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Invited Review

Effects of stretching on injury risk reduction and balance

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Abstract

Evidence for the effectiveness of acute and chronic stretching for improving range of motion (ROM) is extensive. Improved flexibility can positively impact performances in activities of daily living and both physical and mental health. However, less is known about the effects of stretching on other aspects of health such as injury incidence and balance. The objective of this narrative review is to examine the existing literature in these areas. The review highlights that both pre-exercise and chronic stretching can reduce musculotendinous injury incidence, particularly in running-based sports, which may be related to the increased force available at longer muscle lengths (altered force-length relationship) or reduced active musculotendinous stiffness, among other factors. Evidence regarding the acute effects of stretching on balance is equivocal. Longer-term stretch training can improve balance, which may contribute to a decreased incidence of falls and associated injuries and may thus be recommended as an important exercise modality in those with balance deficits. Hence, both acute and chronic stretching seem to have positive effects on injury incidence and balance, but optimum training plans are yet to be defined.

Key Words: flexibility; stretch training; stability; falls; injury incidence

Major Takeaways on Injury Incidence

1. Pre-exercise muscle stretching typically does not influence all-cause injury risk.
2. There is moderate evidence for greater protection from muscle-tendon unit (MTU) injuries with pre-exercise and chronic static stretching; there is insufficient evidence for the effects of acute or chronic dynamic stretching.
3. Decreases in MTU injury incidence may result from changes in tissue compliance or shifts in the active force-length relation towards longer muscle lengths.
4. There is no conclusive evidence for acute impairments in proprioception after static or proprioceptive neuromuscular facilitation (PNF) stretching.

Major Takeaways on Balance

1. Dynamic stretching is demonstrated to have acute beneficial effects on balance.
2. The effects of acute static stretching on balance are equivocal; it is not yet possible to determine the circumstances under which effects may be positive, absent, or negative.
3. Chronic dynamic and static stretch training may provide balance benefits and thus help to reduce the incidence of falls.
4. Mechanisms underlying these benefits may include increased MTU compliance or range of motion (ROM) allowing the individual to accommodate greater disruptive perturbations.
5. Acute and chronic stretch-induced increases in force production at longer muscle lengths (altered muscle force-length relationship) may contribute to a stronger and more rapid reaction to balance perturbations from an extended joint or leg position.

Introduction

Both acute and chronic (i.e., longer-term) muscle stretching can increase active and passive range of motion (ROM) at both a targeted joint (1-5) as well as other non-stretched (non-local) homologous and heterologous joints (3, 6). The stretch-induced ROM increase has been postulated to improve physical performance by permitting more expansive limb movements during actions that necessitate an augmented ROM, such as in gymnastics, figure skating, and combat sports, among many other actions and sports (1, 3). Even activities of daily living, such as the ability to put on shoes and socks or bend to collect an object from the ground can be negatively affected by poor flexibility, impacting an individual's physical independence. In ageing populations, poor joint mobility can compromise balance (7) and gait (8) contributing to an increased chance of falling (9). Another, more clinical example is the inability of people with diabetes to inspect their extremities due to poor flexibility, which could have serious health consequences due to a lack of appropriate monitoring of ulcers and sores. Furthermore, ROM can be compromised in other clinical populations, such as when stroke, arthritis, muscular dystrophy, cystic fibrosis, cerebral palsy and other conditions adversely affect health and functional ability.

An increased resistance to stretch can make daily movements more difficult. The extent of passive and active stretch resistance may be related to the degree of collagenous perimysial tissue (10-12) as well as the number of strongly (during active muscle contraction) and possibly to a small degree, weakly bound (during muscle lengthening) cross-bridge attachments between the myofilaments (13-15). During rapid stretches, reflexive activation of the stretched muscle as well as viscous effects will add to the resistance to stretch. Decreasing the stretch resistance reduces the resistance to the intended movement and improves movement efficiency (3, 16, 17), whether for an athlete or during locomotion (e.g., walking and stair climbing) for a senior adult, impacting movement and both musculoskeletal and overall health. With such potential musculoskeletal benefits of an increased ROM and decreased resistance to stretch during ROM, it might be expected that static stretching (SS) should be universally promoted.

Additionally, substantial static stretch-related cardiovascular and stress-related health benefits have been reported (18), with moderate magnitude improvements in cardiovascular parameters such as reduced arterial stiffness (19, 20) and endothelium-dependent vasodilation and angiogenesis (21) following both acute and chronic stretching. The consistent application of SS can induce greater parasympathetic influence (22) and also reduce chronic stress, stress perception, and cortisol release (23). Thus, the health benefits associated with stretching training, in addition to increases in ROM and decreased resistance, are both strong and convincing.

An expansive body of literature has reported performance impairments shortly following prolonged SS (>60 s per muscle group) when performed without additional dynamic warm-up activities (1, 2, 24-26). SS involves lengthening a muscle-tendon unit (MTU) until a given level of stretch sensation or to the point of discomfort, and then holding the MTU in a lengthened position for a prescribed period of time (2, 24, 27, 28). This literature detailing the potential negative acute effects of SS on force production led to a paradigm shift from the promotion of SS to its near exclusion, particularly as an essential component of a pre-exercise warm-up (3). Nonetheless, when appropriate durations of SS (<60 s per muscle group) are incorporated into a full pre-exercise warm-up (comprising of aerobic activity, static and dynamic stretching (DS), and dynamic activity), the evidence shows only trivial effects on subsequent strength, power, agility, sprint and muscle endurance among other performance measures (1, 2, 29-32). Although these pre-activity stretching recommendations have been published in reviews since 2011 (1, 2, 24-26), there is still some reluctance to promote and incorporate SS into fitness and health regimens.

While the limitations in study designs used to examine the effects of pre-exercise SS (see Appendix; Supplement 7 in Behm et al. (2)) have sown some mistrust in the use of SS for pre-exercise preparation, there is also conflict and confusion regarding its efficacy for reducing musculotendinous injury incidence (2), overuse injuries (e.g., distance running) (33) or all-cause injury incidence (34-36).

Although, the focus of stretching is typically to increase the extensibility (defined as the ability of a muscle to extend to a predetermined endpoint) of muscles and tendons (37) to increase joint ROM (musculoskeletal and connective tissue components), stretching can have widespread effects on injury incidence and balance. The potential effects of stretching on these factors are of substantial clinical importance for the health and independence of individuals in athletic, aged, and a range of clinical populations. The objective of this narrative review is to examine the impact of acute and chronic stretching on factors that could influence health issues such as injury incidence and balance.

