THE IMMEDIATE EFFECTS OF SELF-ADMINISTERED PROPRIOCEPTIVE
NEUROMUSCULAR FACILITATION, MYOFASCIAL RELEASE, AND DYNAMIC
STRETCHING ON RANGE OF MOTION.

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ABSTRACT

The Immediate Effects of Self-Administered Proprioceptive Neuromuscular Facilitation, Myofascial Release, and Dynamic Stretching on Range of Motion

By

Laura Deguzman

Masters of Science in Kinesiology

PURPOSE: The purpose of this study is to compare the effects of self-administered proprioceptive neuromuscular facilitation (PNF), myofascial release (MFR), and dynamic stretching on passive knee extension (PKE) range of motion (ROM).

METHODS: A total of 35 individuals performed each intervention on different days. Range of motion measurements were recorded before and after each treatment intervention.

RESULTS: The paired t-tests indicated a significant increase for the dynamic stretching (t(34)= 12.3; P<0.001), PNF (t(34)= 13.3; P<0.001), and MFR (t(34)= 8.9; P<0.001) interventions (Table 1). We also noted a significant increase in ROM in the control group (t(34)= 5.2; P<0.001). A one-way ANOVA compared the difference scores (post-pre) across all groups. The overall omnibus test was significant (F3,32= 27.7; P<0.001), indicating a difference in the increase in ROM between one or more of the interventions. The post-hoc pairwise comparisons revealed that each of the interventions resulted in a
larger increase in ROM compared to the control condition (all P<0.001). Additionally, the PNF intervention resulted in a significantly greater improvement in ROM compared to MFR (11.1° vs. 7.1°; P<0.01).

CONCLUSION: The findings in this study indicate that dynamic stretching, PNF, and MFR interventions are clinically effective in increasing PKE ROM for individuals with a ≥20° deficit. The underlying causes for these increases are likely attributed to neural and mechanical mechanisms allowing for tissue extensibility, and thus, an increase in ROM. Athletes, clinicians, and coaches should base their choice of intervention on their personal capabilities, treatment goals and setting.
INTRODUCTION

Clinicians implement hamstring stretching techniques to increase flexibility, as investigators have found it to enhance optimal sport performance (McHugh & Cosgrave, 2010; McMillian et al., 2006; Amiri-Khorasani & Sotoodeh, 2013) allow patients to perform activities of daily living (Amiri-Khorasani, Abu Osman, Yusof, 2011), and reduce injuries (Hartig & Henderson, 1999; Verrall, Slavotinek, & Barnes, 2005). Flexibility has been defined as the muscle’s ability to elongate to permit sufficient joint movement through a range of motion (ROM) (Nelson & Bandy, 2004). Range of motion deficiencies have been attributed to myofascial adhesions (MacDonald, Penney, Mullaley, Cuconato, & Drake, 2013; Kuruma, Takei, Nitta, Furukawa, & Shida, 2013; Mohr, Long, & Goad, 2014; Junker & Stoggl, 2015) and muscular resistance (McHugh & Cosgrave, 2010), which decreases the ability of the muscle to deform (McHugh & Cosgrave, 2010; Nelson & Bandy, 2004). Because there is evidence that attaining sufficient ROM allows for an unrestricted and functional movement pattern (McHugh & Cosgrave, 2010), it is important to explore effective treatment options to increase flexibility and thus, ROM. Commonly-practiced techniques to improve joint ROM are static stretching, proprioceptive neuromuscular facilitation (PNF), dynamic stretching, and myofascial release.

Static stretching involves applying a sustained force that elongates the muscle for a period of time (Anderson & Burke, 1991). This technique does not engage active movement through ROM using similar movements to a specific activity, nor does it increase core body temperature as a dynamic stretching would, but it is still practiced as routine prior to physical activity (Mann & Jones, 1999). Some studies show no immediate improvement in joint ROM following static stretching (Amiri-Khorasani & Sotoodeh, 2013; Perrier, Pavol, & Hoffman,
2011; Wicke, Gainey, & Figueroa, 2014), but it appears that repeated bouts of static stretching may increase joint ROM over time (Maddigan, Peach, & Behm, 2012; O’Sullivan, Murray, & Sainsbury, 2009; Yuktasir & Kaya, 2007).

Dynamic stretching is commonly practiced by sports teams prior to physical activity and involves actively moving the body part through the full ROM to mimic movements that are associated with the specific sport, increasing flexibility and therefore resulting in improved ROM. Unlike static stretching, it has been found to enhance power, agility (McMillian, Moore, Hatler, & Taylor, 2006; Amiri-Khorasani & Sotoodeh, 2013), vertical jump, acceleration, maximal speed (Amiri-Khorasani & Sotoodeh, 2013) and suggested to increase motor unit excitability, core body temperature, and kinesthetic awareness (Faigenbaum, Bellucci, Bernieri, Barker, & Hoorens, 2005; Mann & Jones, 1999). Although dynamic stretching varies based on the sport, the goals of increasing ROM and preparing the body are typically the same for every individual. Studies investigating the effect of dynamic stretching on ROM have resulted in inconsistent findings (Konrad & Tilp, 2014; Amiri-Khorasani & Sotoodeh, 2013; Nelson & Bandy, 2004; O’Sullivan et al, 2009; Perrier et al, 2011; Samson, Button, Chaouachi, & Behm, 2012).

Proprioceptive neuromuscular facilitation is a technique that involves contracting the treated muscle and/or its antagonist to result in relaxation and thus increase flexibility of the targeted muscle (Rees, Murphy, Watsford, McLachlan, & Coutts 2007; Yuktasir, 2007). It is thought that activating the quadriceps (agonist) results in relaxation of the hamstrings (antagonist/target muscle). Various types of PNF are implemented based on clinician and patient goals. Common techniques include contract-relax, contract-relax agonist-contract, slow-reversal-hold-relax, and the hold-relax technique. Regardless of the type of technique or
method of implementation, several investigators have found that PNF results in the greatest ROM gains compared to dynamic stretching or static stretching (Maddigan et al, 2012; Rees et al, 2007; Schuback, Hooper, & Salisbury 2004; Wicke et al, 2014; Yuktasir, 2007).

Myofascial release was developed by Mark F. Barnes and is a technique that has gained popularity in recent years. It is a soft tissue mobilization technique that can be manually implemented or self-administered by rolling a foam roll along the muscle being treated. However, the concept and purpose of myofascial release may be poorly understood. Fascia is a connective tissue that encases all of the muscles and organs of the body and becomes more fluid-like with movement, heat, stretching, and massage (Sefton, 2004). Using a foam roll creates pressure and friction on the muscle and fascia, causing an increase in pliability. It is theorized that fibrous adhesions are broken up and soft tissue extensibility increases, improving ROM. In many settings, this method is being used to replace stretching techniques without knowledge of whether fascial tightness is actually restricting the muscle. Recent studies have demonstrated that this technique is effective in increasing ROM (MacDonald et al, 2013; Kuruma et al, 2013; Mohr et al, 2014; Junker & Stoggl, 2015).

