

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 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 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. *Journal of Clinical Exercise Physiology*. 2021;10(3):106–116.

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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 nonstretched (nonlocal) 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) (see Side Bar 1). 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 aging 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.

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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) after both acute and chronic stretching. The consistent application of SS can induce greater parasympathetic influence (22) and 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 after prolonged SS (>60 seconds per muscle group) when performed without additional dynamic warmup 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 (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 warmup (3). Nonetheless, when appropriate durations of SS (<60 seconds per muscle group) are incorporated into a full pre-exercise warmup (comprising 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 and 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 musculoskeletal

SIDE BAR 1: STRETCHING PRESCRIPTIONS

1. Chronic increase in range of motion (ROM):
 - a. Separate training session distinct from warmup activities,
 - b. 2–6 days per week,
 - c. 30 to 60 seconds per muscle group,
 - d. Minimum 5 minutes 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 seconds of static stretching per muscle group;
 - b. Within a full warmup that includes initial ≥5-minute aerobic activity, static and dynamic stretching (≥90 seconds per muscle group), and subsequent 5–15 minutes of dynamic sport or task-specific activities.
3. Reduction in musculoskeletal injury incidence:
 - a. Chronic static and acute ballistic (increased tendon compliance) stretching;
 - b. ≥30 seconds per muscle group (may perform multiple shorter stretches to achieve total time);
 - c. ≥5 minutes per target muscle groups (e.g., stretching for running would involve ≥5 minutes of stretching of the quadriceps, hamstrings, triceps surae, hip adductors, and abductors before lower-limb activities such as walking, running, and jumping).

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. Regarding randomized, controlled trials of the effect of SS during warmup 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 compartment syndrome). In that study, having a limited ROM increased the risk for injury 2.5-fold compared with individuals with average dorsiflexion ROM and eightfold 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 -second 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 6 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, and bursitis, among others). Together, the studies by Pope et al. (39,41) indicate that, while 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 versus 2 injuries with stretch training group) and ankle joint injuries (30%: 27 versus 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 versus 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 seconds SS of 7 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. While 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 8 studies showed some effectiveness of chronic stretching for reducing injury incidence, whereas 4 other studies indicated no significant effect. In a randomized, single-blind, nonsupervised (self-reports), controlled trial, self-reported muscle, ligament, and tendon injuries were reduced in distance runners (2125 participants with 687 people reporting at least 1 injury) who chronically stretched before and after running for 12 weeks (0.66 injuries per person-year in stretch group versus 0.88 injuries per person-year in control) (44). Additionally, Woods et al. (45) concluded that chronic stretch training, performed with or without warmup 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 noncontact 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- 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 warmup including stretching was performed before exercise and a lack of evidence that stretching could increase injury incidence. McKay et al. (48) monitored 3 elite (22% of study participants) and 3 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 than players who did stretch. Dadebo (49) found that implementing SS in a warmup (recommendation: 4×15 –30 seconds) 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 warmup during the 1995 season

compared with warmups 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 these reports, there seems to be a reasonable (moderate) effect of acute SS within a pre-exercise warmup on the attenuation of MTU injuries, but further randomized, controlled trials are needed 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 fibers 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 fibers and fascicles (56,57), which can provide a dissipation of forces over a greater distance and time. While individual MTU fibers 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 regard 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 warmup. Zakaria et al. (59) compared SS + DS with DS alone in high school soccer athletes and detected no difference in lower back and

SIDE BAR 2: UNIQUE RESEARCH FINDINGS ON STRETCHING

1. Commonly reported static stretching (SS)-induced performance impairments are often due to inappropriate or invalid experimental protocols (1,2,3,22,24), including:
 - a. >60 seconds of SS per muscle group;
 - b. Lack of a full complement of warmup activities;
 - c. Testing or performing immediately after stretching when most sport activities commence 5 to 15 minutes poststretching;
 - d. Nocebo effects of using student subjects who have been instructed and expect to experience deficits with SS (self-fulfilling prophecy);
 - e. Reporting bias: statistically significant results are more likely to be published.
2. SS 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. SS 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 SS may either increase or decrease balance (not yet known under which conditions each outcome is likely).

extremity injuries when implementing DS versus the SS + DS combination. However, they did not compare with a nonstretch 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 warmup 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 toward 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

BOX 1: IMPORTANT INFORMATION 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 (SS); there is insufficient evidence for the effects of acute or chronic dynamic stretching (DS).
3. Decreases in MTU injury incidence may result from changes in tissue compliance or shifts in the active force-length relation toward longer muscle lengths.
4. There is no conclusive evidence for acute impairments in proprioception after static or proprioceptive neuromuscular facilitation stretching.

