ScienceFrontier
Research Article
Clinical Case Studies and Review Reports
ISSN Online : 3064-7843 | OPEN ACCESS

Biomechanical and Physiological Properties of Skeletal Muscles under Isometric Stretching Conditions: A Theoretical Review

Sandip Sinha[1*] | Anil Mili[2]

[1]Research Scholar, Dept. of Physical Education & Sports Science, Rajiv Gandhi University (A Central University), Doimukh (India).

[2] Associate Professor and Research Supervisor, Dept. of Physical Education & Sports Science, Rajiv Gandhi University (A Central University), Doimukh (India).

***Corresponding Author:** Sandip Sinha, Research Scholar, Dept. of Physical Education & Sports Science, Rajiv Gandhi University (A Central University), Doimukh (India).

Received Date: June 03, 2025; **Accepted Date:** June 10, 2025; **Published Date:** June 17, 2025

Citation: Sandip Sinha, Anil Mili (2025). Biomechanical and Physiological Properties of Skeletal Muscles under Isometric Stretching Conditions: A Theoretical Review, J *Clinical Case Studies and Review Reports*. 2(3) 29, **DOI:** CCSRR-RA-25-29.

Abstract

Purpose: The objective of this document is to understand and an in-depth discussion on the current biomechanical and physiological properties of muscle stretching interventions and summarize the evidences related to isometric stretching as used in exercise, training and rehabilitation programs. Skeletal muscle powers movement, making it an important determinant of physical fitness.

Methodology: The study emphasizes on the classic excitation-contraction coupling, sliding-filament and crossbridge theories help to describe the processes of muscle activation and the generation of force, work and power.

Conclusion: The mechanical properties of relaxed muscle have been relatively neglected over the years. Skeletal muscles represent fascinating and complex machinery, enabling active force production, movement and stability of the skeleton, storage and transport of substances within the body, and generation of heat during activity. Still, there is a huge research gap regarding the best stretching protocol.

Key words: skeletal muscle; isometric stretching; length-tension relationship; force-length relationship; force-velocity relationship

Abbreviations:

GAG : Glucosoaminoglycans
PAP : Post-Activation Potentiation
DS : Dynamic Stretching
IS : Isometric Stretching
ROM : Range of Motion

GTO : Golgi Tendon Organ
AP : Action Potential
Ach : Acetylcholine
SR : Sarcoplasmic Reticulum
NMJ : Neuromuscular Junction
BS : Ballistic Stretching
PNF : Proprioceptive Neuromuscular Facilitation
SS : Static Stretching

Introduction:

Stretching is an important therapeutic and exercise training modality for increasing joint range of motion and there has been extensive research on the effects of various stretching programs that have documented the clinical effectiveness of these techniques in modifying flexibility (Shrier, 2004; Decoster et al., 2005). Skeletal muscles are voluntary muscles and they work under our control, how and when they are instructed. The skeletal muscles are a vital part of our musculo-skeletal system. They serve a variety of functions in games and sports, which include; expansion and contraction our chest cavity during respiration, maintaining body posture, moving the bones in different parts of our body, and protecting joints and holding them in their original place. Skeletal muscle generates the force required to overcome resistance and the power required for locomotion, making it an important determinant of behavioral capabilities among humans (Miles et al., 2018; Nelson et al., 2018; Lappin and Husak, 2005; Husak et al., 2006).
Skeletal muscle is a highly organized and a multi-scale tissue (Williams and Holt, 2018; Holt, 2020). Sarcomeres are the sub-cellular structures containing contractile protein filaments, are considered as the functional units of muscle. Thin-filaments, containing a helical actin polymer and a regulatory troponin–tropomyosin complex, project from the Z-disks at the ends of the sarcomere and overlap with the central thick filaments, which contain a myosin polymer (Holmes, 2009). These contractile protein filaments are held in place by a sarcomeric cytoskeleton including the large protein titin and create a highly ordered lattice structure when viewed in three dimensions (Shimomura et al., 2016; Gautel & Djinović-Carugo, 2016). Sarcomeres are arranged in series and in parallel in muscle fibers, and are enveloped by the sarcoplasmic reticulum (SR), an internal calcium (Ca2+) store made up of a network of interconnected tubules. Muscle fibers are organized into entire muscles with orientations ranging from parallel to perpendicular to the line of action of the muscle (Taylor-Burt et al., 2018). Muscle fibers and entire muscles are surrounded by connective tissues (Huijing, 2009; Sleboda et al., 2020) and connected to the skeleton by tendons (Roberts & Azizi, 2011).
Pre-exercise warming-up routines typically consist of a submaximal aerobic activity and stretching exercises. The submaximal aerobic activity is performed to increase body temperature, as such increases in body and muscle temperature have been found to increase nerve conduction velocity, enzymatic cycling, and muscle compliance. The second component of warm-up consists of different types of stretching exercises such as static or isometric stretching (SS/IS), dynamic stretching (DS), ballistic stretching (BS) and proprioceptive neuromuscular facilitation (PNF) (Franco, B. L., et al. 2012). The literature is conflicting regarding the effects of warm-up stretching prior to exercise; isometric and dynamic warm-ups are equally effective at increasing ROM prior to exercise (Curry, B. S. et al., 2009; Beedle, B. B., & Mann, C. L., 2007). IS after warm-up decreases performance (Young, W. et al, 2006; Kistler, B. M. et al., 2010), while others report no change or an increase in performance (Cè, E. et al., 2008; Taylor, K. L. et al., 2009; Herman, S. L., & Smith, D. T., 2008; Fletcher, I. M., & Jones, B., 2004). Whether IS performed before or after warming-up do not decrease strength (Behm, D. G. et al., 2004; Beedle, B. B., & Mann, C. L., 2007). Robbins et al. (2008) reported that 4 repetitions of 15-sec hold of IS done do not affect vertical jump, while 6 repetitions reduced performance. A pre-stretching contraction been associated with greater acute gains in ROM compared to IS/SS in many studies however, several studies show similar increases in the ROM (Chow, T. P., & Ng, G. Y., 2010) and performance (Yuktasir, B., & Kaya, F., 2009; Caplan, N. et al., 2009; Shadmehr, A. et al., 2009) when comparing pre-contraction stretching and IS. Both acute IS and pre-contraction stretching has been shown to decrease strength (Babault, N. et al., 2010; Marek, S. M. et al., 2005). Our understanding of muscle contraction and muscle mechanical properties has changed fundamentally with the discovery of the sliding filament theory in 1954 and associated cross-bridge theory in 1957. Nevertheless, experimental evidence suggests that our knowledge of the mechanisms of contraction is far from complete, and muscle properties and muscle function in human movement remain largely unknown (Herzog, W., 2018).
Static muscle stretching or the isometric stretching exercises has lost its importance from the sports arena; once considered an essential part of any sport or exercise, warming-up protocol, is entirely dominated by dynamic stretching or isotonic stretching protocols. To put this matter into context as a research problem, the average performance decreases by 3-5% decrease in muscular strength, muscular power, and speed. Looking at some studies where participants performed muscle stretching within a full sport warm-up i.e. when lower-intensity exercise is done before IS of less than 60 sec per muscle, and higher-intensity sports-specific exercises are performed after stretching then static stretching within this comprehensive warm-up has no significant effects on actual performance e.g. average change in sprint speed was -0.15%.
Specifically, the current study is purposefully designed to understand the mechanism of skeletal muscle contraction at cellular level while examining the factors that influence a muscle's ability to produce force and motion, which includes the force-length relationship, force-velocity relationship and length-tension relationship. Finally, to summarize the evidences related to effect

