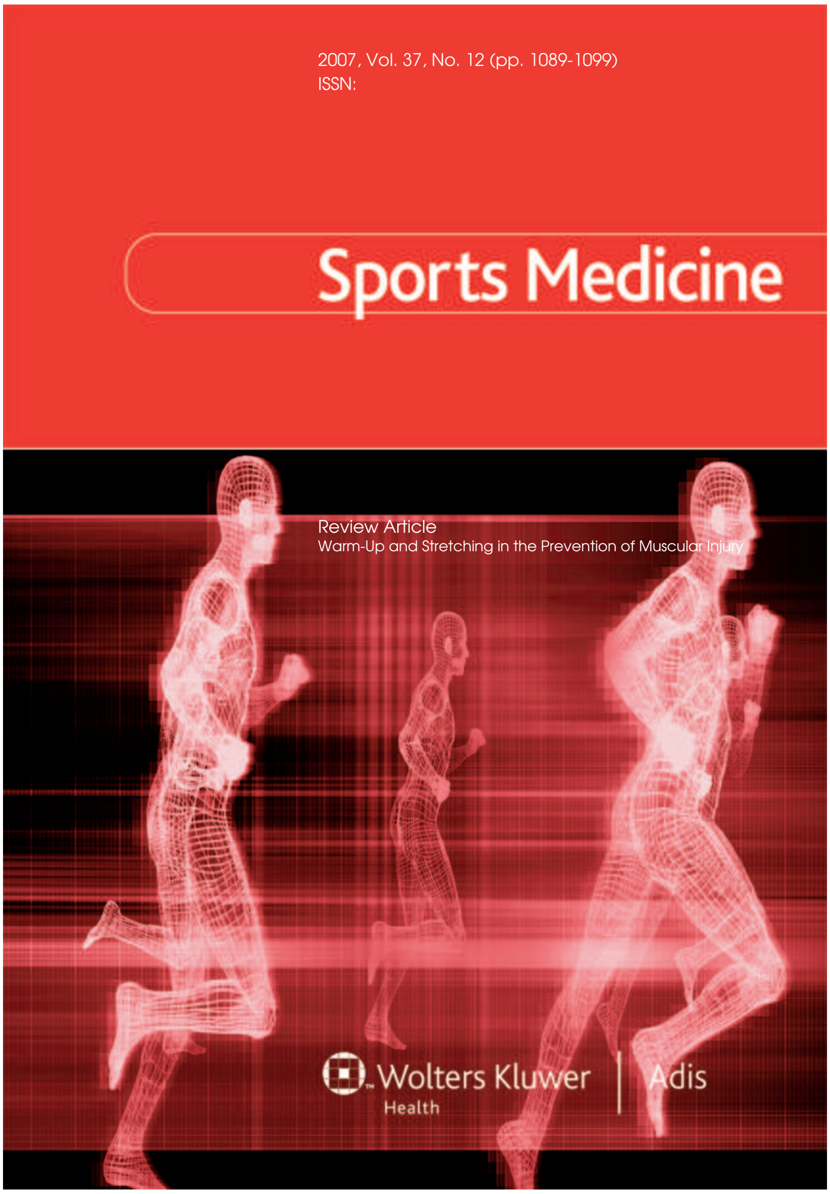
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Warm-Up and Stretching in the Prevention of Muscular Injury

Krista Woods, *Phillip Bishop* and *Eric Jones*

Human Performance Laboratory, University of Alabama, Tuscaloosa, Alabama, USA

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Abstract

Muscular injury is one of the major problems facing today's athletes, both recreational and professional. Injuries to skeletal muscle represent >30% of the injuries seen in sports medicine clinics. As a result, it is imperative to utilise the most effective means to aid in deterring these injuries. However, there are conflicting opinions regarding methods of reducing muscular injury through warm-up and stretching techniques.

Therefore, the purpose of this article is to examine the potential of a warm-up and/or stretching routine in deterring muscular injury during physical activity. The article examines a variety of studies regarding warm-up, stretching and muscular injury. The article also provides a definition of warm-up and stretching to provide clarity on this topic. Many of the differences within previous research were due to conflicting definitions. We also address this issue by examining research on muscular injury and physical adaptations to muscular injury and training.

