Does Flexibility Exercise Affect Running Economy? A Brief Review

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ABSTRACT

A CRITICAL COMPONENT OF RUNNING PERFORMANCE IS RUNNING ECONOMY (RE). SOME FACTORS THAT DETERMINE RE ARE UNABLE TO BE CHANGED THROUGH TRAINING, WHEREAS OTHER COMPONENTS OF RE CAN BE ALTERED THROUGH EXERCISE, WITH OTHER RE FACTORS BEING LESS MODIFIABLE THROUGH TRAINING. THE EFFECT OF FLEXIBILITY (FLX) ON RE IS LESS RESEARCHED AND NOT WELL UNDERSTOOD. THE PURPOSE OF THIS ARTICLE IS TO EXPLAIN RE, DISCUSS IF A CORRELATION EXISTS BETWEEN FLX AND RE, EXAMINE IF ACUTE STRETCHING (STR) AFFECTS RE, REVIEW IF CHRONIC STR AFFECTS RE, AND PROVIDE CONCLUDING STATEMENTS ON THE EFFECTS OF FLX AND STR ON RE.

INTRODUCTION

Performance in long-distance running is primarily dependent on $\dot{V}O_2$ max, lactate threshold, and running economy (RE) (19,22). Further considerations for performance in long-distance running include glycogen utilization, liver and skeletal muscle glycogen concentration, hydration, altitude, and environment (11,14,47). An individual's $\dot{V}O_2$ max will primarily be determined by age, gender, body composition/mass, heredity, training status/history, and mode of testing (39). In fact, as much as 47% of an individual's $\dot{V}O_2$ max may be determined by their heredity (9). However, $\dot{V}O_2$ max is a poor indicator of running performance among elite endurance runners, or runners who possess similar aerobic capacities (2). A better indicator of performance would be $\dot{V}O_2$ max, which is the minimum velocity of running to cause an individual to reach their aerobic capacity (2).

As exercise intensity increases, the accumulation of lactate occurs resulting in several inhibitory factors on the sarcomere of the muscle (15). Therefore, an individual's lactate threshold is of the utmost importance in endurance activities, especially maximal lactate steady state. Maximal lactate steady state is the highest intensity at which an individual can exercise while not accumulating a detrimental amount of lactate (47). Because many running competitions are at a velocity greater than lactate threshold, an individual with a greater maximal lactate steady state has the ability to exercise at higher intensities due to their ability to clear the lactate. Intensities greater than maximal lactate steady state elicit a large accumulation of lactate, which results in a decrease in both the muscle and blood pH levels, thus impairing muscular function (15).

Running economy is the oxygen cost ($\dot{V}O_2$) of running at a given submaximal velocity and is crucial for running performance (2,51). An athlete who has an equal $\dot{V}O_2$ max and lactate threshold to his or her opponent, but possesses a greater RE can preserve glycogen, run at greater velocities, and run further distances than those who are less economical (5). There are several ways to improve RE, including resistance training, plyometrics, hill training, and high velocity running (2,4,45,52). However, there is a debate over whether stretching (STR) and flexibility (FLX) affect RE. Because RE is critical in running performance, the purpose of this article is to explain RE, discuss the correlation between FLX and RE, discuss how acute STR affects RE, review if chronic STR affects RE, and provide a conclusion on the effects of FLX and STR on RE.

RUNNING ECONCOMY

As mentioned, RE is the amount of oxygen consumption used during submaximal steady-state conditions at a given running velocity (2,51). Athletes who need less oxygen consumption per a given running velocity have a greater RE, thus allowing them to run faster or further compared with less economical athletes who possess similar aerobic capacities and lactate thresholds (5). Researchers have suggested that several factors affect RE. Some RE factors can be modified greatly (i.e., running technique), with some factors being less modifiable

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(i.e., muscle fiber composition), and other factors being nonmodifiable (i.e., height). However, it should be noted that not all researchers are in agreement on every factor that may affect RE. For example, some research states that males have a greater RE compared with females (10,22), whereas other research findings contradict these claims (12). One reason that females may possess a lower RE compared with their male counterparts is due to the fact that females usually have a shorter stride length, thus increasing their stride frequencies at a given velocity (5). Regardless, the reader should note that a 1–6% improvement in RE would lead to a 1–6% increase in running performance, respectively (2). Therefore, striving to improve one's RE is of the utmost importance.

DOES FLEXIBILITY AFFECT RUNNING ECONOMY?

