THE ROLE OF FLEXIBILITY AND JOINT MOBILITY IN INJURY PREVENTION AND THEIR EFFECT ON PHYSICAL PERFORMANCE

ULOGA FLEKSIBILNOSTI I POKRETLJIVOSTI ZGLOBOVA U PREVENCIJI POVREDA I NJIHOV UTICAJ NA FIZIČKE PERFORMANSE

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Abstract
Introduction. Flexibility and joint mobility are fundamental determinants of efficient and safe movement execution. They play an important role in injury prevention during daily activities, training, and competitive performance, and substantially influence athletic outcomes. Between the ages of 20 and 49, flexibility declines by approximately 10% per decade. Stretching is one of the primary interventions used to restore, maintain, and enhance flexibility. Evidence suggests that regular and structured stretching programs can preserve joint range of motion and improve mobility. Stretching has also been proposed to enhance physical performance, facilitate post-exercise recovery, and reduce injury risk. **Discussion**. Stretching constitutes an essential component of both athletic training and rehabilitation; therefore, identifying the optimal timing, volume, and intensity of stretching within motor learning and re-education programs is of considerable importance. However, despite widespread application, the scientific literature has not yet reached a clear consensus regarding its effects, as evidence remains inconsistent or insufficient for several commonly cited benefits. The aim of this narrative review is to summarize current evidence on the effects of dynamic and static stretching on injury prevention and physical performance. **Conclusion**. It remains difficult to definitively determine whether stretching exerts predominantly beneficial or adverse effects. Given the heterogeneity and often contradictory findings in the existing literature, stretching protocols should be individualized, with careful consideration of the type, volume, and intensity of stretching in relation to the specific goals of rehabilitation or athletic training.
Key words: Joints; Range of Motion, Articular; Athletic Injuries; Muscle Stretching Exercises; Risk Factors; Accident Prevention; Athletic Performance

Sažetak
Uvod. Fleksibilnost i pokretljivost zglobova su ključni za izvođenje pokreta na optimalan i bezbedan način. Veoma su važni za prevenciju povreda u svakodnevnom životu, tokom treninga i tokom takmičarskog nastupa, te imaju značajan uticaj na sportske performanse. Od 20. do 49. godine dolazi do smanjenja fleksibilnosti za ~10% svake decenije. Jedan od načina za restoraciju, održavanje i poboljšanje fleksibilnosti je proces istezanja. Studije takođe pokazuju, da posvećeno i učestalo istezanje može da očuva obim pokreta u zglobovima, kao i da poveća mobilnost. Smatra se da proces istezanja doprinosi poboljšanju fizičkih performansi, utiče na brzinu oporavka nakon fizičkog napora i smanjuje rizik od povreda. **Diskusija**. Istezanje predstavlja važnu komponentu, kako u sportskom treningu pojedinaca, tako i procesu rehabilitacije, te je od velikog značaja određivanje pravovremenosti, obima i intenziteta istezanja u kontekstu motorne edukacije i reedukacije. Uprkos navedenim činjenicama, u naučnoj zajednici još uvek ne postoji konsenzus po pitanju pomenutih efekata, jer za pojedine ne postoji dovoljno dokaza. Cilj ovog rada je da prikaže aktuelne stavove u vezi sa pozitivnim uticajima dinamičkog i statičkog istezanja na prevenciju povreda i njihov uticaj na fizičke performanse. **Zaključak**. Nije jednostavno doneti sud o tome da li istezanje ima prevashodno pozitivne ili negativne efekte. Kada se uzmu u obzir postojeći, često divergentni rezultati istraživanja na ovu temu, nameće se zaključak da je neophodno prilagoditi vrstu, obim i intenzitet istezanja u odnosu na željeni ishod rehabilitacionog programa ili sportskog treninga.
Ključne reči: zglobovi; opseg pokreta zgloba; sportske povrede; vežbe istezanja; faktori rizika; prevencija povreda; sportski učinak

Introduction

Flexibility and range of motion (ROM) generally refer to the total extent of movement available within a joint or a complex of joints, allowing normal and unrestricted function. These characteristics are influenced by individual, intrinsic, and hereditary properties of connective tissue, tend to decline with aging, and, importantly, can be preserved and enhanced through appropriate exercise interventions [1,2].