While each technique appears to have some utility, the technique chosen depends on a few factors, specifically the clinician, the setting, and the patient/athlete’s preference. Previous work has investigated the effects of myofascial release (MacDonald et al, 2013; Kuruma et al, 2013; Mohr et al, 2014; Junker & Stoggl, 2015), proprioceptive neuromuscular facilitation (Maddigan et al, 2012; Rees et al, 2007; Schuback et al, 2004; Wicke et al, 2014; Yuktasir, 2007), and dynamic and static stretching (Konrad & Tilp, 2014; Amiri-Khorasani & Sotoodeh, 2013; Nelson & Bandy, 2004; O’Sullivan et al, 2009; Perrier et al, 2011; Samson et al, 2012) on ROM. However, the outcomes (increase in ROM) of the majority of the techniques were
compared to static stretching since it is the most traditional stretching technique. No known literature has compared self-administered techniques of myofascial release, proprioceptive neuromuscular facilitation, and dynamic stretching in terms of relative effectiveness. This knowledge could help provide outcomes comparing these different treatments and may offer direction in developing a plan for patient care – to determine which technique will best cater to the patient’s abilities and goals. Additionally, in settings where clinicians may have a large patient load, understanding which technique is most effective and that a patient can self-administer will save the clinician’s time while also achieving the desired outcome. Therefore, the purpose of this study is to compare common methods of stretching on passive knee extension (PKE) ROM. Based on consistent findings of previous investigations, we hypothesize that PNF will result in greater immediate gains in ROM than dynamic stretching and foam rolling.
LITERATURE REVIEW

Importance of flexibility

Flexibility is the muscle’s ability to elongate to permit sufficient joint movement through a ROM (Graham, 2013). It is essential for everyday activities, as inflexible muscles have been known to cause low-back pain (Hasebe, Sairyo, Hada, Dezawa, & Okubo, 2014; Mierau, Cassidy, & Yonghing, 1989), abnormal gait (Wu, Lou, Lee, Chen, & You, 2014), and postural issues (Wong, Coleman, DiPersia, Song, & Wright, 2010). Insufficient flexibility may make an activity, hobby, or occupation less enjoyable and more difficult or painful.

Although some sports demand less joint ROM compared to others, attaining sufficient ROM is essential for every athlete. For example, a cyclist would not need to acquire as much lower extremity ROM as an ice skater or gymnast, just as a long-distance runner would not need the same amount of trunk rotation as a golfer would; the demand for joint ROM varies from sport to sport. Therefore, it is crucial for the athlete to attain sufficient joint ROM to perform effectively and functionally in their specific sport (McHugh & Cosgrave, 2010; McMillian et al, 2006; Amiri-Khorasani & Sotoodeh, 2013).

Increasing flexibility requires decreasing tissue resistance surrounding the joint, which has shown to increase performance (Shrier, 2004). Investigators studied the effects of static stretching and PNF on ROM, maximum voluntary contraction (MVC), contraction velocity, force of contraction (eccentric and concentric), counter-movement jump height, and 50-yard dash (Handel, Horstmann, & Dickhuth, 2014; Wilson, Elliott, & Wood, 1992; Worrell, Smith, Winegarder, 1994). Results demonstrated an increase in these outcome measures, concluding that an increased flexibility improves sport performance.
Attaining sufficient flexibility has also been shown to reduce the risk of injury, specifically hamstring strains (Hartig & Henderson, 1999; Verrall et al, 2005). One study found that 150 seconds of a static hamstring stretch applied every day for 13 weeks significantly decreased lower extremity overuse injuries when compared to the control group (12.4% decrease) (Hartig & Henderson, 1999). Another investigation followed an Australian sports team for 4 years (Verrall et al, 2005). The first 2 years acted as the control and during the third year, the intervention began, which included a minimum of 15-second static hamstring stretches by flexing the trunk and while keeping the knee flexed at varying angles. Additionally, anaerobic interval training and sports specific drills were performed as part of the intervention. Outcomes resulted in 2 hamstring strains that year, and 4 hamstring strains the fourth year. This was a significant decrease compared to the 9 and 11 hamstring strains the first and second year (respectively) prior to the intervention (Verall, 2005).

Due to the benefits of flexibility, it is important for individuals to attain a sufficient amount via a stretching protocol.

**Theories of stretching**

Stretching increases flexibility to provide adequate joint ROM (in those lacking normal ranges) to achieve optimal performance and increases muscle compliance to theoretically reduce the chance of injury (McHugh, 2010). The increase in muscle extensibility is thought to result via mechanical and neuromuscular (sensory) mechanisms. Muscles possess an amount of intrinsic stiffness- the passive (i.e. no neural input), mechanical resistance to stretching. In order to elongate a muscle, a mechanical force that exceeds the intrinsic stiffness must be overcome. A change in muscle stiffness is demonstrated in the slope of the torque-angle data – a decrease in the slope expresses a decrease in muscle stiffness, resulting in an increase in

The theory of viscoelastic deformation (Taylor, Dalton, Seaber, & Garrett, 1990) explains that skeletal muscles are both elastic, meaning that a muscle will stretch when a tensile force is applied to it, but it will return to its original resting length once the tensile force is removed. This stretching response is described as viscous since it depends on the rate and time of the tensile force application. Viscoelastic deformation has been investigated using static stretching to demonstrate viscoelastic stress relaxation, which is when the muscle’s resistance decreases when the muscle is held in a static stretch (Weppler & Magnusson, 2010). This was demonstrated in a study (Magnusson, Simonsen, Aagaard, & Kjaer, 1996) that showed a decrease in hamstring musculotendinous stiffness by passive static stretching. Using an isokinetic dynamometer, PKE ROM was measured after 2 interventions – a test-retest protocol that consisted of 2 static 90-second static PKE stretches administered 1 hour apart, and a repeated stretch protocol consisting of five 90-second static stretches followed by a sixth repetition an hour later. The decrease in stiffness was transient, as baseline was reached within an hour (Magnusson et al, 1996).

The plastic deformation theory suggests that a pull sufficient enough for the muscle to exceed its elastic limitations causes permanent deformation of the musculotendinous tissue (Figure 1). The excessive pull forces the muscle into the plastic region of the torque/angle curve and the tissue no longer returns to its initial length, remaining in an elongated position (Weppler & Magnusson, 2010).
One study (Wessling, DeVane, & Hylton, 1987) implemented a static stretch and a static stretch combined with ultrasound on the triceps surae to observe increases in dorsiflexion. They suggest that their findings display plastic deformation of the muscle, but no evidence in their studies show this occurrence, as they were unable to truly measure the muscle’s plasticity (Wessling, 1987).

The neuromuscular relaxation theory suggests that a slowly applied static stretch or PNF technique promotes neuromuscular reflexes that stimulate relaxation of muscles being stretched. The relaxation then allows for an increase in muscle extensibility (Weppler & Magnusson, 2010). Autogenic and reciprocal inhibition are neurophysiological principles used to explain this theory (Schuback et al, 2004; Yuktasir, 2007). Isometrically contracting a maximally-stretched target muscle results in decreased muscle tension through stimulation of
Golgi tendon organs, leading to decreased resistance to the stretch and length changes, and thus producing an increase in ROM. Reciprocal inhibition involves concentrically contracting the antagonist, resulting in decreased resistance and motor neuron excitability (autogenic inhibition) in the target muscle and thus increasing muscle compliance by providing muscle lengthening (Yuktasir, 2007). It is assumed that an inhibitory interneuron decreases α-motor neuron activity to the antagonist muscle, resulting in the greatest potential for lengthening the muscle (Schuback et al, 2004). Evidence of this theory is shown in studies where stretching the hamstrings resulted in an increase of ROM (Maddigan et al, 2012; Nelson & Bandy, 2004; Schuback et al, 2004; Yuktasir, 2007).