Injury incidence

Traditionally, stretching was purported to increase ROM and consequently decrease injury incidence (3, 38). However, there is a lack of consistent evidence for this effect on injuries (1-5), which may be linked to the type of injuries reported in many studies. With regard to randomized, controlled trials of the effect of SS during warm-up on injury risk, the initial evidence came predominately from studies with military personnel. Pope et al. (39) examined Australian military personnel over 12 weeks of training and reported a significant correlation between dorsiflexion ROM and injury incidence (ankle sprains, tibia or foot stress fractures, tibial periostitis, Achilles tendinopathy and anterior tibial component syndrome). In that study, having a limited ROM increased the risk for injury 2.5-fold compared to individuals with average dorsiflexion ROM and eight-fold greater risk than individuals with high levels of flexibility. Similar relationships have more recently been reported in a systematic review (27 articles) of a general adult population by de la Motte et al. (40), who provided moderate evidence that increased hamstrings and plantar flexors extensibility were associated with decreased musculoskeletal injury risk. However, when a 12-week dorsiflexion stretch training program (2 × 20-s calf muscle stretches before vigorous exercise sessions) for the Australian military was instituted by Pope et al. (39), no statistical effect on injury incidence was detected. A subsequent study in which recruits who were undertaking 12 weeks of basic training stretched each of six lower leg muscles before all physical training sessions (41) again did not reveal a clinically worthwhile reduction in all-cause lower limb injury incidence (including lower body stress fractures, muscle strains, ligament sprains, periostitis, tendinopathy meniscal lesions, compartment syndromes, bursitis among others). Together, the studies by Pope et al. indicate that whilst intrinsic levels of flexibility (ROM) are associated with injury incidence, the imposition of stretch training programs may not influence overall injury rates, at least in military personnel who presumably perform many activities that would not be commonly performed during standard exercise or sports session. However, their data also indicate a lower incidence of thigh muscle strains (80%: 10 vs. 2 injuries with stretch training group) and ankle joint injuries (30%: 27 vs. 19 injuries in the stretch trained group) within the cohort. These were not specifically (independently) submitted to statistical analysis within the study, but were reflected in several reviews (35, 42) that reported a lack of significant reduction in all-cause injury risk in response to chronic stretching. Consistent with these specific data, Amako et al. (43) compared military personnel who performed pre-exercise SS of 18 muscle groups over a 3-month period and found no effect on all-cause injury risk but a significant reduction in musculotendinous injuries (and low back pain) in the SS group (13 injuries in 518 recruits in SS vs. 22 injuries in 383 recruits in control). A similar lack of significant or clinically important positive effects of SS on all-cause injury risk was reported in a 12-week randomized control trial (30 s SS of seven lower limb and trunk muscle groups before and after physical activity) of 2377 physically active adults (44). Despite these data, Weldon and Hill (36) lamented the paucity of well controlled studies and speculated that pre-exercise stretching might even increase injury risk. They speculated that injury risk could be increased due to a stretch-induced elevation of the pain (stretch) threshold, allowing individuals to elongate muscles or tendons beyond a point of damage or when performing high intensity stretching that induced minor muscle damage. Whilst there is no evidence of an increase in injury risk, it is potentially problematic that few randomized, controlled trials have been completed in sports and exercise populations, the quality of these randomized controlled trials is generally low, they do not investigate the effect of pre-exercise stretching on musculotendinous injuries and none include elderly or clinical populations.

It is important when reviewing the literature to be cognizant of the type of injuries examined. A review by Behm et al. (2), reported that eight studies showed some effectiveness of chronic stretching for reducing injury incidence, whereas four other studies indicated no significant effect. In a randomised, single-blind, non-supervised (self-reports), controlled trial, self-reported muscle, ligament, and tendon injuries were reduced in distance runners (2125 participants with 687 people reporting at least one injury) who chronically stretched before and after running for 12 weeks (0.66 injuries per person-year in stretch group, vs. 0.88 injuries per person-year in control) (44). Additionally, Woods et al. (45) concluded that chronic stretch training, performed with or without warm-up before exercise, was associated with a lower incidence of MTU injuries. Furthermore, Azuma and Someya (46) incorporated a 12-week stretching program with male high school soccer players finding an improved ROM and a decrease in muscle tightness, which they indicated may have contributed to the reduction in non-contact lower limb and trunk injuries as well as muscle and tendon injuries after training. Based on this evidence, while stretching may not consistently attenuate all-cause injury risk, a small-moderate positive effect of chronic SS on MTU injury risk in running-based and jump-based sports is observed (38, 47).

Pre-exercise bouts of stretching can also have positive effects on reducing subsequent injuries. For example, the Behm et al. (2) review summarized that pre-exercise stretching of 5 minutes or more should provide greater sprint running-related injury prevention but would be less effective in reducing overuse injuries, such as with endurance running activities. They found a mean 54% injury risk reduction across studies in MTU injuries when acute (i.e., pre-exercise) SS was completed (2). Similarly, a review by Fradkin et al. (34) reported that 3 of 5 studies reviewed showed significant decreases in all cause injury risk when a warm-up including stretching was performed before exercise and a lack of evidence that stretching could increase injury incidence. McKay et al. (48) monitored three elite (22% of study participants) and three recreational (78% of study participants) competitions with over 10,000 players and reported that basketball players who did not stretch before a game had a 2.6-fold greater likelihood of ankle injuries compared to players who did stretch. Dadebo (49) found that implementing SS in a warm-up (recommendation: 4 × 15-30 s) was associated with reduced hamstring strains in Premiership soccer players in England. Also, Cross and Worrell (50) reported a 50% reduction in muscle-tendon strains (195 American football players) when SS was performed in a warm-up during the 1995 season compared to without SS in the 1994 season. Based on such evidence, Small et al. (35) concluded in their review that there was moderate-to-strong evidence that SS did not attenuate overall injury rates but may reduce MTU injuries. Thus, an acute bout of pre-exercise stretching may influence injury across soft tissue types. Based on the aforementioned reports, there seems to be a reasonable (moderate) effect of acute SS within a pre-exercise warm-up on the attenuation of MTU injuries, but further randomized, controlled trials are needed in order to establish a higher level of evidence.

Since acute ballistic stretching (a type of DS involving a bouncing motion that moves the limb into an extended ROM (24)) can significantly increase tendon compliance (51), Witvrouw et al. (52) considered that ballistic stretching-induced reductions in tendon stiffness might ensure a high energy-absorbing capacity to store and release a large amount of elastic energy during subsequent, intense stretch-shortening cycle type activities. Therefore, they recommended ballistic stretching to prevent tendon injuries associated with intense stretch-shortening cycle activities. Additionally, a recent "expert consensus" statement (53) argued for the inclusion of pre-exercise ballistic stretching as part of an injury-prevention program for athletes. In contrast, other researchers (54, 55) have recently stressed the importance of a higher tendon stiffness, particularly in relation to imbalances between muscle strength and tendon stiffness, for the prevention of tendon injuries. Arampatzis et al. (55) suggest that tendon deformation (i.e., strain) may be important from a functional performance perspective, but that excessive deformation (compliance) could be related to tendon structural impairment. They suggest that there should be a significant association between, and simultaneous training-related adaptations in, muscle strength and tendon stiffness (54, 55). However, while the tendon stiffness-to-muscle strength ratio of individual tendon fibres must be high, the role of overall tendon stiffness in the prevention of injury may also be related to the efficiency of sliding between collagen fibres and fascicles (56, 57), which can provide a dissipation of forces over a greater distance and time. Whilst individual MTU fibres must have sufficient stiffness to accommodate the high strains imposed during sprint running, jumping and other activities, there is also a need for architectural adaptations and responses such as muscle and tendon fascicle rotation and translation (sliding). Therefore, a specific 'stiffness' of the tendon may not be the critical factor influencing injury, and further research is required to understand the role of tendon stiffness and potential effects of muscle stretching on it.