This article provides contradictory evidence to conclusions that have been drawn in previous review articles, which determined that warm-up and/or stretching protocols did not deter injury. The research included here conveys that certain techniques and protocols have shown a positive outcome on deterring injuries. As a result, a warm-up and stretching protocol should be implemented prior to physical activity. The routine should allow the stretching protocol to occur within the 15 minutes immediately prior to the activity in order to receive the most benefit. In addition, current information regarding improvements in flexibility is reviewed.

Muscular injury is one of the major problems facing both recreational and professional athletes. Athletic disability is often attributable to an indirect or strain injury to the muscle.[1] Injuries to skeletal muscle represent >30% of the injuries seen in sports medicine clinics.[2] As a result, it is imperative to utilise the most effective means to deter these injuries. However, there are conflicting opinions regarding methods of reducing muscular injury.

It has widely been accepted that athletes should perform warm-up activities and a stretching protocol prior to, and after participating in, a physically demanding activity.[3-5] Various research studies offer different viewpoints regarding the effectiveness of warm-up and stretching protocols in reducing injuries. In their study, Pope et al.[6] concluded that stretching during the warm-up session did not produce clinically meaningful reductions in risk of exercise-related injury in army recruits. As a result, some researchers question the benefits of performing such activities prior to physical activity.

Although some studies have reported that there was no ‘reduction in the risk’[6] of injury or total injuries,[7] other studies reported positive effects and a reduction in musculotendinous injuries from warm-up and stretching intervention programmes. Therefore, the purpose of this article is to examine the impact of a warm-up and stretching routine on muscular injury during physical activity. This article examines a variety of studies regarding warm-up, stretching and muscular injury, as well as the effects of these activities on the muscles themselves. Research on muscular injury and physical adaptations to muscular injury and training is included.

1. Warm-Up

1.1 Definition of Warm-Up

Warm-up is intended to perform the following two major functions: (i) improve a muscle’s dynamics so that it is less inclined to injury; and (ii) prepare the athlete for the demands of exercise. A 1°C rise in muscle temperature has been shown to increase the length to failure of rabbit hind-limb muscles.[8] In general, the warm-up should produce a mild sweat without fatiguing the individual.

1.2 Types of Warm-Up

Warm-up can be either passive or active.[5] Active warm-up can further be classified as either a general warm-up or a specific warm-up. A passive warm-up is one in which muscle temperature or core body temperature is increased by external means. This can include, for example, hot showers, saunas or heating pads.[4,5] The active warm-up involves some type of physical activity. The general active warm-up involves any non-specific body movements such as jogging, cycling or callisthenics.[3-5] The specific warm-up utilises activities and stretches that are specific to the sport for which one is preparing.[3,4] The most effective of the warm-up techniques appears to be the specific warm-up, possibly due to the fact that it mimics the activity to be performed.[3,9]

1.3 Warm-Up Intensity

The warm-up should be structured in such a way that the individual experiences an increase in muscle temperature, but does not experience a significant decrease in high-energy phosphate availability.[5] The intensity of the warm-up should be tailored to meet the needs and abilities of each individual.[3,9]

For example, a poorly conditioned athlete will not require the same intensity or duration of warm-up as the well conditioned athlete to achieve the same elevation in muscle temperature. According to Bishop,[5] although greater intensity will cause a greater increase in muscle temperature, intensity above ~60% of a person's maximal oxygen uptake ($\dot{V}O_{2max}$) has been shown to deplete the concentration of available high-energy phosphates. As a result, it has been reported that an inverse relationship exists between warm-up intensity and short-term performance for intensities above ~60% $\dot{V}O_{2max}$. Therefore, it is suggested that an intensity of ~40–60% $\dot{V}O_{2max}$ should be utilised to increase muscle temperature, while also limiting high-energy phosphate depletion. However, in the absence of appropriate measurement instruments, it appears to be the general consensus that under normal conditions, light to mild sweating, without fatigue, is a reliable indicator of an adequate increase in muscle temperature.[3,4]