Lastly, what is referred to as the “sensory theory” by Weppler et al (2010) suggests that the increase in muscle extensibility resulting from a stretch are attributed to the individual’s modified sensation, allowing the stretch to be tolerated at a greater end-range joint angle. Investigators credit this theory as the reason for an increase in ROM in their studies that resulted in an increase in ROM (Konrad & Tilp, 2014; Nelson & Bandy, 2004).

**Techniques for increasing joint range of motion**

*Static stretching*

Static stretching has become a traditional stretching technique practiced clinically. Increases in lower extremity joint ROM have been reported by investigators (Konrad & Tilp, 2014; Maddigan et al, 2012; Nelson & Bandy, 2004; Yuktasir, 2007) that have studied the effects of static stretching routines. Programs were implemented for six weeks in length, ranging from session frequencies of 3-5 days a week. Konrad et al (2014) implemented 30 sessions during the 6-week period. Sessions consisted of 30-second static self-stretching holds for 4 times. Unlike the other investigators mentioned, Konrad implemented these stretches on
the gastrocnemius medialis muscle and Achilles tendon while all others examined the effects of static stretching on the hamstrings. The 20 participants in the static stretching group had a mean dorsiflexion ROM that significantly increased from 30.9° to 36.3° (Konrad & Tilp, 2014).

Another study (Nelson et al 2004) included 69 high-school-aged males and measured knee extension ROM to determine hamstring flexibility. With 6 sets of a 30-second static self-stretches completed 3 days a week for 6 weeks, 90-90 PKE ROM increased by a mean of 12.05° (Nelson & Bandy, 2004). In a similar study that implemented a 30-second passive static stretch on the hamstrings 4 times a week on 10 male participants, the average 90-90 PKE ROM significantly increased from 21.6° to 27.8° (Yuktasir, 2007).

One investigation (Maddigan et al, 2012) implemented a static hamstring stretch session consisting of two 6-second stretches using the hip flexors to actively increase hip flexion that was measured with an electronic goniometer. In between the two active stretches, the participants were instructed to “reach for their toes” for 5 seconds. Unlike other investigations, the immediate effects of this single-session of stretching were studied. Passive hip flexion ROM increased significantly with a mean improvement of 5.4° (Maddigan et al, 2012).

On the contrary, one study (Wicke et al, 2014) resulted in no significant increase in hip flexion ROM when attempting to increase hip, back, and shoulder flexibility. Researchers implemented 2 sets of a 40-second static self-stretch on the hamstrings of 19 participants for 2 days a week for a 6-week period and utilized the sit-and-reach test. Results indicated no significant increases in mean hip ROM when comparing pre and post-test numbers (Wicke et al, 2014).

Unsurprisingly, a total of 160 seconds of static stretching a week was insufficient time to increase hip ROM over a 6-week period (Wicke et al, 2014). The 160-second duration in 1
week in this long-term study was less than a single session’s stretching that was applied 3 days a week in another study, which resulted in an increase in PKE ROM (Nelson & Bandy, 2004). As for the immediate effects of a single-session stretch, findings resulted in significant hip ROM improvement (Maddigan et al, 2012). Overall, whether a long-term or single-session stretching protocol is implemented, static stretching may be beneficial in increasing ROM if duration and frequency of the stretch is sufficient.

Dynamic stretching

Several investigations (Amiri-Khorasani & Sotoodeh, 2013; O’Sullivan et al, 2009; Perrier et al, 2011; Samson et al, 2012) that studied the effect of dynamic stretching on ROM. Although dynamic stretching is known to prepare the body for physical activity (Perrier, 2011) studies have not shown its efficacy for improving ROM (O’Sullivan et al, 2009; Samson et al, 2012).

One study included 18 injured individuals and 18 uninjured individuals who incurred a hamstring strain within the past year, but not the past month. Beginning with a 5-minute jog, each participant then performed active leg swings or a static hamstring stretch (3x30 seconds). They found that the static passive stretching technique resulted in greater increases in PKE ROM compared to the dynamic stretches for the injured (ROM measurements: 151.1° ± 7.31 vs. 146.8° ± 8.59) and uninjured (ROM measurements: 150.7° ± 5.34 vs. 148.1° ± 5.51) (O’Sullivan et al, 2009). However, 120 seconds of leg swings may be an insufficient duration to observe an increase in PKE ROM. The amount of time that the hip is flexed into a position to stretch hamstrings is roughly a couple of seconds each leg swing. Unlike a static stretch, the hamstrings are not held in an elongated position for an adequate period of time.
Another study (Samson et al, 2012) measured ROM using the sit-and-reach method after the different stretching treatments to compare the conditions amongst each other rather than comparing the pre- and post- ROM measurements. The interventions included 2 static and 2 dynamic treatments with and without a specific stretching program. The general warm-up consisted of a 5-minute run at 70% of the individual’s maximal heart rate, and the specific stretching included high knee skipping, high knee running, and butt kicks. The dynamic stretching comprised 3x30 seconds of hip flexion, extension, abduction, adduction, trunk circles, and passive ankle rotation. Individuals in the static groups had a partner passively stretch their hamstrings, quadriceps, and low back 3x30 seconds. Investigators found that the dynamic stretching conditions resulted in a 2.8% decrease in sit-and-reach score than both static conditions, concluding that a 90-second static stretch will increase ROM over a dynamic stretch (Samson et al, 2012).

A study (Perrier et al, 2011) that examined the acute effects of static and dynamic stretching on low-back and hamstring flexibility used the sit-and-reach test as well. Investigators also did not assess baseline ROM, but rather compared the ROM scores between the control, static and dynamic conditions after the treatment was applied. Twenty one males completed a 5-minute jog followed by no stretch (control), static or dynamic stretch protocol that targeted the major muscle groups of the lower extremity, performing 2x30 seconds of 7 stretches for the static group or 11 exercises over a 36-meter distance for the dynamic group. Investigators found that both interventions resulted in a significant increase compared to the control group, and that no significant difference existed between the static and dynamic conditions (32.8cm and 33.2 cm, respectively) (Perrier et al, 2011).
Despite inconsistent ROM results after dynamic stretching, one study (Amiri-Khorasani & Sotoodeh, 2013) resulted in the opposite findings as the previously mentioned studies. Investigators implemented a 4-minute jog followed by a static, dynamic, combined (static then dynamic), and control stretching programs that included the gastrocnemius, hamstrings, hip extensors, hip flexors, quadriceps, and hip adductors as the treated muscle groups. Because no baseline ROM measurements were done, the ROM results of the static, dynamic, and combined groups were relatively compared to the control group, which only completed the 4-minute jog. Using the V-sit test, results indicated that the dynamic group showed the greatest increase in absolute ROM followed by the combined group then the static group when compared to the control (Amiri-Khorasani & Sotoodeh, 2013). An element that differs from the other studies is that the participants performed fitness tests before their V-sit test was completed, as their goal was to compare stretching methods on various performance tests in addition to ROM improvements. Completing the fitness tests may have affected the outcomes, as the static stretching group being tested for vertical jump, agility, acceleration, and speed tests requires dynamic movement. This may have increased measurement outcomes for the dynamic and combined group, as these tests may have enhanced the dynamic treatment.