With regards to specific evidence for or against the role of DS, no clear data are available. Ekstrand et al. (58) noted in 180 soccer players that "Hamstring strains were most common in teams not using special flexibility exercises for these muscles (t = 2.1)…but all stretching exercises were of the dynamic type and short duration…", in reference to the stretching practices of players during warm-up. Zakaria et al. (59) compared SS + DS to DS alone in high school soccer athletes and detected no difference in lower back and extremity injuries when implementing DS versus the SS + DS combination. However, they did not compare to a non-stretch control group so the overall effect of stretching cannot be determined. Therefore, there is currently no clear evidence on which to draw conclusions as to the effects of DS on injury risk during warm-up for sports or exercise.

Changes in MTU injury incidence in response to chronic stretching may be related to a shift in the active muscle force-length relationship (60-62). As stretching shifts the active muscle length-tension relationship towards longer lengths (60-62), force output is improved at those longer muscle lengths (63-67). Ruan et al. (68) found that both the length of biceps femoris long head to knee torque relationship and biceps femoris long head to hip torque relationship during sprinting were shifted to the right after acute SS, and thus hypothesized this shift could reduce the risk of hamstrings strain injury. Speculatively, for MTU injuries that occur at longer muscle lengths, the ability to generate force or absorb (or dissipate) energy at longer muscle lengths should decrease MTU injury risk. Furthermore, a more compliant MTU (69-72) would have a greater capacity to absorb higher tensile forces (52). Science findings are rarely universal as Barbosa et al. (73) reported contradictory results indicating that following 3 stretching sessions per week for 10 weeks (3 sets of 30 s of SS), there was a significant 15.4% decrease in hamstrings eccentric peak torque, which could contribute to hamstrings strain injuries.

A lack of proprioception (joint and muscle position sense) could adversely affect motor control (motor efferent responses to sensory afferent information) that may impair anticipatory and immediate responses to changes in the environment, leading to injuries. The literature examining the effect of acute SS on proprioception is equivocal with contract-relax proprioceptive neuromuscular facilitation (PNF) stretching (3 × 5-s contraction followed by 20 s of stretch) of the shoulders (74) and SS (3 × 30-s) of knee extensors and flexors (75) showing no effect on respective joint position sense. However, using a similar duration of stretch (3 × 30-s) of the knee extensors and flexors, Ghaffarinejad et al. (76) reported improved knee joint position sense, and both SS (2 × 90-s) and DS (3 × 12 repetitions) of the quadriceps and hamstrings improved knee joint position sense in the study of Walsh (77). Hence, the lack of extensive literature on stretch-induced changes in proprioception does not permit a definite conclusion to be drawn, and thus more research is needed in this area. Regardless, there appears to be no evidence of a decrement in proprioception after acute static or PNF stretching, so stretching may be used without consequence in this regard. However, the effects of chronic stretching on proprioception are yet to be defined.

In summary, while pre-exercise and chronic muscle stretching cannot be expected to decrease all-cause injuries (i.e., fractures, cartilaginous injuries, joint inflammation among many others), the literature does provide moderate evidence for greater protection from MTU injuries, which might speculatively result from alterations in tissue (muscle or tendon) compliance or shifts in the active force-length relation towards longer muscle lengths. Additional randomized, controlled trials are required in sports and exercise populations in order to improve the level of evidence available.

Balance

Balance is essential for most activities of daily living, with static and dynamic balance deficits contributing to falls and related injuries especially in the elderly (78). Falls contribute to 95% of hip fractures in seniors (79), and is the most common cause of traumatic brain injury (80). Strategies to attenuate falls would not only improve health outcomes but also reduce health care costs (81).

There are conflicting reports regarding the acute effect of stretching on balance. Several measures of balance (static balance, increased centre of pressure area, or postural sway) were impaired following either 1 repetition of 30 s (82), 3 repetitions of 45 s (28, 83), 6 repetitions of 45 s (84), or 3 min (85) or 5 min (86) of SS, respectively. These results contrast with reported improved balance following a bilateral intermittent SS (5 repetitions of 1 min; 15 s of rest) protocol (87). Seven minutes of DS (a controlled movement through the ROM of the active joint[s]) provided greater reductions in centre of mass perturbations (i.e., stability / balance) during jumping (squat, countermovement and drop jumps) tasks (88) as well as greater balance improvements on a dynamic stability platform (82) compared to 7 min of SS. There are also reports of similar small magnitude improvements in balance (star excursion balance test) following either 10-to-30 min (15-s repetitions) of SS or DS (89). Costa et al. (90) reported that 2 × 45 s of SS had no adverse effects on balance (Biodex balance system involves a movable circular platform that can tilt 20^0), whereas a 2 × 15-s SS protocol evoked a significant improvement. Furthermore, Handrakis et al. (91) and Nelson et al. (92) reported improved dynamic balance (single leg balance on a Balance System SD movable platform) and postural sway (time to maintain a stabilometer horizontal over two 30 s periods) after 10 min and 20 min of total SS, respectively. Alternatively, contract-relax PNF stretching has been reported to improve dynamic balance on a Biodex balance system and stabilometric platform (93, 94) as well as impair dynamic balance on a stabilometric platform

(95). With the literature demonstrating similar number of SS articles reporting either improved and impaired balance with SS, more research is necessary to ascertain whether SS is more likely to be beneficial or detrimental to balance and under which conditions it might have these different effects. Alternatively, as the three DS articles all report positive effects on balance, DS may be a more reliable recommendation.

A major limitation of the stretch and balance research is the implementation of unrealistic stretching durations in many studies (1-3, 26). While the average stretch durations of American professional and collegiate athletes are 12-30 s per muscle group (96-104) and most guidelines suggest several (2 – 4) repetitions of 15-30 s stretches, stretches in many studies are often imposed for several minutes or even up to 20-to-30 min per muscle group (105, 106). Reviews of the literature have demonstrated that less than 60 s of SS results in trivial effects on subsequent performance, especially when incorporated into a full warm-up that included prior aerobic activity and post-stretch dynamic activities (1-3, 24, 26). However, in relation to balance measures, both improvements (90) and impairments (82) have been observed with 30 s of SS. Furthermore, balance deficits were reported after 135 s (28) of quadriceps, hamstrings, and plantar flexor (PF) stretching (28, 83) as well as 270 s (84), 3 min (85) and 5 min (86) of PF SS. Nonetheless, enhancement of balance was also reported after 5 min (87) and 10 min (91) of low back, hip and knee extensors, knee flexors, and 20 min (92) of hip, knee and ankle joints of total SS. Thus, the recommended maximum of 60 s of SS per muscle group for trivial strength, power, sprint and other performance impairments is not a consistent parameter for balance impairments or enhancements. While the majority of studies reported PF stretching to have both negative and positive consequences, there were also both impairments and improvements when stretching multiple lower body muscle groups. All of the aforementioned studies examined the effects in either young adults or adolescents, so it is unclear whether the findings are relevant to older adults.