of isometric stretching as used in exercise, training and rehabilitation programs.

Methodology:

Experimental evidence suggests that our knowledge of the mechanisms of skeletal muscle contraction under isometric stretching protocol is far from complete, and muscle properties and muscle function in human movement remain largely unknown. Hence, a descriptive based research approach is applied for the current study based on secondary sources literature (from 2000 A.D till date) from books, publications, articles and other relevant secondary sources.
This manuscript is subjected to identify some of the crucial muscle mechanics to offer possible solutions to the current research questions and identify the appropriate possible answers through the following objectives:

- To do an in-depth theoretical understanding of muscular contraction at cellular level.
- To understand the;

a) 'Force-Length' relationship of skeletal muscle.
b) 'Force-Velocity' relationship of skeletal muscle.
c) 'Length-Tension' relationship of skeletal muscle.

- To identify the effect of isometric contraction of skeletal muscle and the clinical significance of isometric stretching.

Findings of the Study:

Muscular contraction at cellular level

The skeletal muscles are the main functional units of the muscular system. The primary function of skeletal muscle contraction is to allow for the performance of specific movements. Skeletal muscle also provides structural support, maintains the body's posture, stores amino acids, and maintains core body temperature (Frontera, W.R. & Ochala, J., 2015). The skeletal muscles of the human body are organized into four groups for every region of the body:

Major Muscles	Location and Description
Muscles of the head and neck	Includes the muscles of the facial expression, muscles of mastication, muscles of the orbit, muscles of the tongue, muscles of the pharynx, muscles of the larynx, and muscles of the neck.
Muscles of the trunk	Muscles of the back, anterior and lateral abdominal muscles, and muscles of the pelvic floor.
Muscles of the upper limbs	Muscles of the shoulder, muscles of the arm, muscles of the forearm and muscles of the hand.
Muscles of the lower limbs	Hip and thigh muscles, leg muscles and foot muscles.

Table 3.1: *Showing the division of body based on major muscle groups*

Muscle fibers are specialized cells whose main feature is the ability to contract. They are elongated, cylindrical, multinucleated cells bounded by a cell membrane called sarcolemma and this structure gives the skeletal muscle tissue four main physiological properties:

Property	Explanation
Excitability	The ability to detect the neural stimuli i.e. action potential.
Contractibility	The ability to contract in response to a neural stimulus.
Extensibility	The ability of a muscle to be stretched without tearing.
Elasticity	The ability to return to its normal shape after being extended.