Among these four investigations comparing dynamic and static stretching (Amiri-Khorasani & Sotoodeh, 2013; O’Sullivan et al, 2009; Perrier et al, 2011; Samson et al, 2012), a factor that may be contributing to static stretching resulting in greater ROM improvements over dynamic is the duration and frequency of the stretches. Studies (O’Sullivan et al, 2009; Samson et al, 2012) did not show ROM improvements when dynamic stretching was compared to 90 seconds of static stretching. Sit-and-reach scores in the study by Perrier et al (2011) resulted in no difference when comparing the 60-seconds of static stretching to the dynamic
stretching group, and the V-sit test in the study by Amiri-khorasani et al (2013) resulted with the dynamic stretching showing a greater improvement over the combined stretching and 30-second static stretching groups. Due to the lack of consensus in an effective dynamic stretching treatment, these studies may indicate that dynamic stretching may only be beneficial in preparing the body for physical activity rather than increasing ROM.

*Proprioceptive neuromuscular facilitation*

Investigators have studied the short- (Maddigan et al, 2012; Schuback et al, 2004) and long-term (Rees et al, 2007; Wicke et al, 2014; Yuktasir, 2007) effects of PNF on ROM. Some measured knee extension ROM (Yuktasir, 2007) or hip flexion ROM (Maddigan et al, 2012; Schuback et al, 2004; Wicke et al, 2014) to measure hamstring flexibility, and one researcher measured ankle dorsiflexion ROM (Rees et al, 2007). Regardless of the method of PNF, the results remained consistent.

Researchers conducted a study (Maddigan et al, 2012) that implemented the following 4 types of PNF techniques 4 times on the hamstrings of 13 participants using 70% of maximum strength: Isometric unassisted PNF with strap, unassisted PNF concentric with strap, unassisted PNF eccentric with strap, and partner-assisted isometric PNF. Pre and post measures included dynamic, active static, and passive hip flexion ROM. Although the interventions showed different improvements, mean hip flexion ROM of the techniques combined increased by 3.5% (2.6, 2.7, and 5.4% in dynamic, active static, and passive static, respectively) and no significant difference between the 3 protocols was found. The investigators concluded that said PNF techniques can be implemented using a strap or with assistance from a partner to achieve greater ROM (Maddigan et al, 2012).
Another study (Schuback et al, 2004) compared hip ROM of an unassisted PNF technique group (Group 1) to an therapist-assisted PNF technique group (Group 2) applied to the hamstrings with the components consisting of a 15-second contraction, 15 seconds of relaxation (slow-reversal-hold-relax PNF technique) repeated 4 times. Upon this single session, mean hip ROM increased for both groups (Group 1: 9.6° and Group 2: 12.6°). When stretching techniques were compared to each other, no significant differences were found, indicating a self-administered PNF technique may be as effective in increasing hamstring flexibility as a therapist-assisted (Schuback et al, 2004).

These 2 studies administered a single treatment session only, which consisted of 4 repetitions of each PNF treatment. Although methods differed, both investigations resulted in a significant increase in hip flexion ROM. Participants in Schuback’s study ranged from 20-55 years of age and were not required to meet a physical activity criterion whereas participants in Maddigan’s study were between 19-28 years of age and were healthy and recreationally active. The varied physical activity levels in Schuback’s investigation may have contributed to the 3° decrease in the self-stretch group compared to the physiotherapist-applied group. Because the participants were required to perform a maximal contraction, physically inactive participants may be unfamiliar with their maximum strength, potentially resulting in inconsistent maximum contraction efforts, and therefore, inconsistent treatment. However, because the age population included adults up to 55, it may indicate that the self-administered or assisted slow-reversal-hold-relax PNF is beneficial for a wide-range age group (Maddigan et al, 2012; Schuback et al, 2004).

In another study (Rees et al, 2007), the contract-relax agonist-contract (CRAC) PNF method was applied to the plantar flexors of 20 physically active women. After the researcher
passively moves the ankle to maximal dorsiflexion, the participant would maximally and isometrically contract their plantar flexors for 6-10 seconds, rest 2 seconds, then passively moving the ankle into dorsiflexion followed by 6-10 seconds of active dorsiflexion. These steps were repeated 4-6 times, 3 times a week for 4 weeks with sets and length of contractions increasing each week. With pretest ROM of left and right ankle joints measuring 86.9°, mean ROM increased by 7.8% in both left and right ankle joints, resulting in a ROM of 80.1° (Rees et al, 2007).

In a long-term study (Wicke et al, 2014), investigators implemented a self-administered contract-relax PNF technique on 19 participants for 2 days a week during a 6-week period. With their hip flexed and heel of their foot on the seat of a chair, participants were instructed to perform a static stretch on their hamstrings for 15 seconds, isometrically contract against a 50-cm tall chair for 10 seconds using 90% of maximum effort, and then perform another static stretch for 15 seconds. This was done twice on each leg. Findings show a significant difference between the PNF and static stretching group, with mean increase of 6.2° for PNF and a loss of 0.6° hip ROM for static stretching. Of the investigations mentioned, this was the only long-term study that compared the effects of static stretching and PNF technique on ROM (Wicke et al, 2014).

Another long-term study (Yuktasir, 2007) included the application of the contract-relax PNF technique on the hamstrings of 9 males for 4 times a week for 6 weeks. This method consisted of 5 seconds of active hip extension and ankle plantar flexion against a submaximal force provided by the investigator, 5 seconds of relaxation, then a hip- and dorsi-flexion stretch applied by the investigator for 15 seconds. These steps were repeated 4 times for each leg.
Mean 90-90 PKE ROM significantly increased from 26.33°±6.28 to 7.11°±4.64, pre and post (Yuktasir, 2007).

Rees (2007), Wicke (2013), and Yuktasir et al (2007) implemented a longer treatment that was applied 2-4 times a week for 4-6 weeks. Unlike Reese, Wicke and Yuktasir et al did not administer a familiarization session for the participants to become accustomed to the PNF technique prior to testing. The different levels of familiarization to PNF may have influenced the ROM outcomes, as the learning curve may have varied among the participants of the studies. However, Yuktasir et al ensured that their participants were already well-acquainted to the technique (details of familiarity not mentioned) whereas Wicke et al did not require any familiarization of PNF for their participants.

The long-term studies did not measure joint ROM after each treatment session, which may beg the question of transient ROM increasing after the final treatment session during the final ROM measurement. Had the investigators studying the long-term effects of PNF on ROM (Rees et al, 2007; Wicke et al, 2014; Yuktasir, 2007) recorded ROM measurements after each treatment session, a progression of the ROM increases would be more apparent. However, the overall goal of finding a technique to increase ROM has been concluded in these studies, as the literature demonstrates the efficacy of PNF on increasing ROM regardless of treatment duration, period of treatment time, or method of PNF.

Myofascial release

Studies provide evidence supporting foam rolling and manual myofascial release as a treatment for increasing ROM. One study (MacDonald et al, 2013) conducted an experiment that implemented a self-myofascial release (SMR) technique using a PVC pipe covered with 1-cm thick foam on the quadriceps of 11 males. This treatment was performed for 1 minute,
followed by 30 seconds of rest, then another minute of rolling the PVC pipe under the quadriceps. Passive knee flexion ROM was measured pre- and post-treatment (2 and 10 minutes post foam roll). Results indicated a significant increase of mean passive knee flexion ROM by 12.7% and 10.3% (10.6° and 8.8°), 2 and 10 minutes after treatment, respectively (MacDonald et al, 2013).