The results of balance tests did not reveal a sex-dependent trend, with most studies including both men and women and only two studies involving only women (82, 90) and one study only men (85). With such diversity of results, it is difficult to draw firm conclusions regarding the benefits or costs of acute bouts of muscle SS or DS on balance performance, especially in balance-impaired older individuals where a paucity of research exists. Hence, additional research is needed to clarify the effect of different types, volumes and intensity of stretching on balance.

Reported balance deficits following acute stretching might be related to its effects on proprioception so it is worth briefly examining this possibility. Recent evidence suggests that longer periods of intermittent SS (5 × 60-s PF stretches) might acutely reduce activity in spino-cerebellar pathways (107), which might be expected to influence balance and stability. However, whereas ankle motion sense (proprioception) has been shown to be impaired following 6 × 40-s SS (108), no significant effect on knee joint position sense was detected after 3 × 30-s SS (75), contrasting with improved knee joint proprioception also following 3 × 30-s of SS (76). The ability to react to perturbations affecting stability and balance would not only be regulated by vestibular and proprioceptive afferent and efferent responses (109, 110) but the musculotendinous system would also need to react with sufficient force and speed to overcome the perturbation and return the centre of gravity to within the base of support (metastability (111)). Acute bouts of SS have been reported to reduce passive musculotendinous unit (MTU) stiffness within the knee flexors and extensors and PF (112). In a more compliant system, greater shortening of the contractile element is required to stretch the series elastic components in order to increase overall MTU stiffness and thus for an external force (joint torque) to be exerted. However, when interpreting the literature, it is important to differentiate between passive and active muscle stiffness (stiffness properties measured during dynamic muscle contractions). Factors affecting passive MTU stiffness do not substantially influence maximal voluntary muscle force output (1). Active and passive muscle stiffness are not related when measured in *ex vivo* experiments (113) and when measured in the PF (114, 115) or knee flexors (116). Furthermore, reductions in passive MTU stiffness are reported without modifications in active stiffness following a bout of static PF stretching (117). Thus, whereas stretch-induced reductions in passive MTU stiffness can occur, it is unlikely that a concomitant reduction would occur in active MTU stiffness. Another contributing factor to active MTU stiffness would be the role of co-contractions during an erect stance to modulate or maintain the active stiffness of the joint(s) (118). Hence, increased passive compliance may not play a substantive disruptive role in balance, and the effects of stretching on active muscle stiffness during balance tasks have yet to be studied.

An alternative viewpoint might be that a more compliant system would be better able to absorb disruptive perturbations (52), attenuating centre of mass translocations and increasing the chance that the body's centre of mass would remain within the base of support (i.e., enhanced metastability or balance). A more compliant MTU system (i.e., less stiff), which could absorb the disruptive perturbation over a prolonged duration, could permit greater sensory (afferent) feedback and efferent postural adjustments. In retrospect, individuals may need a proportionality between stiffness and compliance. A stiffer MTU might permit a rapid force-dependent reaction to balance perturbations whereas an appropriate degree of MTU compliance might allow absorption of energy produced during perturbation in order to allow the centre of mass to remain within the base of support (i.e., a 'Goldilocks zone'; (3)). Whilst the few DS studies show balance improvements, SS studies demonstrating deficits (conflicting with those similar number of SS studies that show improvements or no change) might be attributed to non-practical choices within their experimental protocols or to possible adverse effects on proprioception. However, more research is needed to assess the influence of changes in active and passive MTU stiffness.

Another important question to ask is whether chronic stretch training provides an overall benefit to balance capacity. Few studies have examined the effect of stretch training on balance. SS training 4 days per week for 6 weeks of young university aged males improved static balance time (unilateral stance on forefoot with eyes open), while there was a non-significant ($p=0.078$) improvement after PNF stretching (119). Also, a 10-week SS training program of five lower extremity muscles (2 days per week: 3 × 30 s) in high school students improved unilateral stance on a balance beam (1-min Flamingo balance test with dominant leg). The possible improvements in balance with stretch training might be partially attributed to the aforementioned prolongation of disruptive torques by a more compliant system allowing the neuromuscular system more time to adjust and react to these perturbations. Moreover, an augmented ROM may allow an individual to extend farther and closer to the limit of their base of support and return without losing their balance (improved metastability). For example, Hoch et al. (120) reported that an individual's maximum dorsiflexion ROM explained a significant proportion of the variance in anterior reach distance in the Star Excursion Balance Test. In addition, when losing balance or falling, an individual may need to reach out with an extended leg beyond the optimum point on their muscle force-length relationship. With stretching, the active length-tension relationship is shifted towards longer muscle lengths (60-62), with force reductions at short muscle lengths contrasting with moderate improvements at longer muscle lengths (63-67). Thus, following a stretch training program in which ROM and force capacity at long muscle lengths are increased, an individual who is falling may be able to move a limb further to increase their base of support and react more forcefully whilst landing in an extended and unbalanced position. Nonetheless, this specific hypothesis remains to be explicitly tested.

In summary, whilst the effects on balance of an acute bout of DS may be beneficial and the effects of SS equivocal, chronic stretch training may provide benefits and help to reduce the incidence of falls and thus the associated injuries and negative health consequences. The mechanisms underlying these benefits may be related to an increased MTU compliance or ROM allowing the individual to accommodate greater disruptive perturbations and deviations from their base of support and then to react more forcefully from an extended joint position (due to altered muscle force-length relationship) when balance is disrupted.

Conclusion

In summary, there is little evidence that pre-exercise stretching (of either static or dynamic type) decreases all-cause injury risk, but there is stronger evidence for a static stretch-induced reduction in musculotendinous injuries, particularly in running-based sports (Figure 1). However, additional randomized, controlled trials in sports and exercise populations (including elderly, clinical and others) are required in order to provide a higher level of evidence. Nonetheless, there is insufficient evidence on which to base a recommendation for the role of acute or chronic dynamic stretching on injury risk. While the effect of an acute bout of static stretching on balance is equivocal, chronic static stretch training may provide balance benefits, which may then contribute to a reduction in the incidence of falls and associated injuries (Figure 1). In addition, dynamic stretching generally shows favourable effects upon balance and should be incorporated into acute and chronic stretch training programs. Mechanisms underlying these benefits may include an increased musculotendinous compliance and range of motion, allowing an individual to accommodate and respond more efficiently to balance threats. However, adaptations within sensory (e.g., spinothalamic) pathways cannot be ruled out. In conclusion, whilst acute (e.g., pre-exercise) static muscle stretching may provide a small reduction specifically in muscle and musculotendinous injury risks, particularly in running-based sports, chronic stretching training appears to have a moderate impact on muscle injury risk and both standing and walking balance and can therefore be recommended as part of a holistic clinical program. There is no evidence of the effect of dynamic stretching (either pre-exercise or chronic) on injury risk, but its use may provide an acute benefit to balance performance and thus may influence fall risk.