Running, especially at higher velocities, elicits the stretch-shortening cycle (SSC) (46). The SSC is composed of 2 parts, 1 being the series elastic component (SEC), and the second being the neural reflex. When a muscle is rapidly stretched, the SSC activates causing the muscle to be able to generate greater force. A sprinter (i.e., events ≤800 m) has a greater range of motion (ROM) at the hip during competition compared with a long-distance runner (i.e., events ≥800 m). The increased ROM achieved by the sprinter causes a greater stretch on the athlete's hip extensor muscles, thus eliciting the SSC. The SSC will allow the athlete to increase the rate of force development and decrease the ground contact time, thus improving performance and RE simultaneously (46). For instance, researchers have shown that rugby athletes who increase their FLX improved their running mechanics when running at 80% of their maximum velocity (13).

Because their running velocity is less, mid- to long-distance runners do not achieve the same ROM at the hip compared with sprinters. Therefore, it would make sense that a less-flexible mid- to long-distance runner might have a competitive advantage by stimulating the SSC on the hamstrings at a lesser ROM while running at slower than maximal velocities. Using elite collegiate runners (n = 4 males, 4 females), Trehearn and Buresh (54) observed a statistically significant correlation when comparing sit-and-reach (SR) scores to the athletes' RE during absolute velocity (r = 0.826). In addition to this, the authors noted a statistically significant correlation to the athletes' 10-km run time to their RE at an absolute velocity (r = 0.686). Although not statistically significant, which could be due to the small sample size (n = 8), Trehearn and Buresh (54) also noted a trend between the athletes' SR score and RE (r = 0.606, p = 0.056) while at a relative velocity. Therefore, Trehearn and Buresh (54) noted that the less-flexible runners had greater RE, which is in agreement with other research that assessed RE and FLX. (20,25,34). The reader should note that similar to Trehearn and Buresh (54), Jones (34) used the SR to assess FLX, whereas Craib et al. (20) and Gleim et al. (25) used 9 and 11 different measures of FLX, respectively, on RE.

By being inflexible, these athletes create greater elastic energy generated by the SEC for a given ROM (20). Considering that as much as 40–50% of the energy needed for distance running can be obtained from the elastic ability of skeletal muscle (16), being inflexible may provide greater competitive advantage for endurance runners (20). This relationship has been seen for

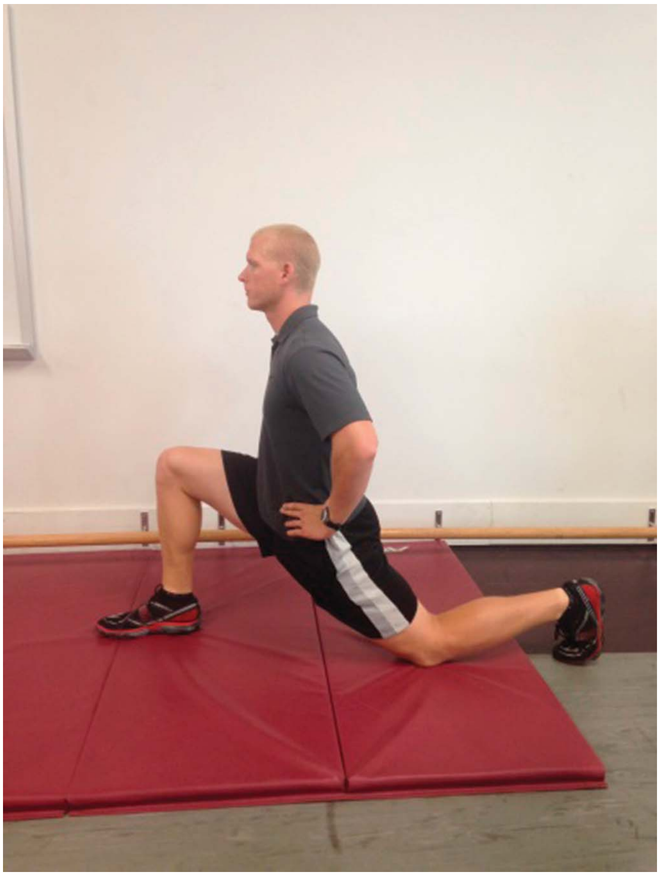

Figure 1. The individual is stretching their hip flexor muscle group. By increasing mobility of their hip flexors, an athlete can go into greater hip extension, thus promoting enhanced gluteus maximus recruitment and rate of force development while running.

both non-elite (20) and elite athletes (34,54). As mentioned, some research states that males have greater RE (10,22), and males also seem to have less FLX (25,54) compared with their female counterparts. However, not all research demonstrates that FLX determines RE for runners (6). Furthermore, some researchers suggest that males do not have greater RE compared with similarly trained females (12).