As early as 1964, Fleischman demonstrated that flexibility represents an independent component of physical fitness and can be improved through static stretching [3]. Subsequent research has shown that ag-

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Abbreviations

ACSM	– American College of Sports Medicine
DS	– dynamic stretching
GTO	– Golgi tendon organ
ROM	– range of motion
SS	– static stretching

ing is associated with reductions in muscle function and flexibility, which may ultimately lead to diminished functional capacity and loss of independence in daily activities [4]. Adequate flexibility of the lower extremity musculature has been linked to a reduced risk of lower back injuries, as well as a lower incidence of spondylolysis and spondylolisthesis [5]. Low back pain is currently the leading cause of disability in 160 countries worldwide [6], with lumbar radiculopathy affecting up to 5% of the general population [7]. Moreover, significant positive correlations have been observed between fear-avoidance behaviors and pain intensity in individuals with lumbosacral radiculopathy [8].

Joint mobility, particularly at the hip, is reduced in patients with hip and knee osteoarthritis [9,10], and stretching has been shown to be an effective intervention for increasing hip abduction ROM [11]. In individuals with lower-limb amputation, limitations in residual limb ROM may negative predict successful prosthetic ambulation [12]; consequently, restricted hip or knee extension is incorporated into several predictive models of ambulation potential with high accuracy [13]. Additionally, greater joint ROM has been associated with a reduced risk of muscle rupture [14].

In clinical practice, ROM is typically assessed as the total movement arc around a joint or joint complex; therefore, the terms *flexibility* and *range of motion* are often used interchangeably. Stretching is defined as the application of tensile force along the rotational or translational plane of joint movement and is traditionally incorporated into training and rehabilitation programs. Two primary stretching modalities are commonly distinguished: static and dynamic stretching.

Despite the widespread use of stretching, scientific literature reports not only beneficial but also potentially adverse effects. One major limitation in drawing definitive conclusions lies in the methodological heterogeneity of existing studies, as the effects of stretching cannot be generalized from protocols that employ highly specific stretching modalities, durations, intensities, and frequencies. Research investigating both the acute and chronic effects of stretching has intensified over the past two decades, yet consensus regarding its overall efficacy remains elusive.

The Physiology of Stretching

Skeletal muscle exhibits the greatest capacity for elongation and accounts for approximately 95% of the total lengthening of the muscle-tendon unit. Tensile forces applied during stretching also affect surrounding soft tissues, including fasciae, ligaments, joint capsules, nerves, blood vessels, and connective tissue. Nevertheless, this review focuses specifically on the biomechanical and neurophysiological mechanisms underlying muscle stretching.

The initial sarcomere length is a critical determinant of muscle function and is regulated by proprioceptors – specialized sensory receptors embedded within muscle tissue, particularly in the muscles of the upper and lower extremities. Proprioceptors relay information concerning muscle length, tension, and movement to the central nervous system, enabling precise neuromuscular control.

Information regarding absolute muscle length and the velocity of length change is primarily provided by muscle spindles, which are arranged in parallel with muscle fibers. Golgi tendon organs (GTOs), located in series with muscle fibers at the musculotendinous junction, detect changes in muscle tension and indirectly contribute to the regulation of muscle length [15]. Muscle spindles contain both dynamic and static components, allowing them to encode both the magnitude and rate of stretch. Rapid elongation of muscle fibers activates the stretch (myotatic) reflex, a protective mechanism that indices reflex muscle contraction to prevent excessive lengthening. In contrast, slow and sustained stretching reduces spindle firing frequency, facilitating accommodation and adaptation to increased muscle length.