Side Bar #1

Stretching prescriptions for:

1. Chronic increase in range of motion (ROM)
    a. Separate training session distinct from warm-up activities
    b. 2-6 days per week
    c. 30 to 60 s per muscle group
    d. Minimum 5 min per week per muscle group
    e. 60-100% of stretch tolerance (point of discomfort).

2. Pre-activity preparation for athletic performance to acutely increase ROM, having trivial or positive effects on performance (e.g., strength, power, agility, sprint), and providing pre-event psychological preparation
    a. <60-s of static stretching per muscle group
    b. Within a full warm-up that includes initial ≥5-min aerobic activity, static and dynamic stretching (≥90-s per muscle group) and subsequent 5-15 min of dynamic sport or task-specific activities.

3. Reduction in musculotendinous injury incidence
    a. Chronic static and acute ballistic (increased tendon compliance) stretching
    b. ≥30 s per muscle group (may perform multiple shorter stretches to achieve total time)
    c. ≥5 min per target muscle groups (e.g., stretching for running would involve ≥5 min of stretching of the quadriceps, hamstrings, triceps surae, hip adductors and abductors before lower-limb activities such as walking, running and jumping).

Side Bar #2

Unique research findings on stretching:

1. Commonly reported static stretching-induced performance impairments are often due to inappropriate or invalid experimental protocols (1, 2, 3, 22, 24), including:
    a. >60-s of static stretching per muscle group
    b. Lack of a full complement of warm-up activities
    c. Testing/performing immediately after stretching when most sport activities commence 5 to 15 min post-stretching
    d. Nocebo effects of using student subjects who have been instructed and expect to experience deficits with static stretching (self-fulfilling prophecy)
    e. Reporting bias: statistically significant results are more likely to be published

2. Static stretching can provide cardiovascular and stress health benefits (16-21), including:
    a. Reduced arterial stiffness
    b. Angiogenesis (increased blood vessel proliferation)
    c. Improved vasodilation
    d. Greater parasympathetic influence
    e. Reduced chronic stress

3. Static stretching can reduce musculotendinous injury incidence, especially in explosive and sprint activities but has trivial effects on all-cause injury risk (2, 33, 36, 42, 43, 44).

4. Acute dynamic stretching may improve balance (73, 79, 80, 82, 83), while static stretching may either increase or decrease balance (not yet known under which conditions each outcome is likely).

Compliance with Ethical Standards

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References

1. Behm DG, Kay AD, Trajano GS, Blazevich AJ. Mechanisms underlying performance impairments following prolonged static stretching without a comprehensive warm-up. *Eur J Appl Physiol.* 2020;121:67–94. doi: 10.1007/s00421-020-04538-8
2. Behm DG, Blazevich AJ, Kay AD, McHugh M. Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: a systematic review. *Appl Physiol Nutr Metab.* 2016;41(1):1-11.
3. Behm DG. The Science and Physiology of Flexibility and Stretching: Implications and Applications in Sport Performance and Health. London, UK.: Routledge Publishers; 2018. 100 p.
4. Decoster LC. Effects of hamstring stretching on range of motion: A systematic review updated. *Athletic Training & Sports Health Care.* 2009;1(5):209-13.
5. Radford JA, Burns J, Buchbinder R, Landorf KB, Cook C. Does stretching increase ankle dorsiflexion range of motion? A systematic review. *Br J Sports Med.* 2006;40(10):870-875.
6. Behm DG, Alizadeh S, Anvar SH, Drury B, Granacher U, Moran J. Non-local acute passive stretching effects on range of motion in healthy adults: A Systematic Review with Meta-analysis. *Sports Med.* 2021. doi: 10.1007/s40279-020-01422-5
7. Emilio EJ, Hita-Contreras F, Jimenez-Lara PM, Latorre-Roman P, Martinez-Amat A. The association of flexibility, balance, and lumbar strength with balance ability: risk of falls in older adults. *J Sports Sci Med.* 2014;13(2):349-57.
8. Christiansen CL. The effects of hip and ankle stretching on gait function of older people. *Arch Phys Med Rehabil.* 2008;89(8):1421-8.
9. Gonzalez-Rave JM, Sanchez-Gomez A, Santos-Garcia DJ. Efficacy of two different stretch training programs (passive vs. proprioceptive neuromuscular facilitation) on shoulder and hip range of motion in older people. *J Strength Cond Res.* 2012;26(4):1045-51.
10. Borg TK, Caulfield JB. Morphology of connective tissue in skeletal muscle. *Tissue Cell.* 1980;12(1):197-207.
11. Purslow PP. Strain-induced reorientation of an intramuscular connective tissue network: implications for passive muscle elasticity. *J Biomech.* 1989;22(1):21-31.
12. Williams PE, Goldspink G. Connective tissue changes in immobilised muscle. *J Anat.* 1984;138 (Pt 2):343-50.
13. Fusi L, Reconditi M, Linari M, Brunello E, Elangovan R, Lombardi V, et al. The mechanism of the resistance to stretch of isometrically contracting single muscle fibres. *J Physiol.* 2010;588(Pt 3):495-510.
14. Bartoo ML, Linke WA, Pollack GH. Basis of passive tension and stiffness in isolated rabbit myofibrils. *Am J Physiol.* 1997;273(1 Pt 1):C266-76.
15. Granzier HL, Wang K. Passive tension and stiffness of vertebrate skeletal and insect flight muscles: the contribution of weak cross-bridges and elastic filaments. *Biophys J.* 1993;65(5):2141-59.
16. Kay AD, Blazevich A.J. Reductions in active plantar flexor moment are significantly correlated with static stretch duration. *Eur J Sport Sci.* 2008;8:41-6.
17. Kay AD, Blazevich AJ. Moderate-duration static stretch reduces active and passive plantar flexor moment but not Achilles tendon stiffness or active muscle length. *J Appl Physiol.* 2009;106(4):1249-56.
18. Thomas E, Bellafiore M, Gentile A, Paoli A, Palma A, Bianco A. Cardiovascular responses to muscle stretching: A systematic review and meta-analysis. *Int J Sports Med.* 2021. doi: 10.1055/a-1312-7131