ACUTE STRETCHING AND RUNNING ECONOMY

Researchers have sought to determine whether acute bouts of static stretching (SS) before exercise affect RE. Wilson et al. (56) showed that SS before running decreases RE. In addition to this, Wilson et al. (56) also noted that performing SS before running caused their subjects to decrease their running distance compared with abstinence from SS during the provided 30-minute time span allotted for running. Furthermore, Lowery et al. (38) recently showed that SS before 1 mile uphill running increased time to completion, increased ground contact time, and increased muscle activation, resulting in an approximately 8% decrease in performance. The increase in muscle activation was a result of the motor units being placed in a fatigued state from the SS, thus, more muscular recruitment was necessary to perform the given task (38). Considering that one of the adaptations to endurance training is asynchronous recruitment of the musculature, having to recruit more muscle fibers per given intensity would be counterproductive to performance for distance running.

However, not all researchers (1,30) have shown that pre-exercise SS impairs RE. Allison et al. (1) did not observe an effect on RE, energy expenditure, stride length, or stride rate after SS, while the subjects ran for 10 minutes at 70% of their aerobic capacity. However, the authors (1) reported a statistically significant effect in the subjects' SR score (2.7 cm), isometric strength (−5.6%), and countermovement jump height (−5.5%), thereby showing that the SS protocol induced a noticeable effect on other exercise parameters. Hayes and Walker (30) had similar findings using SS, progressive SS, and dynamic stretching (DS) while measuring RE. Although Hayes and Walker's (30) STR interventions yielded statistically significant improvements in FLX, there was no effect on RE. However, 1 reason that RE may not have been affected by the STR intervention is that the authors (1,30) measured RE during the final stages of a run. Allison et al. (1) measured RE and energy expenditure during the 3- to 10-minute time period for a 10-minute run, whereas Hayes and Walker (30) measured RE during the last 3 minutes of a 10-minute run. Wolfe et al. (57) showed cycling economy to restore shortly after engaging in exercise after SS, which is in agreement to findings of comparable research (48). By measuring RE at the end stages of a run, the subjects have in essence performed a dynamic warm-up (DWU), which would help mitigate the ergolytic effects of pre-exercise SS.

Godges et al. (27) observed that SS before 12 minutes of treadmill running at the subjects' 40, 60, and 80% $\dot{V}O_2$ max improved RE, whereas a combination of proprioceptive neuromuscular facilitation and soft tissue mobilization improved RE at 60% $\dot{V}O_2$ max. However, it should be noted that all of the male subjects (N = 7) had limited ROM in hip flexion and/or extension, and the STR intervention targeted those limitations. Furthermore, the subjects ran the 12-minute protocol

Figure 2. The individual is placing a greater stretch on his hip flexors, by raising both arms while maintaining a neutral spine. Further coaching cues can involve asking the athlete to contract their abdominal muscles, as well as their gluteus maximus on the leg which knee is on the ground to promote a posterior pelvic tilt, thus increasing the effectiveness of the stretch.

before the STR interventions, rested 10 minutes, performed the STR protocols, and then reran the 12-minute protocol once more. Therefore, most likely SS without the use of a 12-minute prerun on individuals who do not lack ROM at the hip would lead to significant ergolytic effects on RE, since the prerun might have acted as a DWU with the STR improving ROM at the hip.

Recently, there has been research published (42,56,58) using similar experimental methods to study the effect of various warm-up procedures on RE for different populations. These 3 studies (42,56,58) measured RE in trained subjects over a 60-minute period of running. The first 30 minutes of running were conducted at 65% of the subjects $\dot{V}O_2$ max, with the last 30 minutes of running being a "performance" run. The performance run was categorized by the distance covered in the 30-minute time period. For all 3 studies (42,56,58), the subjects reported to the laboratory 3 times, with the first visit establishing their baseline fitness, and the second and third visits being randomly assigned to experimental and control conditions. The control conditions involved quiet sitting (QS) in place of the experimental trial.