Table No 3.2: *Showing the physiological properties of muscles*

The ability to stretch muscles could be explained from the neurological when considering the neurophysiological basics of muscle tone and biomechanical models of the skeletal muscle. Intramuscular connective tissue framework i.e. non-contractile components, serves to distribute forces during muscle stretching. Optimal muscle function is probably achieved by increasing muscle length, length extensibility, passive elastic stiffness, mass and strength. The force a muscle generates is dependent on the length of the muscle and its shortening velocity. These two fundamental properties limit many key biomechanical properties, including running speed, strength, and jumping distance.
The process of muscle contraction begins at the site where a motor neuron's terminal meets the muscle fiber; called as the neuromuscular junction (NMJ). Every skeletal muscle fiber in every skeletal muscle is innervated by a motor neuron at a NMJ. Excitation signals from the motor neuron are the only way to functionally activate skeletal muscle fibers to contract. The skeletal

muscle contraction initiation and execution occur in the following steps:

- An action potential (AP) travels along a motor nerve to its endings on muscle fibers.
- At each motor nerve ending, the nerve secretes acetylcholine (ACh).
- ACh acts locally on the muscle fiber membrane to open ACh-gated cation channels.
- The opening of ACh-gated channels allows large quantities of sodium (Na) ions to diffuse to the interior of the muscle fiber membrane.
- This action causes a local depolarization, leading to the opening of voltage-gated sodium (Na) channels, which initiates an AP at the membrane.
- The AP depolarizes the muscle membrane, causing the sarcoplasmic reticulum (SR) to release large quantities of Ca ions stored within the reticulum.
- The Ca ions produce attractive forces to act between actin and myosin filaments, causing them to slide alongside each other, leading to the contractile process.
- After a fraction of a second, the Ca ions are pumped back into the SR by a Ca-membrane pump and remain stored in the SR until a new muscle AP occurs.
- The removal of Ca ions from the myofibrils causes muscle contraction to cease.

3.2. Force-Length Relationship:

Due to the presence of titin, muscles are innately elastic. Skeletal muscles are attached to bones via tendons that maintain the muscle under a constant level of stretch called the resting length.

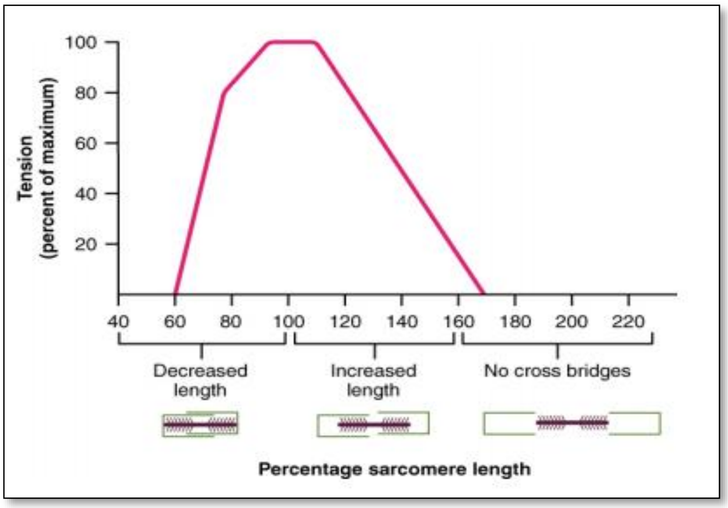

Figure. 3.1: *Showing the ideal length of a sarcomere. Sarcomeres produce maximal tension when thick and thin filaments overlap between about 80% - 120%.*

Muscles exist in this state to optimize the force produced during contraction, which is modulated by the interlaced myofilaments of the sarcomere. When a sarcomere contracts, myosin heads attach to actin to form cross-bridges. Then, the thin filaments slide over the thick filaments as the heads pull the actin. This results in sarcomere shortening, creating the tension of the muscle contraction. If a sarcomere is stretched too far, there will be insufficient overlap of the myofilaments and the less force will be produced. If the muscle is over-contracted, the potential for further contraction is reduced, which in turn reduces the amount of force produced. Simply, the tension generated in skeletal muscle is a function of the magnitude of overlap between actin and myosin myofilaments. In mammals, there is a strong overlap between the optimum and actual resting length of sarcomeres (Rassier, D. E., 2017).

3.3. Force-Velocity Relationship:

The force-velocity relationship in muscle relates the speed at which a muscle changes length with the force of this contraction and the resultant power output (force × velocity = power). The force generated by a muscle depends on the number of actin and myosin cross-bridges formed; a larger number of cross-bridges results in a larger amount of force. However, cross-bridge formation is not immediate, so if myofilaments slide over each other at a faster rate the ability to form cross bridges and resultant force are both reduced. At maximum velocity no cross-bridges can form, so no force is generated, resulting in the production of zero power (fig. 3.2). The reverse is true for stretching of muscle. Although the force of the muscle is increased, there is no velocity of contraction and zero power is generated (fig. 3.2). Maximum power is generated at approximately one-third of maximum shortening velocity. As velocity increases force and therefore power produced is reduced. Although force increases due to stretching with no velocity, zero power is produced. Maximum power is generated at one-third of maximum shortening velocity.