19. Bisconti AV, Ce E, Longo S, Venturelli M, Coratella G, Limonta E, et al. Evidence for improved systemic and local vascular function after long-term passive static stretching training of the musculoskeletal system. *J Physiol.* 2020;598(17):3645-66.
20. Yamamoto K, Kawano H, Gando Y, Iemitsu M, Murakami H, Sanada K, et al. Poor trunk flexibility is associated with arterial stiffening. *Am J Physiol Heart Circ Physiol.* 2009;297(4):H1314-H8.
21. Hotta K, Behnke BJ, Arjmandi B, Ghosh P, Chen B, Brooks R, et al. Daily muscle stretching enhances blood flow, endothelial function, capillarity, vascular volume and connectivity in aged skeletal muscle. *J Physiol.* 2018;596(10):1903-17.
22. Inami TS, T.; Baba, R.; Nakagaki, A. Acute changes in autonomic nerve activity during passive static stretching. *Amer J Sports Sci Med.* 2014;2(4):166-70.
23. Corey SM, Epel E, Schembri M, Pawlowsky SB, Cole RJ, Araneta MR, et al. Effect of restorative yoga vs. stretching on diurnal cortisol dynamics and psychosocial outcomes in individuals with the metabolic syndrome: the PRYSMS randomized controlled trial. *Psychoneuroendocrinol.* 2014;49:260-71.
24. Behm DG, Chaouachi A. A review of the acute effects of static and dynamic stretching on performance. *Eur J Appl Physiol.* 2011;111(11):2633-51.
25. Chaabene H, Behm DG, Negra Y, Granacher U. Acute Effects of Static Stretching on Muscle Strength and Power: An Attempt to Clarify Previous Caveats. *Front Physiol.* 2019;10:1468.
26. Kay AD, Blazevich AJ. Effect of acute static stretch on maximal muscle performance: a systematic review. *Med Sci Sports Exerc.* 2012;44(1):154-64.
27. Cronin J, Nash M, Whatman C. The acute effects of hamstring stretching and vibration on dynamic knee joint range of motion and jump performance. *Phys Ther Sport.* 2008;9(2):89-96.
28. Behm DG, Bambury A, Cahill F, Power K. Effect of acute static stretching on force, balance, reaction time, and movement time. *Med Sci Sports Exerc.* 2004;36(8):1397-402.
29. Blazevich AJ, Gill ND, Kvorning T, Kay AD, Goh AG, Hilton B, et al. No effect of muscle stretching within a full, dynamic warm-up on athletic performance. *Med Sci Sports Exerc.* 2018;50(6):1258-66.
30. Murphy JR, Di Santo MC, Alkanani T, Behm DG. Aerobic activity before and following short-duration static stretching improves range of motion and performance vs. a traditional warm-up. *Appl Physiol Nutr Metab.* 2010;35(5):679-90.
31. Reid JC, Greene R, Young JD, Hodgson DD, Blazevich AJ, Behm DG. The effects of different durations of static stretching within a comprehensive warm-up on voluntary and evoked contractile properties. *Eur J Appl Physiol.* 2018;118(7):1427-45.
32. Samson M, Button DC, Chaouachi A, Behm DG. Effects of dynamic and static stretching within general and activity specific warm-up protocols. *J Sports Sci Med.* 2012;11(2):279-85.
33. Baxter C, Mc Naughton LR, Sparks A, Norton L, Bentley D. Impact of stretching on the performance and injury risk of long-distance runners. *Res Sports Med.* 2017;25(1):78-90.
34. Fradkin AJ, Gabbe BJ, Cameron PA. Does warming up prevent injury in sport? The evidence from randomised controlled trials? *J Sci Med Sport.* 2006;9(3):214-20.
35. Small K, McNaughton NL, Matthews M. A systematic review into the efficacy of static stretching as part of a warm-up for the prevention of exercise-related injury. *Res Sports Med.* 2008;16(3):213-31.
36. Weldon SM, Hill RH. The efficacy of stretching for prevention of exercise-related injury: a systematic review of the literature. *Man Ther.* 2003;8(3):141-50.
37. Weppler CH, Magnusson SP. Increasing muscle extensibility: a matter of increasing length or modifying sensation? *Phys Ther.* 2010;90(3):438-49.

38. Witvrouw E, Mahieu N, Danneels L, McNair P. Stretching and injury prevention: an obscure relationship. *Sports Med.* 2004;34(7):443-9.
39. Pope R, Herbert R, Kirwan J. Effects of ankle dorsiflexion range and pre-exercise calf muscle stretching on injury risk in army recruits. *Australian Physiother*. 1998;44(3):165-77.
40. de la Motte SJ, Lisman P, Gribbin TC, Murphy K, Deuster PA. Systematic review of the association between physical fitness and musculoskeletal injury risk: Part 3-Flexibility, Power, Speed, Balance, and Agility. *J Strength Cond Res.* 2019;33(6):1723-35.
41. Pope R, Herbert R, Kirwan J, Graham B. A randomized trial of preexercise stretching for prevention of lower-limb injury. *Med Sci Sports Exerc.* 2000;32(2):271-7.
42. Shrier I. Does stretching improve performance?: a systematic and critical review of the literature. *Clin J Sport Med.* 2004;14(5):267-73.
43. Amako M, Oda T, Masuoka K, Yokoi H, Campisi P. Effect of static stretching on prevention of injuries for military recruits. *Mil Med.* 2003;168(6):442-6.
44. Jamtvedt G, Herbert RD, Flottorp S, Odgaard-Jensen J, Havelsrud K, Barratt A, et al. A pragmatic randomised trial of stretching before and after physical activity to prevent injury and soreness. *Br J Sports Med.* 2010;44(14):1002-9.
45. Woods K, Bishop P, Jones E. Warm-up and stretching in the prevention of muscular injury. *Sports Med.* 2007;37(12):1089-99.
46. Azuma N, Someya F. Injury prevention effects of stretching exercise intervention by physical therapists in male high school soccer players. *Scand J Med Sci Sports.* 2020;30(11):2178-92.
47. McHugh MP, Cosgrave CH. To stretch or not to stretch: the role of stretching in injury prevention and performance. *Scand J Med Sci Sports*. 2010;20(2):169-81.
48. McKay GD, Goldie PA, Payne WR, Oakes BW. Ankle injuries in basketball: injury rate and risk factors. *Br J Sports Med.* 2001;35(2):103-8.
49. Dadebo B, White J, George KP. A survey of flexibility training protocols and hamstring strains in professional football clubs in England. *Br J Sports Med*. 2004;38(4):388-94.
50. Cross K, Worrell T. Effects of a static stretching program on the incidence of lower extremity musculotendinous strains. *J Athletic Training*. 1999;34(1):11-4.
51. Mahieu NN, McNair P, De MM, Stevens V, Blanckaert I, Smits N, et al. Effect of static and ballistic stretching on the muscle-tendon tissue properties. *Med Sci Sports Exerc.* 2007;39(3):494-501.
52. Witvrouw E, Mahieu N, Roosen P, McNair P. The role of stretching in tendon injuries. *Br J Sports Med.* 2007;41(4):224-6.
53. Donaldson A, Cook J, Gabbe B, Lloyd DG, Young W, Finch CF. Bridging the gap between content and context: establishing expert consensus on the content of an exercise training program to prevent lower-limb injuries. *Clin J Sport Med*. 2015;25(3):221-9.
54. Mersmann F, Bohm S, Arampatzis A. Imbalances in the development of muscle and tendon as risk factor for tendinopathies in youth athletes: A Review of Current Evidence and Concepts of Prevention. *Front Physiol.* 2017;8:987.
55. Arampatzis A, Mersmann F, Bohm S. Individualized muscle-tendon assessment and training. *Front Physiol.* 2020;11:723.
56. Thorpe CT, Udeze CP, Birch HL, Clegg PD, Screen HR. Capacity for sliding between tendon fascicles decreases with ageing in injury prone equine tendons: a possible mechanism for age-related tendinopathy? *Eur Cell Mater.* 2013;25:48-60.
57. Thorpe CT, Godinho MSC, Riley GP, Birch HL, Clegg PD, Screen HRC. The interfascicular matrix enables fascicle sliding and recovery in tendon, and behaves more elastically in energy storing tendons. *J Mech Behav Biomed Mater*. 2015;52:85-94.