During muscle contraction, tension rises within the tendon and is sensed by GTOs, which monitor both the magnitude and rate of tension development. When tension exceeds a certain threshold – serving as a safeguard against structural damage – a reflex inhibition of muscle contraction is initiated through spinal synapses, with modulation by supraspinal centers [16]. Through their coordinated activity, muscle spindled and GTOs play primary central role in protecting the muscle-tendon unit from injury. Proprioceptors also mediate the reciprocal inhibition, whereby activation of an agonist muscle results in reflex relaxation of its antagonist muscle [17].

Muscle responds differently to acute (short-term) and chronic (repeated) stretching. Acute stretching typically produces and immediate increase in ROM, primarily attributable to neural adaptations, including reduced motor neuron excitability, excessive sarcomere elongation, and reorganization of tendons. However, these short-term adaptations are often accompanied by temporary reductions in maximal muscle strength, power output, and muscle endurance [18].

In contrast, chronic stretching – characterized by regular, intensive sessions lasting at least 10 to 15 minutes, performed three to four times per week – has been associated with sustained improvements in flexibility, mobility, muscular strength, aerobic endurance. Evidence from animal studies suggests that these adaptations may be partially explained by the addition of sarcomeres in series within muscle fibers, with a process distinct from the parallel sarcomere addition observed during hypertrophy induced by resistance training [19].

During static stretching, tensile force initially acts on the sarcomeres, causing elongation and reduction in overlap between thin and thick myosin filaments, thereby increasing muscle fiber length. Once sarcomeres – and consequently muscle fibers – reach their maximal length, further stretching forces are transmitted to the surrounding connective tissue. This process promotes collagen fiber reorganization, aligning fibers parallel to the direction of applied force [15,20]. The overall increase in muscle length depends on the number of muscle fibers effectively elongated, as individual fibers may respond heterogeneously to the stretching stimulus.

A comprehensive understanding of neuromuscular interactions and adaptive responses during stretching is essential. Stretch-induced elongation of muscle spindles generates afferent signals transmitted to the spinal cord, activating the stretch reflex and opposing further lengthening through reflex contraction. Simultaneously, afferent input is conveyed to higher cortical centers, particularly the insular cortex, where integration of sensory input with emotional, motivational, and cognitive factors occurs. Von Economo neurons play a key role in this process, enabling individuals to tolerate discomfort and sustain stretching [21]. When external force or stretch velocity exceeds the biomechanical and neurogenic capacity of the neuromuscular system – surpassing the so-called "safe zone" – GTO activation predominates. Afferent signals from GTOs inhibit motor neuron activity, overriding spindle-mediated contraction and allowing controlled muscle relaxation. This coordinated activity between the two proprioceptors protects the muscle from injury.

Static Stretching

Static stretching (SS) involves elongating a muscle to the point of perceived tension or tolerable discomfort and maintaining this position for a defined duration. From a physiological perspective, SS primarily relies on adaptation and reduced activity of muscle spindles when a muscle is held at an extended length, together with reflex muscle relaxation mediated by activation of GTOs [22,23].

The key advantage of static stretching over other stretching modalities is its capacity to achieve a relatively high stretch intensity through effective isolation of the target muscle group. Consequently, stretching is widely used in both clinical and athletic settings when the primary objectives are to increase joint range of motion and reduce injury risk [2]. Nevertheless, growing evidence suggests that static stretching – particularly when performed for prolonged durations (≥60 seconds) – may adversely affect certain aspects of muscle performance. These findings have important implications for the design of training and rehabilitation programs. Prolonged or excessively intense static stretching has been associated with reductions in strength- and speed-related performance, potentially due to muscle fatigue [19,23,24]. Specifically, SS has been reported to exert a significant negative effect – ranging from -1.2% to -8.5% – across multiple performance parameters, including sprint velocity, jump height, and maximal voluntary contraction of the knee extensors [19,23,25]. In contrast, several studies have reported positive effects of SS on sprint performance, jump height, and peak cycling power [26,27]. Although many of these findings did not reach statistical significance, the frequency of reported positive effects exceeded that of negative effects for measures such as jump height, running speed, and maximal cycling power. Consequently, no clear consensus exists regarding the impact of short-duration static stretching (<60 seconds) on athletic performance, suggesting that individual responsiveness may play a decisive role [19].