Another study (Kuruma et al, 2013) included 40 participants receiving 8 minutes of treatment. The different conditions included manual MFR on the quadriceps, manual MFR on the hamstrings, static stretching of the quadriceps, and a control. Each group, consisting of 10 participants, received said treatment for 8 minutes. Active and passive knee flexion ROM were measured before and after the interventions. Active knee flexion ROM significantly increased in both MFR groups (quadriceps: +4.1°, hamstrings: +3.1°) and stretching group (+3.5°), but not the control. Passive ROM only significantly increased in the quadriceps MFR and stretching group, (+3.6° and +3.2° mean increase, respectively). When the intervention groups were compared to each other, no significant differences were found (Kuruma et al, 2013). This investigation indicates that a MFR applied to the hamstrings may be just as effective in increasing active knee flexion ROM as a MFR or stretching of the quadriceps. Researchers took it a step further by including MFR treatment group on the hamstrings, as fascia is a connective web that will affect areas other than the treated site (Kuruma et al, 2013).

An investigation (Mohr et al, 2014) treated the hamstrings by having 40 participants (10 per intervention) complete 3 minutes of static stretching, 3 minutes of foam rolling, a combination of the two (6 minutes total), and the control to determine the effects of each intervention on passive hip flexion ROM. Results indicated that all interventions increased hip flexion ROM with the combination group having a greater increase (23.55° ± 3.53) compared
with the other 3 interventions (static: 12.3° ± 4.2, foam rolling: 6.9° ± 4.0, control: 3.7° ± 1.8). The investigators concluded that a combination of foam rolling and static stretching will increase the greatest passive hip flexion ROM in individuals with less than 90° hip flexion ROM.

A more recent study (Junker & Stoggl, 2015) investigated the long-term (3 times a week for 4 weeks) effect of foam rolling and self-administered contract-relax PNF on the hamstrings of both legs of 40 participants. Thirteen participants performed foam rolling 3 times for 30-40 seconds, 14 participants performed 50 seconds of PNF, and 13 participants were the control group. The PNF and foam rolling treatments resulted in a greater increase in Stand-and-Reach scores when compared to the control group, however, there was no difference between the 2 interventions (PNF: 3.0 ± 2.1cm, CRPNF: 4.0 ± 2.9 cm). Researchers concluded that 3 repetitions of foam rolling for 30-40 seconds and 50 seconds of contract-relax PNF done 3 times for 4 weeks are effective techniques in increasing ROM.

These studies indicate that manual or self-administered MFR are effective treatments to increase ROM. Furthermore, as little as 1.5 minutes of foam rolling is shown to result in greater ROM improvements and still be effective after 10 minutes of inactivity. However, the mechanisms of foam rolling are still uncertain as it is impossible to truly determine if myofascial adhesions are being released.

**Conclusion**

Range of motion results of investigations studying the effects of static and dynamic stretching varied; however, factors such as stretch duration, type of stretch, and method of measurement differed greatly among these studies and may have contributed to the fluctuating outcomes. Despite the method of PNF applied, it has demonstrated to be an effective technique
to increase ROM. Although there is limited literature on myofascial release on ROM, the outcomes demonstrate its effectiveness in increasing ROM.
METHODS

Participants

We included participants who were physically active (participated in physical activity at least 3 days a week for 30 minutes), had a body mass index \( \leq 28 \text{ kg/m}^2 \), and had at least a 20° deficit in PKE ROM (from full knee extension = 0°) with hip flexed to 90°. Participants were excluded if they had a neuromuscular disorder affecting their lower extremities, hamstring pain or any pain that would contraindicate stretching, had undergone surgery in the last 12 months, or if they marked “Yes” to any items on the PAR-Q.

Consent and screening procedures

Individuals were contacted via email to determine a meeting time for a familiarization and testing session for each of the 4 interventions, which was conducted in Room 174 of Redwood Hall of California State University, Northridge. During the screening, the researcher ensured that the participants met the inclusion criteria, including PKE ROM of their dominant limb, measured with an Acumar digital inclinometer (Lafayette Instrument Co., Lafayette, IN). If the potential participant met all criteria and wished to participate, they were asked to read and sign a consent form. They were assigned a subject code number for confidentiality purposes, and their order of interventions were determined via a counterbalance scheme (E.g. Counterbalance 1 = PNF, MFR, Dynamic stretching, Control; Counterbalance 2 = MFR, Dynamic stretching, Control, PNF). The participants were familiarized to all testing procedures and the 4 testing techniques.

In order to minimize the introduction of potentially-confounding factors that could affect ROM, participants were instructed not to perform any stretching, weight-training, or arduous physical activity the day before and day of testing (López-Miñarro & Alacid, 2010).
Also, to prevent carry-over effects of each intervention from affecting the outcome of the other treatments, each testing was completed at least 3 days apart, as one study (Perrier et al, 2011) ensured 3-7 days between interventions and another separated them a maximum of 10 days apart (O’Sullivan et al, 2009). Lasting effects of stretching on active knee extension ROM have shown to last 6 minutes (Spernoga, Uhl, Arnold, & Gansneder, 2001) and 25 minutes (Ford & McChesney, 2007) after PNF was performed.

**Testing procedures**

On the day of testing, participants wore shorts to allow for accurate palpations of the bony landmarks required to take the PKE ROM measurements. Height and weight was measured on the participant’s first day of testing using a standard stadiometer and scale, respectively.

Assessing hamstring flexibility by measuring the knee extension angle is found to be the gold standard (Davis, Quinn, Whiteman, Williams, & Young 2008). To measure PKE ROM, an apparatus attached to a treatment table with clamps is designed to stabilize the participant’s hip to 90°.
The participants laid supine on the treatment table (Figure 2) while the investigator established 90° hip flexion of the dominant leg, which happened to be the right leg for all participants. After the investigator established the participant’s greater trochanter and lateral femoral epicondyle, the participant held 1 finger on their greater trochanter and the lateral femoral epicondyle was pen-marked on the skin with the knee passively extended to a point where resistance in the hamstrings is felt by the investigator. The axis of a standard goniometer was positioned over the pen-marked lateral femoral epicondyle and both arms pointed at the participant’s finger. While passively flexing the participant’s hip with their anterior thigh against the plank of the apparatus, the investigator directed the participant to move up or down the treatment table to ensure the goniometer (parallel to femur) is directly parallel to the vertically positioned board of the apparatus. Using the Acumar digital inclinometer, the stabilization board of the apparatus was measured to be 0°, indicating it is perpendicular to the
treatment table. The inclinometer was placed on the mid-point of the anterior border of the tibia, which was determined by using measuring tape to measure the participant’s tibia length from the medial malleolous to the medial tibial condyle. A handheld dynamometer (*Hoggan Scientific, LLC*, Salt Lake City, UT) was used to measure peak force applied during each participant’s testing sessions, and was placed 2 inches proximal to the participant’s posterior heel. The inclinometer was held in place using the investigator’s left hand and the hip was passively flexed and stabilized against the plank at 90° using the right hand, which also held the handheld dynamometer. The investigator began with the knee flexed, then passively and slowly extended the knee until the participant reported discomfort in their hamstrings (Figure 3). We chose to use the digital inclinometer instead of the goniometer because of the greater speed at which we could acquire the joint angle, which decreased the amount of the time that the participant was placed on a maximal stretch. During pilot testing, we validated the digital inclinometer against the goniometer and determined that acceptable inter-instrument agreement existed \((ICC_{2,1} \text{ (SEM)}=0.92 \pm 3.40^\circ)\). The investigator also established excellent day-to-day reliability \((ICC_{2,1}= 0.94)\) with a measurement precision of 3.43°.