1.4 Physiological Effects of Warm-Up

It has been hypothesised that warm-up provides many physiological benefits. For example, it may lead to an increase in the speed and force of muscle contractions by speeding up metabolic processes and reducing internal viscosity, which results in smoother contractions. Also, an increase in temperature leads to the dissociation of oxygen from haemoglobin at higher plasma oxygen concentrations, providing more oxygen to working muscles. The speed of nerve transmission may also increase with the increase in temperature, which may, in turn, increase contraction speed and reduce reaction time. In addition, the temperature increases that accompany warm-up lead to vasodilation, which produces an increased blood flow through active tissues.[3,4,10,11] Finally, in research involving rabbit muscles, it has been reported that a warm-up provides a protective mechanism to muscle by requiring a greater length of stretch and force to produce a tear in the warmed muscle.[8] Although much of the aforementioned research highlights the effects of warm-up, Magnusson et al.[12] concluded that passive energy absorption of skeletal muscle is not dependent on increases in intramuscular temperature.

2. Stretching

2.1 Definition of Stretching

Throughout most studies, the amount of force used for each stretching protocol is subjective. As a result, certain terms commonly appear throughout the studies when describing the amount of stretch to which an individual is subjected. For example, subjects are often instructed to continue the stretch to the point where 'tightness without pain' is experienced.[13,14] Also, terms such as 'gentle stretch', 'pulling sensation', 'stretching sensation' and 'noticeable tension without pain' are often used when guiding subjects through the various stretching protocols.[14-17]

2.2 Types of Stretching

The three most common variations of stretching techniques are (i) dynamic; (ii) static; and (iii) proprioceptive neuromuscular facilitation (PNF).[18] The dynamic stretching technique involves the use of bouncing or jerking type motions to stretch a muscle group.[18] An example of this type of stretching is using a bouncing method while bending downward to touch the toes. Static stretching is often referred to as slow or passive stretching.[19] In this method, a slow, deliberate movement is used to achieve a lengthening of the muscle. According to Amako et al.,[18] each stretch should be maintained for approximately 20 seconds to facilitate connective tissue plastic elongation. PNF requires the following combination of steps: a static stretch, an isometric contraction and relaxation, and then another static stretch.[18] For a more detailed examination of these techniques, consult Kreighbaum and Barthels[19] or Weerapong et al.[20]

2.3 Stretching Protocols

As mentioned in the introductory section, this article examines a variety of different studies. In addition to reviewing studies focusing on physical activity and injury, research focusing on muscular injury, as well as the physical adaptations to muscular injury and training are also examined. As a result, there are a variety of different stretching protocols used throughout these studies. Therefore, only a few of the more common techniques will be discussed in this section. Table I lists all stretching protocols included within this article.

Hartig and Henderson[15] used a protocol in which each subject completed five hamstring stretches, of 30 seconds in length, each session. The subjects performed three sessions per day for 13 weeks while in the Army's basic training programme. The stretching technique required the subjects to be paired. The subjects faced each other while one subject extended his leg straight out in front, positioning the hip at 90° of flexion. While the partner was holding the subject's leg in this position, the subject would lean forward while keeping the back straight, creating an anterior tilt of the pelvis, until he experienced a 'stretching sensation without pain'. This stretch was then held for 30 seconds before relaxing.

Sullivan et al.[13] also had subjects perform hamstring stretches while in the standing position. However, subjects utilised a padded table instead of a partner to stabilise the stretched leg and hold the hip at a 90° angle. Subjects were assigned to either a posterior pelvic tilt (PPT) group or an anterior pelvic tilt (APT) group. Also, these subjects were then assigned to either a static stretch or PNF stretch group. For the PPT, subjects were instructed to let their arms hang freely at their sides and to tuck their chins to the chest. While in this position they were instructed to lean forward in an attempt to touch their head to their knee, until they 'perceived a hamstring tightness without pain'. For the APT, subjects were instructed to put their hands on their hips and to look straight ahead. Depending upon the randomly assigned groups, while in either the PPT or APT position, subjects performed either the PNF stretches or the static stretches. For the PNF stretch, subjects utilised the contract-relax-contract method