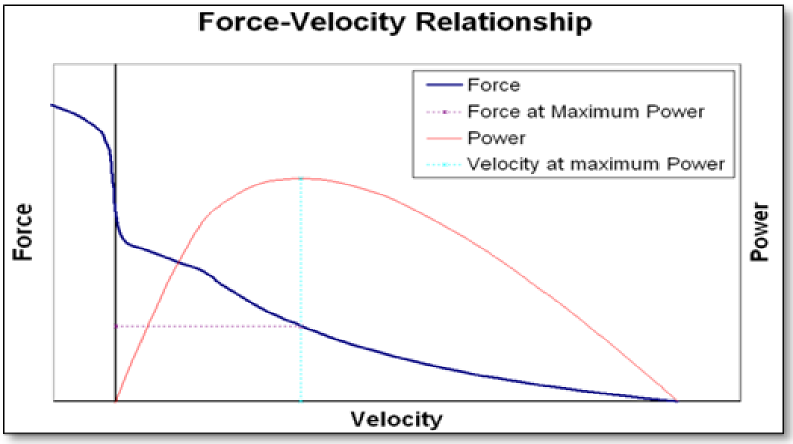

Figure 3.2: *Showing the Force-Velocity relationship*

3.4. Length-Tension Relationship:

Tension refers to the amount of force built up within a muscle. The total tension is a combination of passive (non-contractile) & active (contractile units) tension. Generally, a muscle is capable of being shortened to approximately half of its normal resting length & stretched about 2 times its normal resting length. The distance between maximum elongations to maximum shortening is referred to as excursion, and usually a muscle has sufficient excursion to allow the joint to move through the joint's entire range. The action responsible for the contraction of a muscle occurs within a sarcomere and force generation is dependent on the amount of overlap between thin and thick myofilaments. The greater the number of cross bridges attached to the actin filaments, the larger the contraction force. The length-tension curve below summarizes the relationship between muscle length and tension during force production. It is important to note that two joint muscles undergo active and passive insufficiency during simultaneous movements (Hazari, A. et al., 2021).

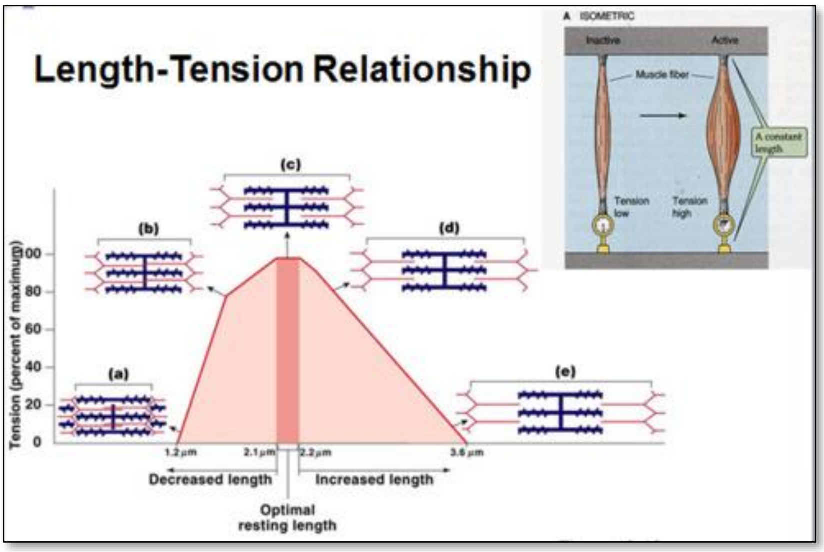

Figure 3.3: *Showing the length-tension relationship during isometric contraction.*

3.5. Effect of Isometric Contraction of Muscle:

In contrast to isotonic contractions, isometric contractions generate force without changing the length of the muscle, common in the muscles of the hand and forearm responsible for grip. Isometric contractions are frequently used to maintain posture. Isometric contractions are sometimes described as yielding or overcoming. Regular isometric stretching exercise shows that it improves force and performance in activities. It is shown that if stretching a muscle group for 30-60 sec/day over months results in hypertrophy. The evidence shows that performing static stretching exercises before sports activities lead to decreased performance and increase the risk of injury; while on the other hand performing regular stretching exercises lead to improved force production and performance in all activities (Kay, A. D., & Blazevich, A. J., 2012). The acute effects of isometric stretching on muscle:

- Decreases the visco-elastic behavior of muscle and tendon only on the short term with no long term effect.
- Decreases motor neuron excitability through inhibitory effect from the Golgi Tendon organ (GTO) and by activation of Renshaw recurrent loop (recurrent inhibition).
- Decreases the activity of motor unit.
- Decreases the activity of muscle spindles, which results in decreasing the activity of stretch reflex.

- Decreases in sensitivity of nociceptors and joint receptors which are fundamental mechanisms for the protection of structures involved in motion.
- Facilitates type III and IV joint receptors sending inhibitory drive to the α-moto-neuron pool.
- Collectively all these acute changes in the muscle lead to decrease in force production, performance and increasing in the risk of injury.