The angle displayed on the inclinometer was recorded at the point where the participant verbally reported discomfort.
Measurement of peak knee extension range of motion (PKE ROM) when the hip is placed in 90° of flexion. The digital inclinometer was placed mid-shank while force was applied to the distal shank with a handheld dynamometer to passively push the knee into extension to the point of the participant’s report of discomfort.

After recording baseline PKE ROM (PRE) before each intervention, all participants completed a 5-minute jog at a self-selected pace (Amiri-Khorasani & Sotoodeh, 2013; Perrier et al, 2011; O’Sullivan; Samson et al, 2012) followed by their assigned treatment for that day, as described below:

**Treatment 1: Self-administered Proprioceptive Neuromuscular Facilitation (PNF)**

Participants were instructed to sit on a treatment table with the knee of treated leg extended and perform 8 minutes of the Hold-Relax PNF technique. With the treated leg and hip on the table and the other foot on the ground, participants leaned their trunk down toward the table (trunk + hip flexion) until they feel their hamstrings are stretched to the point of discomfort. With their knee and foot pointing directly upward to avoid hip rotation, the
participants remained in this position to stretch their hamstrings for 5 seconds. After, they pushed the heel of their foot into the table for 5 seconds using maximum effort, relaxed for 5 seconds, leaned their trunk further toward the table, and repeated this process for 8 minutes. A 10-second break was permitted every 3 repetitions.

Standing, seated, and supine positions of hamstring stretching have not demonstrated a significant difference in ROM improvements (Decoster, Cleland, Altieri, & Russell, 2005).

**Treatment 2: Foam Rolling**

Participants performed 8 minutes of self-myofascial release treatment using a foam roller on the entire length of the hamstrings, from the ischial tuberosity to the posterior knee. They rolled out their hamstrings at a rate of 3-4 times per minute (MacDonald et al, 2013) with 10 seconds of rest after each minute (Maddigan et al, 2012; Yaktusir & Kaya, 2007). This rate was controlled by timing the participant’s pace of rolling out – 15-20 seconds over the entire length of the hamstrings.

**Treatment 3: Dynamic stretching**

Participants were instructed in the performance of a dynamic stretching targeting the hamstrings. They performed 16 repetitions of each exercise over an 18-meter distance, adding, adding up to approximately 8 minutes for the entire protocol. Table 1 lists the exercise with a description of each.
<table>
<thead>
<tr>
<th>Exercise</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Butt kicks</td>
<td>Bend knee and drive heel to buttock while keeping knee pointed toward the ground. Alternate between legs.</td>
</tr>
<tr>
<td>Lunges</td>
<td>With chest in upright position, take a step forward, lower body by flexing knee and hip of lead leg to 90°, using the lead foot to support body weight and the back leg for balance. Lead foot remains flat on ground, and when the 90° hip and knee flexion is attained, push off of lead foot to bring body into standing position. Alternate between legs.</td>
</tr>
<tr>
<td>Walking high knee pull</td>
<td>With chest in upright position, step forward into a single-leg balance. Bring knee towards chest with foot dorsi-flexed, grab knee with both hands and pull knee as close to chest as possible. Alternate between legs.</td>
</tr>
<tr>
<td>Walking hamstrings</td>
<td>Keeping back flat, step forward and extend knee fully while dorsi-flexing foot maximally. Bend waist forward and reach for toes. Alternate between legs.</td>
</tr>
<tr>
<td>Walking toe-touch</td>
<td>Step forward, place foot flat on the ground, extend knee fully, bend forward at waist and touch ground while simultaneously lifting opposite leg behind body and extending hip. Alternate between legs.</td>
</tr>
<tr>
<td>High knees</td>
<td>With chest in upright position, maximally flex knee and hip to bring knee as high as possible, quickly alternating between legs and moving in a forward direction. Opposite arms coordinate movement of legs.</td>
</tr>
<tr>
<td>Russian walk</td>
<td>With chest in upright position, maximally flex hip by bringing knee to chest then fully extend knee with foot dorsi-flexed. Alternate between legs.</td>
</tr>
<tr>
<td>Flexed leg drive</td>
<td>With chest in upright position, drive knee and leg maximally upwards into hip flexion with knee slightly flexed, and swing opposite arm to coordinate the movement. Alternate between legs.</td>
</tr>
<tr>
<td>Extended leg drive</td>
<td>With chest in upright position, drive foot upwards while keeping knee extended, and reach hands forward and upwards towards foot. Alternate between legs.</td>
</tr>
<tr>
<td>Graduated sprints</td>
<td>At 50% of maximum speed for 10 meters. At 75% of maximum speed for 15 meters. At 100% of maximum speed for 20 meters.</td>
</tr>
</tbody>
</table>
**Treatment 4: Control**

Participants completed a 5-minute jog at a self-selected pace, then sat in a chair for 8 minutes. The 8-minute time period was chosen to ensure equal treatment time for each group.

Immediately following each treatment, the participants’ PKE ROM was measured by the investigator (POST).

**Data Reduction**

The peak knee flexion position achieved out of the three trials was used for the analysis. The difference score (Post-Pre) was calculated and used as the dependent variable for analysis.

**Statistical analysis**

To determine whether the interventions resulted in a significant increase in PKE ROM, paired t-tests first compared the pre- and post- test PKE ROM scores for each of the interventions separately. Then, to determine whether any of the interventions elicited a larger increase in ROM compared to the other interventions, a one-way ANOVA compared the difference scores (post-pre) in PKE ROM between the 4 interventions (PNF, foam rolling, dynamic stretching, and control). An a priori power analysis (G*Power 3.0.10) indicated that 56 total participants (14 per intervention) would be needed to achieve 85% power to detect differences between group and across time with a moderate effect size of 0.25 at an alpha level of 0.05. Data analysis was conducted using SPSS Statistics (v. 22) software (IBM Corp., Armonk NY).
RESULTS

Thirty five healthy young adult males and females (173.8±9.39 cm, 72.1±13.8 kg, 24.6±2.5 yr.) completed all 4 interventions. Rather than recruiting 56 participants to complete 1 intervention each, 35 were recruited to complete all 4 interventions. All participants were right leg dominant (i.e. indicated that they preferred to kick a ball with their right foot).

Descriptive statistics for PKE ROM before and after each intervention are displayed in Table 2 as well as the pre-post change and effect size.

<table>
<thead>
<tr>
<th>Intervention</th>
<th>N</th>
<th>Pre (°)</th>
<th>Post (°)</th>
<th>Change (°)</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic</td>
<td>35</td>
<td>59.8±7.8</td>
<td>68.9±8.7</td>
<td>9.1±4.4</td>
<td>1.05</td>
</tr>
<tr>
<td>PNF</td>
<td>35</td>
<td>60.7±8.2</td>
<td>71.7±9.1</td>
<td>11.1±4.9</td>
<td>1.21</td>
</tr>
<tr>
<td>MFR</td>
<td>35</td>
<td>58.6±8.6</td>
<td>65.7±8.9</td>
<td>7.1±4.7</td>
<td>0.80</td>
</tr>
<tr>
<td>CTRL</td>
<td>35</td>
<td>60.0±8.8</td>
<td>62.4±9.8</td>
<td>2.4±2.8</td>
<td>0.24</td>
</tr>
</tbody>
</table>

The paired t-tests indicated a significant increase for the dynamic stretching (t(34)= 12.3; P<0.001), PNF (t(34)= 13.3; P<0.001), and MFR (t(34)= 8.9; P<0.001) interventions (Table 2). We also noted a significant increase in ROM in the control group (t(34)= 5.2; P<0.001).