Table I. Stretching protocols and results

Study	Protocol	Type and results
Amako et al.[18]	4 upper body, 7 lower body, 7 trunk: 30 sec each 1 × 20 min session/day; 12wk	Static: researchers found that the protocol limited the amount of muscle-related injury
Bixler and Jones[7]	Trunk twist: 15 sec Hamstring, groin, quad stretches: 25 sec each	Static: researchers found that the protocol reduced injury
de Weijer et al.[14]	Hamstring only: 1 × 30 sec for each leg 3 reps with 10 sec rest in between stretches	Static: NA (measured changes in hamstring length over time)
Hartig and Henderson[15]	Hamstring only: 5 × 30 sec stretches 3 sessions/day; 13wk	Static: researchers concluded that the protocol reduced lower extremity overuse injury
Pope et al.[6]	1 × 20 sec stretch for each of 6 major lower-limb muscle groups: 1 session/day; 12wk	Static: researchers concluded that the protocol did not significantly reduce total injuries
Rosenbaum and Hennig[16]	2 lower-leg stretches: 30 sec each 3 reps	Static: NA (measured changes in force output and muscle compliance)
Sullivan et al.[13]	Hamstring only: 30 sec total (5 sec/each phase) 1 × 5 min session/day; 4 days/wk; 2wk period	Static and PNF CRC method): NA (measured changes in flexibility)
Verrall et al.[21]	Hamstring stretches: 15 sec each with knee in 0, 10, and 90° of flexion, utilising trunk flexion to enhance stretch	Passive: researchers concluded that protocol resulted in significant reduction in injury

CRC = contract-relax-contract; **NA** = not applicable (did not examine injury specifically); **PNF** = proprioceptive neuromuscular facilitation; **reps** = repetitions.

in which the following steps were used: a 5-second hamstring contraction; a 5-second relaxation; a 5-second quadriceps contraction; a 5-second hamstring contraction; a 5-second relaxation; and a final 5 seconds of quadriceps contraction.

The static-stretch protocol required one 30-second stretch. Although PNF is mentioned as a stretching technique within this review, it should be noted that Sullivan et al.[13] concluded that pelvic tilt position was more important than the stretching technique for increasing hamstring length.

2.4 Results of Stretching Protocols

Stretching results in an elongation of soft tissues and muscles.[20,22] Increases in muscle length as a result of stretching are time and history dependent due to viscoelastic responses.[14,22] Static stretches held for 30 seconds and performed for three repetitions have been reported to increase muscle length.[14] In addition, de Weijer et al.[14] found that this increase in muscle length was maintained for at least 24 hours, with the greatest increases being maintained during the first 15 minutes immediately following the stretching protocol. As a result, it is suggested that stretching should occur within the 15 minutes immediately preceding an activity in order to have the optimal lengthening benefit of the stretch.

According to Kreighbaum and Barthels,[19] long-term benefits of stretching programmes include an increase in flexibility (range of motion available). Connective tissue, which is the focus for flexibility, has two components when lengthening: elastic and plastic (non-recoiling) stretching. The amount of plastic stretch determines the amount of permanent lengthening for the connective tissue. Also, it is reported that the most effective lengthening for connective tissue occurs when a lower force of longer duration is applied to a tissue with an elevated temperature.

Although this article focuses mainly on stretching and injury prevention, some researchers have suggested that excessive stretching may be detrimental to athletic performance.[23] Church et al.[23] conducted a study in which 40 female participants were asked to perform a general warm-up only, warm-up and static stretching, and warm-up and PNF stretching on 3 nonconsecutive days. Each treatment was followed by a vertical jump test. It was concluded that warm-up and PNF stretching before a vertical jump test were detrimental to performance. The results of the aforementioned study are based on the premise that performance level is dependent on muscular capability; however, the studies mentioned within this review do not quantify performance.

3. Injury

3.1 Definition of Injury

Amako et al.[18] suggest that injuries can be classified into groups depending upon which tissue is injured. Amako et al.[18] defines the first group as bone injuries; bone injuries are injuries in which a fracture occurs. Next, muscle/tendon injuries consist of muscle strains and sprains; however, ligament sprains are classified as ligament injuries. In addition, joint injuries involve any type of injury within a given joint. Finally, spinal injuries involve any type of injury to the spine, including lower-back pain.