indicating that, after 3 stretching sessions per week for 10 weeks (3 sets of 30 seconds 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-second contraction followed by 20 seconds of stretch) of the shoulders (74) and SS (3 × 30 seconds) of knee extensors and flexors (75) showing no effect on respective joint position sense. However, using a similar duration of stretch (3 × 30 seconds) of the knee extensors and flexors, Ghaffarinejad et al. (76) reported improved knee joint position sense, and both SS (2 × 90 seconds) 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, and 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 toward longer muscle lengths (see Side Bar 1). Additional randomized, controlled trials are required in sports and exercise populations 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 are 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 center of pressure area, or postural sway) were impaired after either 1 repetition of 30 seconds (82), 3 repetitions of 45 seconds (28,83), 6 repetitions of 45 seconds (84), or 3 minutes (85) or 5 minutes (86) of SS, respectively. These results contrast with reported improved balance after a bilateral intermittent SS (5 repetitions of 1 minute, 15 seconds of rest) protocol (87). Seven minutes of DS (a controlled movement through the ROM of the active joint[s]) provided greater reductions in center 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) than 7 minutes of SS. There are also reports of similar small magnitude improvements in balance (Star Excursion Balance Test) after either 10- to 30-minute (15-second repetitions) of SS or DS (89). Costa et al. (90) reported that 2 × 45 seconds of SS had no adverse effects on balance (Biodex balance system involves a movable circular platform that can tilt 20°), whereas a 2 × 15-second 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-second periods) after 10 and 20 minutes 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 numbers of SS articles reporting either improved or 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 3 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) (see Side Bar 2). While the average stretch durations of American professional and collegiate athletes are 12–30 seconds per muscle group (96–104) and most guidelines suggest several (2–4) repetitions of 15- to 30-second stretches, stretches in many studies are often imposed for several minutes or even up to 20 to 30 minutes per muscle group (105,106). Reviews of the literature have demonstrated that less than 60 seconds of SS results in trivial effects on subsequent performance, especially when

incorporated into a full warmup that included prior aerobic activity and poststretch dynamic activities (1–3,24,26). However, in relation to balance measures, both improvements (90) and impairments (82) have been observed with 30 seconds of SS. Furthermore, balance deficits were reported after 135 seconds (28) of quadriceps, hamstrings, and plantar flexor (PF) stretching (28,83) as well as 270 seconds (84), 3 minutes (85), and 5 minutes (86) of PF SS. Nonetheless, enhancement of balance was also reported after 5 minutes (87) and 10 minutes (91) of low back, hip and knee extensors, and knee flexors, and 20 minutes (92) of hip, knee, and ankle joints of total SS. Thus, the recommended maximum of 60 seconds 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 most 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 these 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 2 studies involving only women (82,90) and 1 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 after 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 -second PF stretches) might acutely reduce activity in spinocerebellar pathways (107), which might be expected to influence balance and stability. However, whereas ankle motion sense (proprioception) has been shown to be impaired after 6×40 -second SS (108), no significant effect on knee joint position sense was detected after 3×30 -second SS (75), contrasting with improved knee joint proprioception also after 3×30 seconds 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 center of gravity to within the base of support (metastability (111)). Acute bouts of SS have been reported to reduce passive 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 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

BOX 2: IMPORTANT INFORMATION ON BALANCE

1. DS is demonstrated to have acute beneficial effects on balance.
2. The effects of acute SS 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 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.

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 after 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 cocontractions 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 center of mass translocations and increasing the chance that the body's center 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 to allow the center of mass to remain within the base of support (i.e., a "Goldilocks zone" (3)). While the few DS studies show balance improvements, SS studies demonstrating deficits

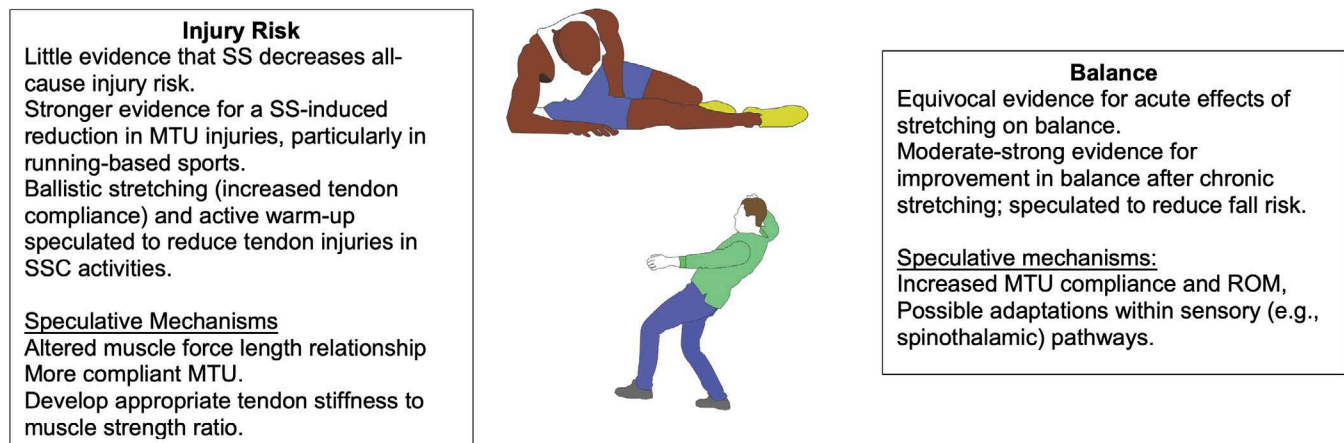


FIGURE 1. Summary figure. SS = static stretching; MTU = muscle-tendon unit.

(conflicting with those similar numbers of SS studies that show improvements or no change) might be attributed to nonpractical 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 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 5 lower extremity muscles (2 days per week: 3×30 seconds) in high school students improved unilateral stance on a balance beam (1-minute flamingo balance test with dominant leg). The possible improvements in balance with stretch training might be partially attributed to the 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 toward longer muscle lengths (60–62), with force reductions at short muscle lengths contrasting with moderate improvements at longer muscle lengths (63–67). Thus, after 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 while landing in an extended and unbalanced position. Nonetheless, this specific hypothesis remains to be explicitly tested.

In summary, while 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 (see Side Bar 2). 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.

CONCLUSIONS

Boxes 1 and 2 provide brief important information emphasized in this review. 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 exercising populations (including elderly, clinical, and others) are required 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 DS on injury risk. While the effect of an acute bout of SS 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, DS generally shows favorable 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 ROM, 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, while 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 DS (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.

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