3.5.1. Clinical Significance of Isometric Stretching:

There are a variety of good reasons to do isometrics or any other module of stretching. The main benefit of isometric exercises is that they can be used for rehabilitation as well as general strengthening without placing stress on the joints. This is an important aspect of isometric exercises because exercises that require joint movement can place a lot of stress on individual joints, especially over time with repeated usage (Gajdosik, R. L., 2001). Isometric exercises are much easier on the joints in both the short term and the long term. For this reason, isometric exercises are often used in rehabilitation routines for individuals that have had joint problems or issues. Some sports require a high level of static muscle strength; gymnastics, yoga, rock climbing, and downhill skiing, and all of these have static strength requirements, these exercises require a lot of strength, if not a lot of joint movement.

For a general fitness program, the American College of Sports Medicine recommends isometric stretching for most individuals that is preceded by an active warming-up, at least 2-3 days per week. Each stretch should be held 15-30 seconds and repeated 2-4 times (ACSM, 2013). Stretching performed as part of a limbering-up prior to exercise is thought to reduce passive stiffness and increase range of movement during exercise. In general, it appears that isometric stretching is most beneficial for athletes requiring flexibility for their sport, whereas DS may be better suited for athletes requiring running or jumping performance (Behm, D. G., & Kibele, A., 2007).

Discussion:

Skeletal muscle powers movement, making it an important determinant of physical fitness. The classic excitation-contraction coupling, sliding-filament and crossbridge theories help to describe the processes of muscle activation and the generation of force, work and power. The mechanical properties of relaxed muscle have been relatively neglected over the years. Skeletal muscles represent fascinating and complex machinery, enabling active force production, movement and stability of the skeleton, storage and transport of substances within the body, and generation of heat during activity. IS is a type of stretching exercises in which elongation of muscle with application of low force and long duration (30-60 sec). IS has a relaxation, elongation effect on muscles which increases ROM, decreases musculotendinous stiffness and also reduces the risk of acute muscle strain injuries. It is a slow controlled movement with emphasis on postural awareness and body alignment (Kay, A. D., & Blazevich, A. J., 2012). Stretching is believed to enhance physical performance, prevent injury, alleviate muscle soreness and increase flexibility (Bradley, P. S. et al., 2007). Traditionally, isometric stretching exercise is preferred when compared to other types of stretching exercises in many athletic events (McMillian, D. J. et al., 2006). However, some researchers report that acute static stretching exercises have detrimental effects on isometric and isokinetic force, jump height, sprint time, balance, reaction times and agility performance (Murphy, J., et al. 2010).

Kubo, K. et al. (2001), concluded that the increase in the stiffness of tendon structures, which means an increase in the ability to transmit muscle force more effectively, plays an important role in shortening the electromechanical delay. The shortened electromechanical delay as well as the increased stiffness after training will be considered to be suitable changes for improving muscle performances during various rapid movements. Also, suggested that the isometric training for 12 week resulted in an increase in the stiffness. Kurt, C. (2016), analysed variance indicated that “aerobic running combined with isometric stretching” increased agility ($p \leq 0.05$) and decreased relative average power, and relative maximum power ($p \leq 0.05$). However, no significant effect of IS on minimum power was detected ($p > 0.05$). The fatigue index score was greater following “aerobic running” and “aerobic running combined with DS” than following “aerobic running combined with IS”. Observed that aerobic running combined with IS or DS increased the flexibility more effectively than aerobic running alone ($p \leq 0.05$). Ogura, Y., et al. (2007), found that 30 second of IS done do not affect muscular performance; however, 60 second of IS caused a significant decrease in strength. In light of this result, we can speculate that the duration of stretching may be a significant factor. Since IS has negative effects on physical performance; coaches, trainers and athletes have recently tended to prefer DS to IS. These positive effects of DS are attributable mainly to elevated muscle and body temperature; post-activation potentiation (PAP) in the stretched muscle caused by voluntary contractions of the agonist, stimulation of the nervous system and decreased inhibition of antagonist muscles.

Stretching acutely reduces fascia stiffness and the magnitude of this decrease is comparable to that in the skeletal muscle. When compared to dynamic application, static stretch seems to have superior effects. A small association exists between changes of fascia stiffness and ROM increases, meaning that fascial but not muscle stiffness reductions could be a contributor of ROM improvements (Warneke, K. et al. 2024). Stretching did not negatively influence athletic performance in general (when compared to both passive and active controls); in fact, a positive effect on subsequent jumping performance ($ES = 0.15$, $p = 0.006$) was found in adults. Regarding strength testing of isolated muscles (e.g., leg extensions or calf raises), our results confirm previous findings. Nevertheless, since no (or even positive) effects could be found for athletic performance, our results do not support previous recommendations to exclude static stretching from warm-up routines prior to, for example, jumping or sprinting (Warneke, K., & Lohmann, L. H., 2024).

Another study revealed an overall unclear chronic effect of SS on skeletal muscle hypertrophy, although interpretation across the range of PI suggests a potential modest beneficial effect. Subgroup analysis indicated larger stretching-induced muscle gains in trained individuals, a more varied selection of SS exercises, longer mean duration of single stretching exercise, increased time under SS per session, week, and in total, and possibly in samples with a higher proportion of females. From a practical perspective, it appears that SS exercises may not be highly effective in promoting skeletal muscle hypertrophy unless a higher duration of training is utilized (Arntz, F. et al. 2024).