To determine whether any of the interventions resulted in a larger increase in ROM compared to the others, a one-way ANOVA compared the difference scores (post-pre) across all groups. The overall omnibus test was significant (F3,32= 27.7; P<0.001), indicating a difference in the increase in ROM between one or more of the interventions. The post-hoc pairwise comparisons (Figure 4) revealed that each of the interventions resulted in a larger
increase in ROM compared to the control condition (all P<0.001). Additionally, the PNF intervention resulted in a significantly greater improvement in ROM compared to MFR (11.1 vs. 7.1°; P<0.01).

The greatest (across the 3 trials) peak force (N) for each participant was recorded during pre- and post- ROM measurements (Appendix). The majority of the peak force recordings for each participant demonstrated little to no difference within their interventions and between pre- and post- ROM measurements. However, some participants demonstrated a substantial peak force difference up to 12 Newtons between pre- and post- ROM measurements of an intervention or up to a 7-Newton difference between interventions.
Figure 4. The changes in ROM following each intervention. All interventions resulted in a significant increase in ROM with the dynamic stretching, PNF, and myofascial release groups revealing a significant increase compared to the control group, and with PNF resulting in a significant increase compared to the myofascial release group.

* Significant increase in ROM following intervention.
† increase > Control (P<0.001)
‡ increase > MFR (P<0.01)
DISCUSSION

The primary finding was that self-administered PNF, dynamic stretching, and foam rolling resulted in statistically significant increases in PKE ROM. We noted a statistically significant increase in PKE ROM the control intervention, which is likely attributed to the tissue warming from the jog; however, it is doubtful that a 2.4° ROM increase would translate into a clinically-relevant increase in function. Additionally, although there was a 2° difference between self-administered PNF and dynamic stretching, and a significant difference of 4° between self-administered PNF and foam rolling, it is also improbable that one treatment is more effective than the other in improving functionality due to the difference in ROM increases being so minor.

Self-administered PNF

As hypothesized, PNF resulted in PKE ROM improvements in this study. This intervention was hypothesized to yield the greatest increases due to the consistency of previous investigations that have investigated interventions for increasing ROM. (Maddigan et al, 2012; Schuback et al, 2004; Yuktasir, 2007; Wicke et al, 2014). Investigations comparing between different types of PNF as well as self-administered versus clinician-applied PNF resulted in an increase in ROM (Maddigan et al, 2012; Schuback et al, 2004). Long-term studies (Wicke et al, 2014; Yaktusir & Kaya, 2007) comparing PNF and static stretching also found a ROM increase with PNF, with one study finding ROM increases only with PNF (Wicke et al, 2014).

Proprioceptive neuromuscular facilitation may have increased PKE ROM due to the underlying mechanisms by which PNF works, as compared to the other two interventions. Unlike the other interventions in the current study, PNF operates via a neural and mechanical adaptation mechanism whereas the other treatments function through just a mechanical
adaptation mechanism. Autogenic inhibition and reciprocal inhibition are responsible for the neural mechanism in PNF. In the current study, it is likely that autogenic inhibition is the neural factor in increasing ROM, and mechanical mechanism refers to the component in the PNF technique that involved a 5-second static stretch by leaning the trunk forward to increase hip flexion, positioning the hamstrings to stretch and increase ROM. We surmise that PNF effectively increased PKE ROM in this study because of the combination of the two mechanisms.

Previous studies investigating PNF reported ROM improvements regardless of the number of sessions or duration of treatment (Maddigan et al, 2012; Schuback et al, 2004; Yuktasir, 2007; Wicke et al, 2014). Treatments of studies involving a minute or less of PNF (Maddigan et al, 2012; Schuback et al, 2004) and long-term studies involving 6 weeks of PNF (Wicke et al, 2014; Yaktusir & Kaya, 2007) have both shown ROM improvement. However, one of the long-term studies (Yaktusir & Kaya, 2007) that shares very similar PKE ROM measurement methods as the current elicited a 19.2° increase in PKE ROM, compared to the 11.1° in the current study. And although the ROM outcomes cannot be directly compared across the previous studies due to various measurement methods, it is also apparent that the long-term investigations that applied frequent treatments generate a greater ROM improvement when compared to the studies that implemented a single session. The larger treatment effect can likely be attributed to the frequency and duration of the treatment. This may imply that a long-term application of PNF will result in greater increases in PKE ROM than a single session. Additionally, as the larger increase in ROM was the result of 4 minute treatments compared to a single 8-minute treatment in the current study, this may suggest that treatment frequency should be emphasized over treatment duration. However, this also leaves the
potential for an even larger gain in ROM if longer treatments (i.e. similar to our study) are administered over a longer duration (like the aforementioned study (Yaktusir & Kaya, 2007)).

Overall, since PNF operates via 2 mechanisms, ROM can be expected to show significant improvement to its greatest potential with a long-term treatment consisting of just a few repetitions per session. With the participants assessing their point of discomfort during the treatment, they are able to reach the musculotendinous unit’s elastic limitations, thus causing permanent tissue deformation to improve ROM. Additionally, due to the sensory theory, it is very likely that the individual will show ROM improvements after each session with a long-term treatment due to their sensation being modified with each treatment, and therefore determining their point of discomfort at a further ROM over time. As for ROM measurements, it should be performed using bony landmarks, as goniometric alignment provides accuracy among participants unlike methods using the researcher’s estimation skills to eyeball the midline of a thigh. Bisecting the thigh is not only subjective to what the researcher deems as the midline of the thigh, but also may be inaccurate depending on the participant’s soft tissue mass. The goniometer arm may be aligned differently for participants with more muscle mass compared to a sedentary participant with a significantly less muscle mass. The varying body types in addition to the contrasting muscle masses will likely lead to measurement errors in investigations that did not align the goniometer to bony landmarks.

*Dynamic stretching*

Due to inconsistent findings in the literature, it is surprising that the dynamic stretching intervention showed a significant increase in PKE ROM. The physiological basis by which dynamic stretching is proposed to work is via an exercise-induced increase in core body temperature and blood flow, leading to an increase in muscle extensibility. Additionally, some
stretches in the dynamic stretching protocol utilized the reciprocal inhibition mechanism. For example, the participants performed straight leg raises to maximum hip flexion, requiring quadriceps contraction as the hamstrings are stretched as the leg reaches maximum hip flexion.

We observed a 9.1° increase in ROM following our dynamic flexibility warm-up, which is larger than that reported in previous investigations reporting acute adaptations. The current study included a 5-minute jog and focused the entire 8-minute dynamic stretching intervention on treating just the hamstring muscle group rather than distributing the treatment time among many muscle groups. Previous studies (Amiri-Khorasani & Sotoodeh, 2013; Perrier et al, 2011) investigating the effects of a 4-5 minute jog and dynamic stretching on low-back/hamstring flexibility resulted in average increases of approximately 3.51 centimeters (using the Sit-and-Reach test) compared to the control group despite the protocols focusing on multiple leg and hip muscle groups. With just the jog, tissue temperature increased due to the increased blood flow to the muscles. With the warmth of the blood flow increasing muscle tendon flexibility and the dynamic stretch implemented immediately after, the stretches allowed for the body to maintain its increased blood flow, resulting in tissue warmth and thus increasing muscle tendon flexibility (Herman, 2008).