According to Garrett Jr.,[1] there are several variations of injury that can occur in skeletal muscles. The first variation of injury as reported by Garrett Jr.,[1] delayed muscle soreness, is usually the result of unaccustomed exercise or activity. Skeletal muscle injuries can also occur as a result of a direct blow or force to the muscle. The final type of injury is the injury occurring in response to excessive strain or force within the muscle, without any direct contact. This type is commonly referred to as a muscle strain or pull and usually presents as an acute painful injury experienced during physical activity.

Morgan and Allen[24] define eccentric injury as an injury that occurs when the muscle is stretched while activated. This results when the external tension on the muscle exceeds the tension that would be developed at a constant muscle length. These eccentric contractions of skeletal muscle can lead to muscle injury.[2,25-27] Although it is beyond the scope of this review, Armstrong[28] provides an in-depth look at the pathology underlying the events of exercise-induced muscular injury. Reisman et al.[29] examined the effects of warm-up stretches after eccentric exercise (causing soreness or minor muscle damage) and concluded that passive stretch reduces passive tension, thereby reducing the sensations of stiffness and soreness.

The energy that is absorbed by a given muscle prior to muscle failure is a measure of the muscle's ability to withstand force and strain.[1] It is explained that there are two components of energy absorption. The passive component is "not dependent on muscle activation and is a property that is due to the connective tissue elements within the muscle." Also, the contractile ability of the muscle provides an added ability to absorb energy. Kirkendall and Garrett Jr.[2] report that the more energy that a muscle can absorb, the more resistant this muscle will be to injury. Therefore, it is noted that a condition that diminishes the contractile ability of a muscle would reduce the ability of the muscle to absorb energy and, as a result, potentially make the muscle more susceptible to injury.[1,2] Magnusson[30] determined that after 13 weeks of isometric strength training, stiffness increased (stiffness is defined as stress from an outside force strain, which is proportional to the amount of strain placed on the muscle), and that increased passive stiffness provides potential for energy absorption of the muscle-tendon unit prior to failure.

Several factors are potentially important in preventing muscle strain injuries.[1,2] These factors include flexibility, stretching and warming-up prior to activity. It is noted that the benefits of stretching are attributed to the stretch reflex mechanisms. In addition, it is also noted that viscoelasticity should be considered as well.[1,2] Stress-relaxation refers to the gradual reduction in tension at a given length achieved by stretching and holding a tissue to a constant length over time.[1,2] McHugh et al.[31] demonstrated viscoelastic stress relaxation in human skeletal muscle. It has been shown that repetitive cyclic stretching reduces the tension at a given length with each successive stretch.[32] Kirkendall and Garrett Jr.[2] state that it is the viscoelastic properties of the muscle that contribute to changes in the muscle length and that this increased length can be seen to decrease the strain in the muscle. However, studies conclude that the increase in hamstring extensibility was attributed to an increase in stretch tolerance, and not range of motion changes.[33-35] Reisman et al.[29] suggests that the property of thixotropy and resultant slack may prevent inappropriate reflex action, which may lead to muscle injury.

The focus of this article is on muscular injury only. It would not seem beneficial to include those traumatic injuries, such as fractures or injuries resulting from direct contact of an outside force, which presumably could occur regardless of the effects of an intervention method like warm-up or stretching. In general, the majority of research examined in this article classified an event as an injury if it resulted in time absent from the sport or activity, affected the level of play, or if it was recognised by a medical professional (team trainer or medical physician) as an injury.[6,7,18,21]

3.2 Effects of Warm-Up on Injury

Warm-up has been shown to have a positive effect on the reduction of muscle injuries. The aforementioned study by Bixler and Jones[7] focused on the number of injuries occurring during the third-quarter of high-school football games and the effects of a half-time warm-up and stretching routine on reducing these injuries. Teams were assigned to either an intervention group or a control group. The intervention group followed a prescribed warm-up and stretching protocol, while the control group continued their normal half-time activities. Although there was no significant difference in the total number of third-quarter injuries, the intervention group experienced significantly fewer (0.04 [mean intervention] vs 0.46 [mean non-intervention]; $p < 0.05$) third-quarter musculotendinous injuries (sprains and strains) per game.