Conclusion:

The cellular and molecular mechanisms underlying the changes in joint flexibility, muscle strength, and power are not well clarified in medicine and cell biology, and thus, further investigations are needed. The additional effects of individual training status, age, sex, and different pathological states that moderate the influences of stretching exercises on the joints, muscles, tendons, and ligaments can be characterized as indirect (Knudson, D., 2006; Cipriani, D. J. et al. 2012; Kataura, S. et al. 2017; Hotta, K. et al. 2018; Hagiwara, Y. et al. 2010).
Decades of research in skeletal muscle physiology have provided multi-scale insights into the structural and functional complexity of this important anatomical tissue, designed to accomplish the task of generating contraction, force and movement. Skeletal muscle can be viewed as a biomechanical device with various interacting components including the autonomic nerves for impulse transmission, vasculature for efficient oxygenation, and embedded regulatory and metabolic machinery for maintaining cellular homeostasis. Stretching modulates the synthesis, deposition, concentration, degradation, and distribution of collagen and glucosoaminoglycans (GAGs), affecting the remodelling of the extracellular matrix (Abusharkh, H. A. et al. 2021). Stretching has not been shown to be effective at reducing the incidence of overall injuries. While there is some evidence of stretching reducing musculotendinous injuries (Small, K. et al., 2008) more evidence is needed to determine if stretching programs alone can reduce muscular injuries (McHugh, M. P., & Cosgrave, C. H., 2010). Still, there is a huge research gap regarding the best stretching protocol.

Acknowledgement:

The author extends heartfelt gratitude to his research supervisor for the invaluable guidance and contributions to this research, his expertise and dedication was instrumental in shaping the study, from the conceptualization and design to the meticulous collection and analysis of data.

Conflicts of Interest:

The authors hereby declare that there are no conflicts of interest related to this research.

References:

1. Abusharkh, H. A., et al. (2021). Combining stretching and gallic acid to decrease inflammation indices and promote extracellular matrix production in osteoarthritic human articular chondrocytes. Experimental cell research, 408(2), 112841.
   View at Publisher | View at Google Scholar
2. American College of Sports Medicine. (2013). ACSM's guidelines for exercise testing and prescription. Lippincott williams & wilkins.
   View at Publisher | View at Google Scholar
3. Babault, N., Kouassi, B. Y., & Desbrosses, K. (2010). Acute effects of 15 min static or contract-relax stretching modalities on plantar flexors neuromuscular properties. Journal of science and medicine in sport, 13(2), 247-252.
   View at Publisher | View at Google Scholar
4. Behm, D. G., & Kibele, A. (2007). Effects of differing intensities of static stretching on jump performance. European journal of applied physiology, 101, 587-594.
   View at Publisher | View at Google Scholar
5. Behm, D. G., & Chaouachi, A. (2011). A review of the acute effects of static and dynamic stretching on performance. European Journal of Applied Physiology, 111(11), 2633–2651.
   View at Publisher | View at Google Scholar
6. Behm, D. G., et al. (2004). Effect of acute static stretching on force, balance, reaction time, and movement time. Medicine & Science in Sports & Exercise, 36(8), 1397-1402.
   View at Publisher | View at Google Scholar
7. Beedle, B. B., & Mann, C. L. (2007). Acomparison of Two Warm-Ups on Joint Range of Motion. The Journal of Strength & Conditioning Research, 21(3), 776-779.
   View at Publisher | View at Google Scholar
8. Bradley, P. S., Olsen, P. D., & Portas, M. D. (2007). The effect of static, ballistic, and proprioceptive neuromuscular facilitation stretching on vertical jump performance. Journal of Strength and Conditioning Research, 21(1), 223–226.
   View at Publisher | View at Google Scholar

