain gauges. Team sports were the most commonly reported upon sports, in which vertical jumps and sprints and isometric KE/KF tests were the most tests commonly used. The tests most commonly used in individual sports were vertical jumps, isometric KE/KF and EMG tests.

Research regarding sport-induced NMF of lower limb muscles has grown since 1994, with a minimum of three studies published annually since 2012. This fact is consistent with the information from Da Silva et al.,[69] who suggested that the assessment of NMF has rapidly grown in recent years in sport science. The number of studies published each year showed a significant increase in 2022, probably influenced by the effects of COVID-19, as suggested by different researchers.[70-73]

Table 3. Frequency distribution of general characteristics.

Variable	Category	Frequency n	Frequency %
Country	Australia	20	20.6
	United Kingdom	15	15.5
	Spain	13	13.4
	France	6	6.2
	Brazil	5	5.2
	Italy	4	4.1
	Portugal	4	4.1
	United States	4	4.1
	Norway	3	3.1
	Colombia	2	2.1
	Finland	2	2.1
	Qatar	2	2.1
	Taiwan	2	2.1
	Turkey	2	2.1
	Canada	2	2.1
	Other [a]	12	12.4
Study design	Longitudinal	48	49.5
	Cross-sectional	35	36.1
	Mixed	14	14.4
Gender	Male	66	68.0
	Female	13	13.4
	Both	8	8.2
	NR	10	10.3
Level	Professional	45	46.4
	Semi-professional	12	12.4
	Amateur	19	19.6
	Recreational	17	17.5
	NR	7	7.2
Sport	Soccer (football)	31	32.0
	Rugby	18	18.6
	Running	16	16.5
	Basketball	9	9.3
	Handball	7	7.2
	Australian football	4	4.1
	Cycling	4	4.1
	Futsal	4	4.1
	No athletes	3	3.1
	Sky	2	2.1
	Tennis	2	2.1
	Triathlon	2	2.1
	Other [b]	7	7.2

NR = Not reported.
[a] Arabia Saudi, China, Greece, Iceland, Japan, Lithuania, Morocco, Netherland, New Zealand, NR, Sweden, Tunisia
[b] Cricket, Decathlon, Ice hockey, Judo, Muay Thai, Undefined team sport

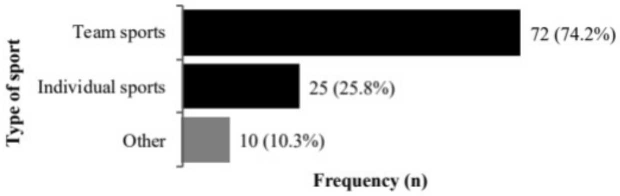

Figure 3. Classification of sports (Based in classification of Delleli et al.,[67] Frisch et al.,[64] and Land[68]).

Other = implement sports and combat sports

Out of all studies included in this research, more than half of these studies were from Australia, the United Kingdom, and Spain. Countries like Australia or the United Kingdom have a long history of research in the field of sport sciences. These countries have been pioneers in this area, with organizations like the Australian Institute of Sport or the English Institute of Sport, incorporating the the sport scientist in the organizational chart, who plays a key role in the assessment of performance.[74]

The studies included in this scoping review examined predominantly male athletes. Given that several studies have recognized that gender is an important factor in NMF,[75,76] research involving female athletes should increase. Regarding the level of athletes, the sample of the present study involved mostly professional athletes, therefore does not represent the assessment of NMF in other levels of athletes well.

Regarding the sports that athletes participated in, soccer was the sport most commonly reported in the studies included in this scoping review. These results are consistent with the review of Kirkendall,[77] who stated that soccer is the sport with the largest number of worldwide participants and the most studied sport, with nearly 14,000 citations on Pubmed and 60% more publications than the second most commonly studied sport. Similarly, team sports were the most commonly studied type of sports.[64,67,68] These results could be due to the fact that team sports have larger coaching staffs. There is also the possibility of ease of collecting more data due to the larger number of players on a team.

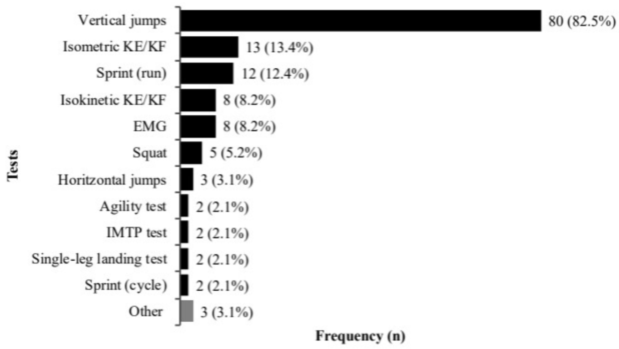

Figure 4. Tests tasks used and frequency according the articles included (n = 97).

EMG = Electromyography; IMTP = isometric mid-thigh pull; KE = Knee extension; KF = Knee flexion; MVIC = Maximum voluntary isometric contraction
Other= Change of directions (COD) test, Hamstring test, Isometric Posterior Chain lower-limb muscle test.