With respect to muscle strength, three studies have documented a significant average reduction of approximately 4.2% in eccentric contraction parameters following prolonged static stretching (≥60 seconds), whereas six other studies reported no significant effect. Given that most muscle injuries occur during eccentric contractions, further research is warranted to clarify the influence of static stretching on maximal eccentric strength [19,28].

In the context of the general population and injury prevention, the study by Bandi et al. demonstrated that a minimum of 30 seconds of static stretching is required to elicit a meaningful increase in flexibility [29]. However, evidence suggests that long-term improvements in flexibility are more strongly influenced by stretching frequency than by the duration of individual stretching bouts. In a comprehensive review of stretching modalities, Palma et al. reported that optimal maintenance of flexibility can be achieved with a minimum stretching frequency of five sessions per week and a cumulative stretching duration of approximately 5 minutes per muscle group per week [30].

Finally, Wyone and colleagues showed that so-called micro-stretching – defined as 30-40% of maximal stretch intensity and perceived as mildly uncomfortable – was more effective than conventional static stretching protocols. These findings emphasize the importance of consistency and frequency over stretch intensity, an approach that may also enhance adherence and long-term compliance in both clinical and athletic populations [31].

Dynamic Stretching

Dynamic stretching (DS) consists of controlled, repetitive joint movements performed through the available range of motion, accompanied by a subjective sensation of muscular tension [32]. Several factors support the preferential use of DS over SS during warm-up routines preceding physical activity. First, there is a similarity between stretching and exercise in terms of muscle activation patterns [19,32]. Second, muscle activity during DS increases both core body temperature and local muscle temperature. This rise in temperature accelerates nerve conduction velocity, enhances intracellular enzymatic reactions, boosts metabolism and energy production, and facilitates coordinated muscle action in preparation for specific physical activities [33]. Finally, dynamic movement has been shown to increase activation within central nervous system regions involved in motor control and coordination, in contrast to prolonged SS, which appear to have either neutral or inhibitory effects on these neural centers [34].

Although DS has demonstrated moderate positive effects on muscle function, current evidence does not conclusively support its role in directly enhancing athletic performance. Importantly, however, studies examining DS as part of pre-exercise preparation consistently report an absence of detrimental effects on muscle strength, jump height, or running speed [35,36].

The effects of DS appear to be influenced by both movement frequency and joint-movement amplitude. While some investigations report no significant association between these parameters and performance outcomes, others suggest that meaningful differences exist [2,27,32]. Higher frequencies of DS – and ballistic stretching, which involved momentum-driven movements intended at increase ROM – are associated with increased afferent input from muscle spindles, leading to greater excitation of motor neurons [37]. In this context, DS performed at a frequency of 100•min^{-1} has been shown to elicit significantly greater improvement in vertical jump height (6–9.1%), countermovement jump height (4.9%), quadriceps torque during both eccentric and concentric contractions (7–15%), and knee extensor strength (10.1%) compared with DS performed at 50•min^{-1} [38].

In contrast, Franko et al. reported a negative effect of DS on parameters assessed using the Wingate test, including reduced peak power and a prolonged time to peak power following a DS-based warm-up. These findings may reflect a mismatch between the motor patterns employed during DS exercises and those required for high-intensity cycling, underscoring the importance of movement specificity when designing warm-up protocols [39].

Despite evidence supporting the capacity of DS to increase ROM, relatively few studies have examined the underlying mechanisms responsible for this effect. DS typically involves repeated cycles of muscle loading and unloading over several minutes [32]. The most plausible explanation, extrapolated from animal models, suggests that repetitive muscle elongation elevates intra-fiber and extracellular temperatures, thereby reducing the viscosity of extracellular and intracellular matrix – referred to as the thixotropic effect [40]. This reduction in tissue viscosity may facilitate decreased muscle stiffness and enhanced ROM in humans [41].