Despite these investigations resulting in a ROM increase, one study (O’Sullivan et al, 2009) did not find a ROM increase after a 5-minute jog and 90 seconds of dynamic stretching consisting of leg swings (at a rate of 1 swing per second). Although the blood flow increased to the tissues with the jog, it is likely that the 90 leg swings was insufficient in increasing ROM due to the lack of treatment. A dynamic stretching protocol of a previous study (Perrier et al, 2011) included 8 hamstrings exercises at a distance of 36 meters and the current study included 16 repetitions of 9 exercises. Another study (Amiri-Khorasani & Sotoodeh, 2013) included
only 1 hamstring exercise of 5 repetitions of a gradual rate progression (slow, moderate, fast). However, this investigation included performance tests (vertical jump, agility, acceleration, and speed test) prior to post-ROM measurements, which more than likely affected the outcome for hamstring flexibility. Like PNF, this indicates that treatment frequency for dynamic stretching is crucial for ROM improvement. One researcher (Smith, 1994) indicated that dynamic stretching prepares the body for physical activity by increasing muscle and tendon flexibility and increasing blood flow and core temperature to result in coordinated movement. With sufficient treatment frequency, it may also increase muscular flexibility leading to a ROM improvement. Additionally, it is critical that the form of patients is monitored and corrected, as they may not understand that dynamic stretching is a complex process.

Foam Rolling

Foam-rolling resulted in an increase in an average of 7° PKE ROM, which was consistent with previous studies (Kuruma et al, 2013; MacDonald et al, 2013; Mohr et al, 2014; Junker & Stoggl, 2015). It is possible that foam rolling was a less effective technique for increasing ROM since it is conjectured to release myofascial adhesions that may restrict the muscle from lengthening and allowing full joint motion. Thus, it is possible that the immediate ROM improvement following the foam rolling intervention may be attributed to a release of myofascial restrictions and not an increase in hamstring flexibility. In the current study, the participants were not evaluated for myofascial restrictions, which could help explain our results. According to the proposed mechanism of this technique, participants with myofascial adhesions should show an increase in PKE ROM after foam rolling whereas participants without myofascial adhesions would not. Based on the current and previous research, individuals with both, a myofascial restriction and hamstring inflexibility, would ideally benefit
the most with a treatment consisting of a myofascial release and PNF treatment. However, to our knowledge, there are no investigations that address this claim, and therefore should be studied. Additionally, there is no definitive connection between MFR and foam rolling. Because myofascial adhesions are unmeasurable and based on theory, it is virtually impossible to determine if an individual has myofascial adhesions. It is possible that the force of the participants’ body weight on the foam roll created tension on the hamstring muscles, potentially causing a stretch and leading to an increase in PKE ROM.

**Clinical significance**

Our study specifically addressed PKE ROM deficits, and indirectly, hamstring flexibility. Self-administered PNF, dynamic stretching, and foam rolling are appropriate interventions to increase PKE ROM for individuals with a $\geq 20^\circ$ deficit in PKE ROM. Because of this finding, any of these techniques can be used for patients with a PKE ROM deficit. Self-administered PNF may be beneficial for patients who are unable to perform the dynamic stretching protocol or foam rolling. Because there was no difference in the improvements elicited by self-administered PNF and dynamic stretching interventions, it appears that either technique can be used. However, with PNF, the athlete does not get the benefits of the dynamic warmup to rehearse coordinated movements replicated in sports. Additionally, if several athletes of a sports team have inflexible hamstrings, the hamstring-focused dynamic stretching protocol can be integrated into their warm-up prior to practice or competition. Since the foam-rolling demonstrated to be an effective technique for increasing PKE ROM, and because there was no difference between foam rolling and dynamic stretching, it appears that either technique can be used.
Limitations and suggestions for further research

In the current study, neither the researcher nor the participants were blinded to the interventions before recording ROM measurements, so there is the possibility of bias. While it would not be possible to blind the participants to their interventions, it would be prudent in the future to at least blind the researcher.

With the current study implementing only one duration for the treatment period for each intervention (8-minute treatment), the optimal treatment time for each treatment is unknown. It is possible that the participants’ greatest PKE ROM was achieved at a lesser treatment duration. Future studies investigating ROM increases after varying treatment durations may determine the optimal treatment time that will allow the ROM to reach its plateaued improvement without wasting time.

While the outcome measurement of peak PKE ROM was measured objectively with an inclinometer, the point at which the measurement was acquired included a subjective aspect since the participant determined their own end-range by indicating to the researcher when they were stretched to the point of discomfort. The results could have been affected if the participant inconsistently reported their point of discomfort across interventions. It is also possible that since the participants understood the purpose of the study, if they were biased towards any of the interventions, they may have consciously or subconsciously allowed the researcher to apply more force to achieve a larger ROM improvement. In order to gauge this possibility, we used a handheld dynamometer to record the amount of force used to push the distal shank to achieve the maximum PKE position. Appendix 1 displays the average peak force used for each participant during each intervention. These measurements revealed some differences in force
across interventions. However, it is unknown how these differences in force application actually translated to degrees of ROM. Future work should attempt to control for or normalize the amount of force used to achieve peak passive end-range.

It is also possible that participants’ effort was not 100% present for all of the interventions. Some may have lost motivation or became fatigued and therefore not investing all their effort into the interventions. This may have caused fluctuating data among the treatments. Future studies should consider assigning each participant to only 1 intervention.

Although participants were instructed to refrain from participating in any stretching, weight-training, or arduous physical activity the day before and day of testing, they were not monitored between testing sessions to ensure that they followed instructions. Participating in such activities could have resulted in soreness, and thus possibly reaching a point of discomfort at less of a PKE ROM angle than if the activities were ensured to be avoided. This could also support the suggestion to assign each participant to only 1 intervention.

We included participants with at least a 20° deficit in PKE ROM when the hip was in 90° of flexion. However, we did not assess the underlying reason for the lack of knee extension. As such, it was unclear whether the foam rolling was effective as a “replacement” for stretching or whether many of our participants indeed had fascial restrictions to the hamstrings and hence, achieved greater PKE ROM because the foam rolling technique addressed the fascia. Future studies should investigate methods that determine if individuals have myofascial adhesions. Doing so will no longer describe myofascial release as a theoretical basis, but rather as an evidence-based practice. Following that investigation, participants in future studies should be evaluated to determine if they have myofascial adhesions; those who do should be excluded from the study to ensure that the ROM improvement is attributed to the
flexibility in muscle to result in a ROM improvements rather than the myofascial adhesions being released. Further, there is a likely possibility that joint ROM may be restricted due to a combination of myofascial restriction and myofascial tightness. In that case, it would be helpful to examine the combined effects of interventions aimed at both pathologies. In the current study, we only examined PKE ROM as an indication of hamstring flexibility. As such, it is unclear whether the interventions investigated and their relative effectiveness can be extended to other joints with ROM restrictions.
REFERENCES


The following is the greatest (across the 3 trials) force (N) applied for pre- and post-
measurements for each intervention. The purpose is to record the force used to bring the knee
to its end range for each participant. Due to individuals feeling different thresholds of “the
point of discomfort,” the researcher was able to assess if similar force was applied to each
participant within their 4 interventions.

Appendix. Pre and post peak force (N) applied for each intervention for each participant.
<table>
<thead>
<tr>
<th></th>
<th>26</th>
<th>27</th>
<th>28</th>
<th>29</th>
<th>30</th>
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