9. Beedle, B. B., & Mann, C. L. (2007). Acomparison of Two Warm-Ups on Joint Range of Motion. The Journal of Strength & Conditioning Research, 21(3), 776-779.
View at Publisher | View at Google Scholar
10. Caplan, N., et al. (2009). The effect of proprioceptive neuromuscular facilitation and static stretch training on running mechanics. The Journal of Strength & Conditioning Research, 23(4), 1175-1180.
View at Publisher | View at Google Scholar
11. Cipriani, D. J., et al. (2012). Effect of stretch frequency and sex on the rate of gain and rate of loss in muscle flexibility during a hamstring-stretching program: a randomized single-blind longitudinal study. The Journal of Strength & Conditioning Research, 26(8), 2119-2129.
View at Publisher | View at Google Scholar
12. Cè, E., et al. (2008). Effects of stretching on maximal anaerobic power: the roles of active and passive warm-ups. The Journal of Strength & Conditioning Research, 22(3), 794-800.
View at Publisher | View at Google Scholar
13. Chatzopoulos, D. et al. (2014). Acute effects of static and dynamic stretching on balance, agility, reaction time and movement time. PubMed.
View at Publisher | View at Google Scholar
14. Condon, S. M., & Hutton, R. S. (1987). Soleus muscle electromyographic activity and ankle dorsiflexion range of motion during four stretching procedures. Physical Therapy, 67(1), 24-30.
View at Publisher | View at Google Scholar
15. Chow, T. P., & Ng, G. Y. (2010). Active, passive and proprioceptive neuromuscular facilitation stretching are comparable in improving the knee flexion range in people with total knee replacement: a randomized controlled trial. Clinical rehabilitation, 24(10), 911-918.
View at Publisher | View at Google Scholar
16. Curry, B. S., et al. (2009). Acute effects of dynamic stretching, static stretching, and light aerobic activity on muscular performance in women. The Journal of Strength & Conditioning Research, 23(6), 1811-1819.
View at Publisher | View at Google Scholar
17. Ferber, R., Gravelle, D. C., & Osternig, L. R. (2002). Effect of proprioceptive neuromuscular facilitation stretch techniques on trained and untrained older adults. Journal of aging and physical activity, 10(2), 132-142.
View at Publisher | View at Google Scholar
18. Franco, B. L., et al. (2012). Acute effects of three different stretching protocols on the wingate test performance. DOAJ (DOAJ: Directory of Open Access Journals).
View at Publisher | View at Google Scholar
19. Frontera, W. R., & Ochala, J. (2015). Skeletal muscle: a brief review of structure and function. Calcified tissue international, 96(3), 183–195.
View at Publisher | View at Google Scholar
20. Fletcher, I. M., & Jones, B. (2004). The effect of different warm-up stretch protocols on 20 meter sprint performance in trained rugby union players. The Journal of Strength & Conditioning Research, 18(4), 885-888.
View at Publisher | View at Google Scholar
21. Gajdosik, R. L. (2001). Passive extensibility of skeletal muscle: review of the literature with clinical implications. Clinical Biomechanics, 16(2), 87–101.
View at Publisher | View at Google Scholar
22. Gash, M. C., et al. (2023). Physiology, Muscle Contraction. In StatPearls. StatPearls Publishing.
View at Publisher | View at Google Scholar
23. Godges, J. J., et al. (1989). The effects of two stretching procedures on hip range of motion and gait economy. Journal of Orthopaedic & Sports Physical Therapy, 10(9), 350-357.
View at Publisher | View at Google Scholar
24. Hagiwara, Y., et al. (2010). Expression of collagen types I and II on articular cartilage in a rat knee contracture model. Connective tissue research, 51(1), 22-30.
View at Publisher | View at Google Scholar
25. [25] Hazari, A., Maiya, A. G., & Nagda, T. V. (2021). Conceptual Biomechanics and Kinesiology. Springer.
View at Publisher | View at Google Scholar
26. Herzog, W. (2018). Correction to: skeletal muscle mechanics: questions, problems and possible solutions. Journal of Neuroengineering and Rehabilitation.
View at Publisher | View at Google Scholar
27. Herman, S. L., & Smith, D. T. (2008). Four-week dynamic stretching warm-up intervention elicits longer-term performance benefits. The Journal of Strength & Conditioning Research, 22(4), 1286-1297.
View at Publisher | View at Google Scholar
28. Hotta, K. et al. (2018). Daily muscle stretching enhances blood flow, endothelial function, capillarity, vascular volume and connectivity in aged skeletal muscle. The Journal of physiology, 596(10), 1903-1917.