NMF has been mainly evaluated by assessing what occurred after matches and trainings. Given that the magnitude and the etiology of fatigue depend on the exercise performed (task dependency),[19,78] it is important that there is a similarity between the sports the fatiguing task, and the characteristics of the test, however, NMF induced by multi-joint exercise is often quantified using single-joint tasks.[6] The lack of specificity in assessment may reduce the effectiveness for understanding the development of NMF.[19]

The present review exposed the use of several varied tests, such as vertical jumps, isometric KE/KF, isokinetic KE/KF tests, or sprint performance. The vertical jump tests were the tests most commonly used in all types of sports, similar to Taylor et al.[79] who also described vertical jumps as the most commonly used. These tests have been shown to be valid and reliable, which makes them potentially valuable for detecting recovery times from demanding training or competitions[79] and alterations in explosive power,[80-82] which may be associated with fatigue.[26,83,84] Regarding the popularity of vertical jumps, Twist et al.[85] suggested that they are commonly used due to being inexpensive, easy to administer, and produce little additional fatigue, which allows for repeated assessments of multiple individuals over a short time period.[86] Another important factor is that the

Table 4. Frequency distribution of fatiguing protocols used.

Variable	Category	Frequency n	Frequency %
Fatiguing protocol	Match play and/or trainings	58	59.8
	Endurance test (run)	13	13.4
	Sprint test	11	11.3
	Cycling test	6	6.2
	Trail running	4	4.1
	Kicks protocol	2	2.1
	Combined tests	2	2.1
	Other [a]	2	2.1

[a] Skating, Slide board

Table 5. Frequency distribution of tests tasks according to the type sport.

Type of sport (n)	All n = 97*	Team sports n = 72**	Individual sports n = 25**	Other [a] n = 10**
Vertical jumps	80 (82.5%)	56 (77.8%)	18 (72.0%)	6 (60.0%)
Isometric KE/KF	13 (13.4%)	7 (9.7%)	6 (24.0%)	0
Sprint (run)	12 (12.4%)	11 (15.3%)	0	1 (10.0%)
Isokinetic KE/KF	8 (8.2%)	6 (8.3%)	2 (8.0%)	0
EMG	8 (8.2%)	4 (5.6%)	3 (12.0%)	1 (10.0%)
Squat	5 (5.2%)	2 (2.8%)	2 (8.0%)	0
Horizontal jumps	3 (3.1%)	1 (1.4%)	1 (4.0%)	0
Agility test	2 (2.1%)	2 (2.8%)	0	0
IMTP	2 (2.1%)	1 (1.4%)	0	1 (10.0%)
Single-leg landing	2 (2.1%)	2 (2.8%)	0	0
Sprint (cycle)	2 (2.1%)	1 (1.4%)	1 (4.0%)	1 (10.0%)
COD test	1 (1.0%)	1 (1.4%)	0	0
Hamstring test	1 (1.0%)	1 (1.4%)	0	0
IPC test	1 (1.0%)	1 (1.4%)	0	0

EMG = Electromyography; COD = Change of direction; IPC = Isometric posterior chain; IMTP = Isometric mid-thigh pull; KE = Knee extension; KF = Knee flexion; ROM = Range of movement

* Number of studies included in this review

** Number of studies according the type of sport assessed

[a] Implement sports (n = 3), Combat sports (n = 2) and No-athletes (n = 5)

vertical jump also reflects the SSC capacity of the lower-limb muscles.[29,87] Variations in SSC may reflect alterations in neuromuscular functions, thus the SSC provides a good basis for studying NMF.[28] Additionally, given that SSC is utilized in many accelerations, decelerations, and changes of direction in athletes' training or competitions, it will be involved in almost all types of sports, and may be reflected similarly in vertical jumps.[88-90]

Regarding the materials used in vertical jumps, the most commonly used was the force platform, which presented the advantages that it is easy to transport, is of low cost, and is highly accessible.[91] While several variables have been evaluated using vertical jumps, such as peak power, flight time, MVIC, and peak velocity,[92] the variable most commonly evaluated has been jump height,[79] consistent with what is seen in this scoping review. These results may be due to the fact that loss of jump height has been shown to be strongly correlated with fatigue.[45] Several materials or tools allow for the assessment of the same test. However, this could lead to variability in the measurement results because some materials have shown lower reliability compared to others such as the force platform, which is considered the "gold standard".[1] This scoping review exposed the use of dynamometers or strain gauges for the assessment of isometric KE/KF and isokinetic KE/KF tests. These devices are important in performance[93] and the health fields,[94,95] due to their ability to provide objective evaluation of muscle strength, power, and endurance.[96]

To the best of the authors' knowledge, this scoping review is the first to describe the different tests used to assess NMF, differentiating the NMF tests according the type of sport. Despite this, there are several aspects of NMF that need more investigation such as the inclusion of female or amateur sport athletes. On the other hand, only two studies conducted in United States were found, although this country has presented an increase of sport science budgets in recent years, with growing interest in developing various sport science initiatives.[97]

The main limitation of this study was the low number of studies in some type of sports, possibly caused by the strict eligibility criteria used leading to underrepresentation of some sports. This prevents drawing conclusions between test tasks used and different type of sports was variable. The fact that numerous studies in this scoping review focused on male athletes is also a limitation, not allowing generalizability of the findings to female athletes. Finally, the "Not Reported" items found in gender of sample, sport level or materials from some studies included in this scoping review may be generating a lack of information.

CONCLUSIONS

The results of this scoping review indicate that there are several tests that are used to assess NMF, the most common of which are vertical jumps using force platforms. NMF has been most commonly studied in professional level athletes and athletes who participate in team sports, particularly soccer. In these populations and in the rest of type of the sports studied, vertical jumps are also the most used tests. Because of the variety of the methods that exist to measure NMF, the results of this scoping review could be used by coaches, physical trainers and therapists, as well as sport scientists to select the most appropriate tests for NMF assessment based on the characteristics of a given sport. Finally, further investigations are needed, focusing on female and amateur athletes.

CONFLICT OF INTEREST DISCLOSURE

The authors report no conflicts of interest.

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SUPPLEMENTARY MATERIALS

Appendix 1. Material and variables analyzed according the tests used in studies included (n = 97).

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