3.3 Effects of Stretching on Injury

Several studies included in this article examined the effects of stretching on injury. The stretching protocols for each of these studies are included in table I. Amako et al.[18] examined the effects of a stretching programme on training-related injuries in military recruits. Injury data were collected from medical records for the recruits during the training programme and assessed for the incidence and location of injuries. The rate of total injuries between the control and intervention groups was not statistically significant. However, when injuries were classified by type, the occurrence of muscle/tendon-related injuries and low back pain was statistically significantly lower (2.5% vs 6.9%; $\chi^2 = 6.170$; $p < 0.05$) in the stretching group. In other words, although the stretching intervention had no significant effect on bone or joint injuries, it did decrease the incidence of muscle-related injuries. As mentioned in section 3.2, Bixler and Jones[7] also found a significant effect of stretching and warm-up on reducing muscular injury.

Jones et al.[36] reported that the most common injuries associated with the physical training of army recruits were muscle strains, sprains and overuse injuries. Several risk factors for these injuries were identified. For example, age, previous injury and flexibility were among the risk factors identified. In a later study, Hartig and Henderson[15] examined the effect of increased flexibility on decreasing lower-extremity overuse injuries in military basic trainees. Some of these overuse injuries included stress fractures, knee pain, muscle strains and shin splints. Hamstring flexibility was measured before and after the 13-week basic training programme. The implemented stretching protocol is discussed in detail earlier in section 2.3. Increases in hamstring flexibility within the intervention group compared with the control group were statistically significant. The intervention group's mean flexibility increased from 41.7 to 34.7°, while the control group increased slightly from 45.9 to 42.9° (7 vs 3°; $p < 0.001$). In addition, the intervention group also experienced significantly fewer (25 vs 43 injuries; $p = 0.02$) lower-extremity overuse injuries than the control group. The results of this study demonstrate the ability of an increase in flexibility to reduce lower-extremity overuse injuries.

Pope et al.[6] also looked at lower-limb injuries in a military population. The purpose of the study was to examine the effects of pre-exercise stretching on lower-limb injury. Military recruits participating in the study were followed through 12 weeks of basic training. The stretch group followed the stretching protocol outlined in the introductory section of this article and included in table I. Injuries were defined as a lower-limb injury that kept the recruit from resuming full duties within 3 days. The results of this intervention showed no significant effect of stretching on 'all-injuries risk' (intervention group: 158 injuries vs control group: 175 injuries; $p = 0.67$). Also, no effect was observed for soft-tissue or bone injuries when examined separately.

In another study, conducted by Verrall et al.,[21] the effect of a sport-specific intervention programme on hamstring muscle injuries was examined. Researchers followed a professional Australian Rules football team for a total of four playing seasons, focusing on the occurrence and consequences of hamstring injuries. After the first two seasons in which data were recorded, an intervention programme was designed and implemented. This programme was implemented in the preseason of the third year and included stretching, sport-specific training drills, and an emphasis on increasing the amount of high-intensity anaerobic interval training. The following positive results were reported following the intervention programme: a fewer number of players experienced hamstring injuries (injuries each successive year: 9 and 11 vs 2 and 4 injuries, pre- and post-intervention, respectively; $p = 0.05$); fewer competition games were missed due to injury (injuries each successive year: 31 and 38 vs 5 and 16, pre- and post-intervention, respectively; $p < 0.001$); and a decrease in hamstring strains per 1000 hours of playing time (4.7 pre-intervention vs 1.3 following the intervention; $p = 0.01$). Refer to Verrall et al.[21] for a more detailed examination of the results.

4. Discussion

Warm-up is beneficial for several reasons. It has been shown to increase the speed and force of muscle contractions. The muscles become less viscous, which results in smoother contractions. In addition, the warm-up produces an increase in muscle temperature. This increase in temperature produces an increased blood flow through active tissue and also facilitates the dissociation of oxygen from haemoglobin. In addition, an increase in the speed of nerve transmission is achieved.[3,4,10,11] Finally, it has been reported that a warm-up provides a protective mechanism to muscle by requiring a greater length of stretch and force to produce a tear in the warmed muscle.[8] At least some of these alterations may be beneficial in injury prevention. For example, increasing neural transmission speed may improve reaction time and allow athletes to avoid injurious twists or falls.