58. Ekstrand J, Gillquist J, Moller M, Oberg B, Liljedahl SO. Incidence of soccer injuries and their relation to training and team success. *Am J Sports Med*. 1983;11(2):63-7.
59. Zakaria AA, Kiningham RB, Sen A. Effects of static and dynamic stretching on injury prevention in high school soccer athletes: A Randomized Trial. *J Sport Rehabil*. 2015;24(3):229-35.
60. Cramer JT, Beck TW, Housh TJ, Massey LL, Marek SM, Danglemeier S, et al. Acute effects of static stretching on characteristics of the isokinetic angle - torque relationship, surface electromyography, and mechanomyography. *J Sports Sci*. 2007;25(6):687-98.
61. Takeuchi K, Nakamura M. Influence of High Intensity 20-Second Static Stretching on the Flexibility and Strength of Hamstrings. *J Sports Sci Med*. 2020;19(2):429-35.
62. Weir DE, Tingley J, Elder GCB. Acute passive stretching alters the mechanical properties of human plantar flexors and the optimal angle for maximal voluntary contraction. *Eur J Appl Physiol.* 2005;93:614-23.
63. Balle SS, Magnusson SP, McHugh MP. Effects of contract-relax vs static stretching on stretch-induced strength loss and length-tension relationship. *Scand J Med Sci Sports*. 2015;25(6):764-9.
64. Herda TJ, Cramer JT, Ryan ED, McHugh MP, Stout JR. Acute effects of static versus dynamic stretching on isometric peak torque, electromyography, and mechanomyography of the biceps femoris muscle. *J Strength Cond Res.* 2008;22(3):809-17.
65. McHugh MP, Nesse M. Effect of stretching on strength loss and pain after eccentric exercise. *Med Sci Sports Exerc*. 2008;40(3):566-73.
66. McHugh MP, Tallent J, Johnson CD. The role of neural tension in stretch-induced strength loss. *J Strength Cond Res*. 2013;27(5):1327-32.
67. Nelson AG, Allen JD, Cornwell A, Kokkonen J. Inhibition of maximal voluntary isometric torque production by acute stretching is joint-angle specific. *Res Q Exerc Sport*. 2001;72(1):68-70.
68. Ruan M, Li L, Chen C, Wu X. Stretch could reduce hamstring injury risk during sprinting by right shifting the length-torque curve. *J Strength Cond Res*. 2018;32(8):2190-8.
69. Bouvier T, Opplert J, Cometti C, Babault N. Acute effects of static stretching on muscle-tendon mechanics of quadriceps and plantar flexor muscles. *Eur J Appl Physiol*. 2017;117(7):1309-15.
70. Konrad A, Reiner MM, Thaller S, Tilp M. The time course of muscle-tendon properties and function responses of a five-minute static stretching exercise. *Eur J Sport Sci*. 2019;19(9):1195-203.
71. Longo S, Ce E, Rampichini S, Devoto M, Venturelli M, Limonta E, et al. Correlation between stiffness and electromechanical delay components during muscle contraction and relaxation before and after static stretching. *J Electromyogr Kinesiol*. 2017;33:83-93.
72. Opplert J, Genty JB, Babault N. Do stretch durations affect muscle mechanical and neurophysiological properties? *Int J Sports Med*. 2016;37(9):673-9.
73. Barbosa GM, Trajano GS, Dantas GAF, Silva BR, Vieira WHB. Chronic effects of static and dynamic stretching on hamstrings eccentric strength and functional performance: A Randomized Controlled Trial. *J Strength Cond Res*. 2020;34(7):2031-9.
74. Bjorklund M, Djupsjobacka M, Crenshaw AG. Acute muscle stretching and shoulder position sense. *J Athl Train*. 2006;41(3):270-4.
75. Larsen R, Lund H, Christensen R, Rogind H, nneskiold-Samsoe B, Bliddal H. Effect of static stretching of quadriceps and hamstring muscles on knee joint position sense. *Br J Sports Med*. 2005;39(1):43-6.
76. Ghaffarinejad F, Taghizadeh S, Mohammadi F. Effect of static stretching of muscles surrounding the knee on knee joint position sense. *Br J Sports Med*. 2007;41(10):684-7.

77. Walsh GS. Effect of static and dynamic muscle stretching as part of warm up procedures on knee joint proprioception and strength. *Hum Mov Sci*. 2017;55:189-95.
78. Bergen G, Stevens MR, Burns ER. Falls and fall injuries among adults aged >/=65 Years - United States, 2014. MMWR *Morb Mortal Wkly Rep*. 2016;65(37):993-8.
79. Hayes WC, Myers ER, Morris JN, Gerhart TN, Yett HS, Lipsitz LA. Impact near the hip dominates fracture risk in elderly nursing home residents who fall. *Calcif Tissue Int.* 1993;52(3):192-8.
80. Jager TE, Weiss HB, Coben JH, Pepe PE. Traumatic brain injuries evaluated in U.S. emergency departments, 1992-1994. *Acad Emerg Med*. 2000;7(2):134-40.
81. Florence CS, Bergen G, Atherly A, Burns E, Stevens J, Drake C. Medical costs of fatal and nonfatal falls in older adults. *J Am Geriatr Soc*. 2018;66(4):693-8.
82. Chatzopoulos D, Galazoulas C, Patikas D, Kotzamanidis C. Acute effects of static and dynamic stretching on balance, agility, reaction time and movement time. J Sports Sci Med. 2014;13(2):403-9.
83. Hemmati L, Rojhani-Shirazi Z, Ebrahimi S. Effects of plantar flexor muscle static stretching alone and combined with massage on postural balance. *Ann Rehabil Med.* 2016;40(5):845-50.
84. Lima BN, Lucareli PR, Gomes WA, Silva JJ, Bley AS, Hartigan EH, et al. The acute effects of unilateral ankle plantar flexors static- stretching on postural sway and gastrocnemius muscle activity during single-leg balance tasks. *J Sports Sci Med*. 2014;13(3):564-70.
85. Nagano A, Yoshioka S, Hay DC, Himeno R, Fukashiro S. Influence of vision and static stretch of the calf muscles on postural sway during quiet standing. *Hum Mov Sci.* 2006;25(3):422-34.
86. Han MJ, Yuk GC, Gak H, Suh SR, Kim SG. Acute effects of 5 min of plantar flexor static stretching on balance and gait in the elderly. *J Phys Ther Sci*. 2014;26(1):131-3.
87. Martinez-Jimenez EM, Losa-Iglesias ME, Diaz-Velazquez JI, Becerro-De-Bengoa-Vallejo R, Palomo-Lopez P, Calvo-Lobo C, et al. Acute effects of intermittent versus continuous bilateral ankle plantar flexor static stretching on postural sway and plantar pressures: A Randomized Clinical Trial. *J Clin Med.* 2019;8(1).
88. Fletcher IM. The effect of different dynamic stretch velocities on jump performance. *Eur J Appl Physiol*. 2010;109(3):491-8.
89. Belkhiria-Turki L, Chaouachi A, Turki O, Hammami R, Chtara M, Amri M, et al. Greater volumes of static and dynamic stretching within a warm-up do not impair star excursion balance performance. *J Sports Med Phys Fitness*. 2014;54(3):279-88.
90. Costa PB, Graves BS, Whitehurst M, Jacobs PL. The acute effects of different durations of static stretching on dynamic balance performance. *J Strength Cond Res*. 2009;23(1):141-7.
91. Handrakis JP, Southard VN, Abreu JM, Aloisa M, Doyen MR, Echevarria LM, et al. Static stretching does not impair performance in active middle-aged adults. *J Strength Cond Res.* 2010;24(3):825-30.
92. Nelson AG, Kokkonen J, Arnall DA, Li L. Acute stretching increases postural stability in nonbalance trained individuals. *J Strength Cond Res*. 2012;26(11):3095-100.
93. Szafraniec R, Chromik K, Poborska A, Kawczynski A. Acute effects of contract-relax proprioceptive neuromuscular facilitation stretching of hip abductors and adductors on dynamic balance. *Peer J*. 2018;6:e6108.
94. Ryan EE, Rossi MD, Lopez R. The effects of the contract-relax-antagonist-contract form of proprioceptive neuromuscular facilitation stretching on postural stability. *J Strength Cond Res* 2010;24(7):1888-94.