View at Publisher | View at Google Scholar

29. Kay, A. D., & Blazevich, A. J. (2012). Effect of acute static stretch on maximal muscle performance. Medicine and Science in Sports and Exercise, 44(1), 154–164.
View at Publisher | View at Google Scholar
30. Kataura, S., et al. (2017). Acute effects of the different intensity of static stretching on flexibility and isometric muscle force. The Journal of Strength & Conditioning Research, 31(12), 3403-3410.
View at Publisher | View at Google Scholar
31. Kistler, B. M., et al. (2010). The acute effects of static stretching on the sprint performance of collegiate men in the 60-and 100-m dash after a dynamic warm-up. The Journal of Strength & Conditioning Research, 24(9), 2280-2284.
View at Publisher | View at Google Scholar
32. Kubo, K., Kanehisa, H., Ito, M., & Fukunaga, T. (2001). Effects of isometric training on the elasticity of human tendon structures in vivo. Journal of Applied Physiology, 91(1), 26–32.
View at Publisher | View at Google Scholar
33. Kuo, I. Y., & Ehrlich, B. E. (2015). Signaling in muscle contraction. Cold Spring Harbor perspectives in biology, 7(2), a006023.
View at Publisher | View at Google Scholar
34. Kurt, C. (2016). Comparison of the acute effects of static and dynamic stretching exercises on flexibility, agility and anaerobic performance in professional football players. Türkiye Fiziksel Tıp Ve Rehabilitasyon Dergisi, 62(3), 206–213.
View at Publisher | View at Google Scholar
35. Knudson, D. (2006). The biomechanics of stretching. Journal of Exercise Science and Physiotherapy, 2, 3-12.
View at Publisher | View at Google Scholar
36. Libretexts. (2023). 9.3A: force of muscle contraction. Medicine LibreTexts.
View at Publisher | View at Google Scholar
37. Lowey, S., Waller, G. S., & Trybus, K. M. (1993). Function of skeletal muscle myosin heavy and light chain isoforms by an in vitro motility assay. The Journal of biological chemistry, 268(27), 20414–20418.
View at Publisher | View at Google Scholar
38. Ludwig, P. E., Reddy, V., & Varacallo, M. (2022). Neuroanatomy, Central Nervous System (CNS). In StatPearls. StatPearls Publishing.
View at Publisher | View at Google Scholar
39. Magnusson, S. P. (1998). Passive properties of human skeletal muscle during stretch maneuvers. Scandinavian Journal of Medicine & Science in Sports, 8(2), 65–77.
View at Publisher | View at Google Scholar
40. Marek, S. M., et al. (2005). Acute effects of static and proprioceptive neuromuscular facilitation stretching on muscle strength and power output. Journal of athletic training, 40(2), 94.
View at Publisher | View at Google Scholar
41. McHugh, M. P., & Cosgrave, C. H. (2010). To stretch or not to stretch: the role of stretching in injury prevention and performance. Scandinavian journal of medicine & science in sports, 20(2), 169-181.
View at Publisher | View at Google Scholar
42. Mendoza, E., Moen, D. S., & Holt, N. C. (2023). The importance of comparative physiology: mechanisms, diversity and adaptation in skeletal muscle physiology and mechanics. The Journal of Experimental Biology, 226(Suppl_1).
View at Publisher | View at Google Scholar
43. McMillian, D. J., et al. (2006). Dynamic vs. Static-Stretching Warm Up: The Effect on Power and Agility Performance. Journal of Strength and Conditioning Research, 20(3), 492.
View at Publisher | View at Google Scholar
44. MEFANET, Czech and Slovak medical faculties network. (n.d.). Biomechanics of muscle contraction - WikiLectures.
View at Publisher | View at Google Scholar
45. Mili, A., Sinha, S., (2023). The Effect of Static Stretching Exercise when combined with the FIFA 11+ Warming-Up Programme on selected Physical Performance Parameters in Female Recreational Futsal Players. Education and Society. Vol. 47 (1). No. 1. pp. 44-53. ISSN: 2278-6864.
View at Publisher | View at Google Scholar
46. Mili, A., Sinha, S., and Hussain, A. (2023). The Effect of Isometric Stretching Combined as Post-Dynamic Warming-Up on Skill related Physical Fitness Components among Football Players. Madhya Bharti. Vol. 83 (5). pp. 23-32. ISSN: 0974-0066.
View at Publisher | View at Google Scholar
47. Murphy, J., et al. (2010). Aerobic activity before and following short-duration static stretching improves range of motion and performance vs. a traditional warm-up. Applied Physiology, Nutrition, and Metabolism, 35(5), 679–690.
View at Publisher | View at Google Scholar
48. Moore, M. A., & Hutton, R. S. (1980). Electromyographic investigation of muscle stretching techniques. Medicine

and science in sports and exercise, 12(5), 322-329.
View at Publisher | View at Google Scholar

49. Ogura, Y., et al. (2007). Duration of static stretching influences muscle force production in hamstring muscles. Journal of Strength and Conditioning Research, 21(3), 788.
View at Publisher | View at Google Scholar
50. Rassier D. E. (2017). Sarcomere mechanics in striated muscles: from molecules to sarcomeres to cells. American journal of physiology. Cell physiology, 313(2), C134–C145.
View at Publisher | View at Google Scholar
51. Rosenblueth, A., Alanis, J., & Rubio, R. (1958). A comparative study of the isometric and isotonic contractions of striated muscles. Archives internationales de physiologie et de biochimie, 66(3), 330–353.
View at Publisher | View at Google Scholar
52. Robbins, J. W., & Scheuermann, B. W. (2008). Varying amounts of acute static stretching and its effect on vertical jump performance. The Journal of Strength & Conditioning Research, 22(3), 781-786.
View at Publisher | View at Google Scholar
53. Šimić, L., Šarabon, N., & Markovic, G. (2012). Does pre-exercise static stretching inhibit maximal muscular performance? A meta-analytical review. Scandinavian Journal of Medicine & Science in Sports, 23(2), 131–148.
View at Publisher | View at Google Scholar
54. Sweeney, H. L., & Hammers, D. W. (2018). Muscle contraction. Cold Spring Harbor Perspectives in Biology, 10(2), a023200.
View at Publisher | View at Google Scholar
55. Taylor, K. L., et al. (2009). Negative effect of static stretching restored when combined with a sport specific warm-up component. Journal of Science and Medicine in Sport, 12(6), 657-661.
View at Publisher | View at Google Scholar
56. Williams, P. E., & Goldspink, G. (1984). Connective tissue changes in immobilised muscle. Journal of anatomy, 138 (Pt 2)(Pt 2), 343–350.
View at Publisher | View at Google Scholar
57. Young, W., Elias, G., & Power, J. (2006). Effects of static stretching volume and intensity on plantar flexor explosive force production and range of motion. Journal of sports medicine and physical fitness, 46(3), 403.
View at Publisher | View at Google Scholar
58. Zvetkova, E., et al. (2023). Biomechanical, Healing and Therapeutic Effects of Stretching: A Comprehensive review. Applied Sciences, 13(15), 8596.
View at Publisher | View at Google Scholar