Stretching provides many potential benefits for an individual. For example, soft tissues and muscles are elongated when stretched.[20,22] Viscoelastic responses to stretching in a muscle are time and history dependent.[14,22] For example, performing three 30-second repetitions of static stretch have been reported to lead to muscle lengthening.[14] Another important point to note is that these increases in length have been found to be maintained for at least 24 hours following the stretching protocol.[14] It has also been found that long-term (non-acute) stretching programmes can lead to an increase in flexibility, or the range of motion available for a particular joint.[19] These are important findings when considering the potential benefits of stretching on muscular injury. For example, ability to lengthen without damage may allow athletes to assume unusual positions that would otherwise result in injury.

When attempting to examine the effects of an intervention protocol, such as warm-up or stretching, it is important to classify all observed injuries into specific groups, or types, of injuries.

The importance of defining and classifying injuries can be seen in the results of some of the previously discussed studies. For example, if Bixler and Jones[7] had only examined total third-quarter injuries, the results would have shown no significant effect of the half-time warm-up and stretching routine on injury. However, when injuries were classified, it was found that the intervention group experienced significantly ($p < 0.05$) fewer third-quarter musculotendinous injuries (sprains and strains) per game. Likewise, Amako et al.[18] initially found that the rate of total injuries between groups was not statistically significant. However, when injuries were classified by type, the stretching intervention had no significant effect on bone or joint injuries, but it did significantly decrease the incidence of muscle-related injuries. These authors were thorough in the examination of data and demonstrate the remarkable difference the classification of injury can have on the results of the study. This attention to the type of injury may explain why this review of studies found prophylactic benefits, whereas previous reviews did not.

Pope et al.[6] looked at lower-limb injuries in a military population. The purpose of this study was to examine the effects of pre-exercise stretching on lower-limb injury. Injuries were defined as a lower-limb injury that kept the recruit from resuming full duties within 3 days. The results of this intervention showed no significant effect of stretching on all-injuries risk ($p = 0.67$). In addition, no effect was observed for soft-tissue or bone injuries when examined separately. This study has been used as the basis for a previous review,[37] which also reported no effect of stretching on injury occurrence.

Initially, it appears that these findings clearly contradict other previously mentioned studies such as Amako et al.,[18] Bixler and Jones,[7] Hartig and Henderson,[15] and Verrall et al.[21] However, upon closer examination of the study, one can potentially see why conflicting findings were reported. First, the definition of injury for the Pope et al.[6] study is a potential point of concern. Injuries were initially reported to medical assistants or nurses. If the recruit was unable to resume normal activities without signs or symptoms in 3 days, the recruit was then referred to the regimental medical officer for further diagnosis. Only after diagnosis by the regimental medical officer was a recruit referred to the researchers. While other studies report including all reported injuries, it appears this study only included injuries significant enough to require a participant's normal routine to be affected for at least 3 days. As a result, it is possible that because the Pope et al.[6] study is only including the more severe injuries, it overlooked the potential reduction in overall injuries, as defined by other studies.

While this is a potential cause for concern when comparing these studies, it is not the major difference to emphasise. The major point to notice is the difference in the classification of injuries within the Pope et al.[6] study compared with the previously mentioned studies. Initially it appears that Pope et al.[6] followed the previous suggestion to classify injuries when reporting the results. Why, then, were conflicting findings reported? The potential reason for conflict can be found by examining the injury classifications reported by Pope et al.[6] 'Soft-tissue injuries', which included muscle injuries, also included joint and ligament injuries as well as meniscal injuries and 'other' injuries. As mentioned earlier in this section, injuries such as muscle injuries, which stand to benefit directly from a stretching routine, should be examined separately in order to gain a better understanding of the effects of the intervention on injury.

Connective tissue flexibility has two components when lengthening: elastic and plastic (non-recoiling) stretching. The amount of plastic stretch determines the amount of permanent lengthening for the connective tissue. Also, it is reported that the most effective lengthening for connective tissue occurs when a 'lower force of longer duration' is applied to a tissue with an elevated temperature.[19] As a result, stretching should be done following a warm-up.