95. Ghram AD, M.; Costa, P. Effect of acute contract-relax proprioceptive neuromuscular facilitation stretching on static balance in healthy men. *Sci Sports.* 2017;32:e1-e7.
96. Ebben WP, Hintz MJ, Simenz CJ. Strength and conditioning practices of Major League Baseball strength and conditioning coaches. *J Strength Cond Res*. 2005;19(3):538-46.
97. Ebben WP, Carroll RM, Simenz CJ. Strength and conditioning practices of National Hockey League strength and conditioning coaches. *J Strength Cond Res*. 2004;18(4):889-97.
98. Ebben WP, Blackard DO. Strength and conditioning practices of National Football League strength and conditioning coaches. *J Strength Cond Res*. 2001;15(1):48-58.
99. Judge LWA, J.M.; Bellar, D.M.; Hoover, D.L.; Craig, B.W.; Langley, J.; Nordmann, N.; Schoeff, M.A.; Dickin, C. Pre- and post-activity stretching practices of collegiate soccer coaches in the United States. *Int J Exerc Sci*. 2020;13(6):260-72.
100. Judge LW, Petersen JC, Bellar DM, Craig BW, Wanless EA, Benner M, et al. An examination of pre-activity and post-activity stretching practices of crosscountry and track and field distance coaches. *J Strength Cond Res*. 2013;27(9):2456-64.
101. Judge LW, Craig B, Baudendistal S, Bodey KJ. An examination of the stretching practices of Division I and Division III college football programs in the midwestern United States. *J Strength Cond Res.* 2009;23(4):1091-6.
102. Judge LW, Bellar DM, Gilreath EL, Petersen JC, Craig BW, Popp JK, et al. An examination of pre-activity and post-activity stretching practices of NCAA division I, NCAA division II, and NCAA division III track and field throws programs. *J Strength Cond Res*. 2013;27(10):2691-9.
103. Judge LW, Bellar D, Craig B, Petersen J, Camerota J, Wanless E, et al. An examination of pre-activity and post-activity flexibility practices of National Collegiate Athletic Association Division I tennis coaches. *J Strength Cond Res*. 2012;26(1):184-91.
104. Simenz CJ, Dugan CA, Ebben WP. Strength and conditioning practices of National Basketball Association strength and conditioning coaches. *J Strength Cond Res.* 2005;19(3):495-504.
105. Behm DG, Button DC, Butt JC. Factors affecting force loss with prolonged stretching. *Can J Appl Physiol.* 2001;26(3):261-72.
106. Fowles JR, Sale DG, MacDougall JD. Reduced strength after passive stretch of the human plantar flexors. *J Appl Physiol*. 2000;89:1179-88.
107. Pulverenti TS, Trajano GS, Kirk BJC, Bochkezanian V, Blazevich AJ. Plantar flexor muscle stretching depresses the soleus late response but not tendon tap reflexes. *Eur J Neurosci*. 2021;53(9):3185-3198. doi: 10.1111/ejn.15178.
108. Smajla D, Garcia-Ramos A, Tomazin K, Strojnik V. Selective effect of static stretching, concentric contractions, and a one-leg balance task on ankle motion sense in young and older adults. *Gait Posture.* 2019;71:1-6.
109. Behm DG, Anderson KG. The role of instability with resistance training. *J Strength Cond Res.* 2006;20(3):716-22.
110. Anderson K, Behm DG. The impact of instability resistance training on balance and stability. *Sports Med.* 2005;35(1):43-53.
111. Kibele A, Granacher U, Muehlbauer T, Behm DG. Stable, unstable and metastable states of equilibrium: definitions and applications to human movement. *J Sports Sci Med*. 2015;14(4):885-7.
112. Blazevich AJ. Adaptations in the passive mechanical properties of skeletal muscle to altered patterns of use. *J Appl Physiol.* (1985). 2019;126(5):1483-91.
113. Prado LG, Makarenko I, Andresen C, Kruger M, Opitz CA, Linke WA. Isoform diversity of giant proteins in relation to passive and active contractile properties of rabbit skeletal muscles. *J Gen Physiol.* 2005;126(5):461-80.

114. Hunter DG, Spriggs J. Investigation into the relationship between the passive flexibility and active stiffness of the ankle plantar-flexor muscles. *Clin Biomech* (Bristol, Avon). 2000;15(8):600-6.
115. Pinto MD, Wilson CJ, Kay AD, Blazevich AJ. Reliability of isokinetic tests of velocity- and contraction intensity-dependent plantar flexor mechanical properties. *Scand J Med Sci Sports.* 2021.
116. Blackburn JT, Padua DA, Riemann BL, Guskiewicz KM. The relationships between active extensibility, and passive and active stiffness of the knee flexors. *J Electromyogr Kinesiol.* 2004;14(6):683-91.
117. Hunter DGC, V.; Spriggs, J. Investigation into the effect of static stretching on the active stiffness and damping characteristics of the ankle joint plantar flexors. *Physical Therapy Sport.* 2001;2(1):15-22.
118. Granata KP, Marras WS. Cost benefit of muscle co-contraction in protecting against spinal instability. *Spine.* 2000;25(11):1398-404.
119. Kaya FB, B.; Yuktasir, B.; Willems, M.E.T.; Yildiz, N. The effects of two different stretching programs on balance control and motor neuron excitbaility. *J Education Training Studies.* 2018;6(5):85-91.
120. Hoch MC, Staton GS, McKeon PO. Dorsiflexion range of motion significantly influences dynamic balance. *J Sci Med Sport*. 2011;14(1):90-2.