Discussion

There remains considerable debate regarding two commonly attributed benefits of flexibility: injury prevention and enhancement of athletic performance. Although stretching is widely regarded as a preventive measure against athletic injuries, epidemiological evidence supporting this assumption remains limited [42]. Interestingly, earlier theories suggested that a certain degree of muscle stiffness might confer a protective effect by enabling more efficient load distribution across static and dynamic stabilizing structures during joint stress [43]. Conversely, hypermobility or excessive stretching may theoretically increase mechanical stress on ligaments, osseous structures, and articular cartilage, potentially leading to injury or degenerative changes over time. In line with this hypothesis, the main risk factors for joint injury include a history of previous injury and the presence of joint hypermobility.

At present, the role of pre-exercise stretching in injury prevention remains inconclusive. To address this uncertainty, the American College of Sports Medicine (ACSM) supported a systematic review conducted by Taker and colleagues; however, the authors found insufficient evidence to confirm a protective effect of routine stretching on injury incidence [42,44]. More recently, Takeuchi et al. [45] concluded in 2024 literature review that static stretching reduces the risk of muscle injuries but has no significant effect on ligament injuries. Other studies corroborate a reduced incidence of muscle injuries while simultaneously reporting an increased risk of bone and joint injuries [46].

With respect to athletic performance, several laboratory studies have demonstrated that less flexible runners exhibited lower oxygen consumption at a given speed and distance compared to their more flexible counterparts [47]. A 2025 systematic review by Warneke et al. [48] reported that prolonged static stretching (>60 seconds) immediately before strength testing or athletic performance results in an acute reduction in force production. The authors further suggest that combining short-duration static stretching with dynamic stretching during warm-up may increase joint ROM while minimizing strength deficits. In a subsequent publication, Warneke et al. [49] reported limited evidence that chronic static stretching (≥15 minutes, ≥6 weeks, ≥5 sessions per week) can increase maximal strength and muscle size, although the underlying physiological mechanisms remain unclear. Notably, this approach may be particularly valuable in older adults when traditional resistance training is contraindicated.

Another important consideration concerns the sequencing and scheduling of different exercise modalities. Systematic reviews and meta-analyses indicate that optimal therapeutic exercise programs typically emphasize a single primary exercise type – whether aerobic, flexibility-based, or strength training. This recommendation is based on divergent molecular adaptations, as aerobic and resistance exercises stimulate mitochondrial biogenesis and myofibrillar protein synthesis, respectively. Concurrent training appears to attenuate the molecular response to each stimulus. Extrapolating from this concept, stretching could theoretically be performed in a separate training session; however, no current guidelines or empirical studies have evaluated the efficacy of such an approach.

Finally, challenges remain regarding the timing of stretching relative to therapeutic exercises goals. Questions persist concerning the influence of proprioceptive inhibition on motor learning and the potential effects of stretching when incorporated before or after physiotherapy sessions, particularly in the context of neurologic rehabilitation.

Conclusion

At present, no consensus exists regarding the necessity of stretching or its definitive role in injury prevention. Nevertheless, the psychological benefits of stretching – particularly its capacity to reduce perceived muscle tension and mental stress – should not be underestimated. Clinicians and sports professionals should therefore individualize stretching protocols according to therapeutic objectives, injury risk, and performance demands. Research suggests meaningful distinctions between the effects of acute and chronic stretching. Acute stretching may reduce the risk of muscle strains in individuals with excessive muscle tension, whereas those with optimal muscle tone appear to derive minimal preventive benefit. Individuals with inherently greater flexibility tend to be less susceptible to exercise-related injuries, and acquired flexibility can be increased through intensive stretching programs performed three or four times per week. Owing to these differences, many experts currently advocate performing the majority of stretching at the end of training sessions rather than beforehand. As with most interventions in medicine and exercise science, no single stretching strategy is universally applicable. Optimal outcomes depend on individualized assessment, appropriate timing, and clearly defined therapeutic or performance-related goals.

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