As has been discussed earlier in this section, stretching and warm-up each provide potential benefits. Further examination and analytical thought may help to explain why potential benefits to injury prevention may occur with these preventive measures.

Injuries occur at certain lengths, as a result of an eccentric force stretching the muscle beyond its 'free range of motion' to the point of failure. All physical activities can be thought of in terms of requiring a specific range of motion to carry out the activity. In order to successfully complete an activity without injury, the muscle must have the 'stretchability' necessary to move through that range without causing an increased tension/stress or load on the muscle. Muscles absorb as much of this stress as possible before injury.[1,2] Pope et al.[38] concluded that poor flexibility was associated with 2.5 times the risk of injury as compared with average flexibility and with up to 8 times the risk of injury when compared with high flexibility.

Studies have shown that stretching results in an increase in the length of the muscle.[14,20,22] It can be theorised that this increase in the length of muscle (in other words a shift in the optimum length of the muscle[39]) can allow the muscle to move through a greater range of motion, or stretch, before reaching the point of failure.

An increase in flexibility, resulting from long-term (non-acute) stretching would cause a permanent shift in the optimum length of the muscle. To illustrate this theory, consider that an individual muscle has, at any given time, a specific range of motion through which it can freely move. Movement beyond this 'non-injury zone'(NIZ), would result in an injury to the muscle. If the centre of the NIZ is defined by the optimal length of the muscle, an increase in the length of the muscle through stretching would cause an expansion or widening of the NIZ. This widening of the NIZ would allow a greater range of motion through which the muscle can freely move. This would result in less stress on the muscle at a given point in the range of motion and thus require a greater force to stretch the muscle to the point of failure.

5. Future Research

Future research should focus on isolating the warm-up protocol and the stretching protocol to determine the impact of each, individually, on injury. Also, research should be conducted to define the range of motion necessary for successful participation in different physical activities. For example, jogging would require a different range of motion than the dynamic moves involved in football. In addition, flexibility/range of motion standards could then be developed to potentially aid in more successful participation (reduced muscular injury) in each activity. Future research should also focus on the classification of particular types of injuries. Finally, future research should be conducted to determine the potential effects of overstretching on injury prevention.

6. Conclusion

This article provides contradictory evidence to the conclusions that were drawn in previous review articles,[37,40] which determined that warm-up and/or stretching protocols did not deter injury. Much of the research included within this article explains that certain techniques or protocols have shown a positive outcome on injury results. Adding to this conclusion regarding injury is current information regarding improvements in flexibility, as determined by multiple studies.

A warm-up and stretching protocol should be implemented prior to physical activity. Ideally, this routine should allow the stretching protocol to occur within the 15 minutes immediately prior to the activity in order to receive the most benefit. The protocol should be tailored to the needs of the individual as well as the activity. Physiological benefits (e.g. increased blood flow to the tissues and increases in the speed of muscular contractions and nerve transmissions) and physical benefits (e.g. reduced injury and increased flexibility) can be attained through the consistent and proper use of warm-up and stretching routines prior to physical activities. The intensity during warm-up should produce mild sweating without fatigue. This has been shown to be consistent with an intensity of approximately 40–60% of a person's $\dot{V}O_{2max}$. Stretching should be a long-term part of the fitness routine in order to benefit from the long-term plastic changes. These changes result in an increased muscle length and greater range of motion, which potentially may lead to less musculotendinous injury during physical activity. For one particular muscle group, the hamstrings, it has been determined that using an anterior pelvic tilt with the hip at 90° of flexion provides the best result. In general, stretches of longer duration with lower force provide optimal benefits. At a minimum, when designing a stretching protocol, de Weijer et al.'s[14] protocol of three 30-second stretches should be implemented for each muscle group at least once per week in order to achieve improvements in flexibility.

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Correspondence: Dr *Krista Woods*, Department of Kinesiology, University of Alabama, Box 870312, Tuscaloosa, AL 35487-0312, USA.
E-mail: woods021@bama.ua.edu