Using the previously described methods, Wilson et al. (56) noted that 16 minutes of SS was associated with a statistically significant decreased RE noted by the increase in caloric expenditure (kilocalories) during the first 30 minutes of running when compared with QS (425 ± 50 versus 405 ± 50 kcals). In addition to this, Wilson et al. (56) concluded that SS was associated with a statistically significant decrease, evident by the subjects covering less distance compared with the QS (5.8 ± 1.0 versus 6.0 ± 1.1. km). However, Mojock et al. (42) did not see that 18 minutes of SS affected RE, caloric expenditure, or performance between the SS and QS. The difference between the Wilson et al. (56) and Mojock et al. (42) findings could likely be attributed to the subjects used in their respective studies. Wilson et al. (56) used male runners (N = 10), whereas Mojock et al. (42) used female runners (N = 12). Females are typically more flexible compared with males, and therefore, females' RE may be less affected by SS as pre-exercise intervention. Wilson et al.'s (56) SS intervention increased the male subjects' sit-and-reach score by 10.1% (24.7 ± 14.6 to 27.2 ± 14.6 cm), whereas Mojock et al.'s (42) SS intervention increased the females' sit-and-reach score by 11.1% (29.8 ± 8.6 to 33.1 ± 8.1 cm). Mojock et al. (42) suggested that females may recover more quickly in regards to RE and pre-exercise SS since females have lower muscle-tendon unit (MTU) stiffness (28). The reader should note that Mojock et al. (42) controlled for the females' menstrual cycle in the study by separating the QS and SS intervention by a minimum of 21 days, as well as performing the testing 3–7 days before their menstrual cycle.

Although it may seem that females may be less affected by pre-exercise SS in regards to RE, pre-exercise SS should nonetheless be avoided regardless of gender. Performing SS before exercise causes a decrease in MTU stiffness (56), causing an increase in slack for the MTU, which is referred to as creep. An increase in MTU stiffness allows for optimal transmission of the internal forces created by the MTU, and MTU stiffness improves RE (3). It is agreed on that one of the reasons plyometric and resistance training improves RE is due to an increase in MTU stiffness. A decrease in MTU stiffness created from acute SS can negatively affect force transmission by altering the viscoelastic properties of the muscle, which will reduce RE. There are several known ergolytic

Figure 3. The individual is placing a greater stretch on his psoas muscle group by bending laterally away from the hip flexors being stretched.

effects on the physiology of the nervous and muscular systems when engaging in high volumes and intensities of SS before exercise (8,24). Behm et al. (7) showed that initial level of FLX before SS did not affect the ergolytic effects on subsequent performance, meaning that flexible athletes who stretch to the point of discomfort before exercise experience the same detriments to performance when compared with less-flexible individuals. Furthermore, Behm et al. (7) showed that individuals who engage in regular SS routines are negatively affected by engaging in SS before exercise.

As mentioned, Wolfe et al. (57) showed cycling economy to restore shortly after engaging in exercise after SS. Furthermore, Fowles et al. (23) showed that most of the detriments of SS were restored after 15 minutes following approximately 30 minutes of SS on the plantar flexors. However, although the detriments to RE may be restored rapidly after SS, there are several other negative effects of using SS in a warm-up that affect the neurological and muscular systems, which affect power, force, stability, and endurance. In addition to this, consider that an athlete can never make up a bad start. Even if the athlete were to run their personal best race with a subpar start, the athlete has still impaired their performance. Running events can easily be determined by how the athlete starts the competition. If the last place finalist in the men's 1500-m race at the 2008 Beijing's Olympic Games had improved his run time by ~6 seconds, he would have earned the bronze medal (32). Therefore, SS should not be used before competitions for several reasons, including a decrease in RE, impaired running performance, and increased ground contact time.

The athlete should opt for a DWU over SS before competition to help transition the body from rest to exercise (8,24). Using the same methods as Mojock et al. (42) and Wilson et al. (56), Zourdos et al. (58) studied how DS affected male runners (N = 14) over a 60-minute run. The researchers (58) noted that DS was associated with a statistically significant increase in the caloric expenditure for the first 30-minute run compared with QS (416.3 ± 44.9 versus 399.3 ± 50.4 kcals), with no difference in the performance run. Although the reader may be concerned about the increase in caloric expenditure associated with DS, these results are to be expected. The DS raised the subjects' heart rate, $\dot{V}O_2$, and metabolism before the run, which are characteristics of a proper DWU. It is worth noting that the DS increased the subjects SR scores by 16.4% (32.3 ± 8.6 to 37.6 8 cm) (58). However, a DWU will increase FLX due to an increase in muscle compliance, whereas SS promotes an increase in FLX due to muscle and tendon creep, which impairs subsequent performance. Furthermore, it can be hypothesized that the DS could have significantly increased the performance run compared with QS if the performance run was not preceded by the 30-minute preload run. The 30-minute preload run served as a DWU in itself. Therefore, based off the literature regarding RE, as well as a great deal of the literature measuring physiological alterations and performance, a DWU should replace SS as a pre-exercise intervention.

CHRONIC STRETCHING AND RUNNING ECONOMY

As noted previously, acute SS should be avoided before competitions due to its probable negative effects on RE, as

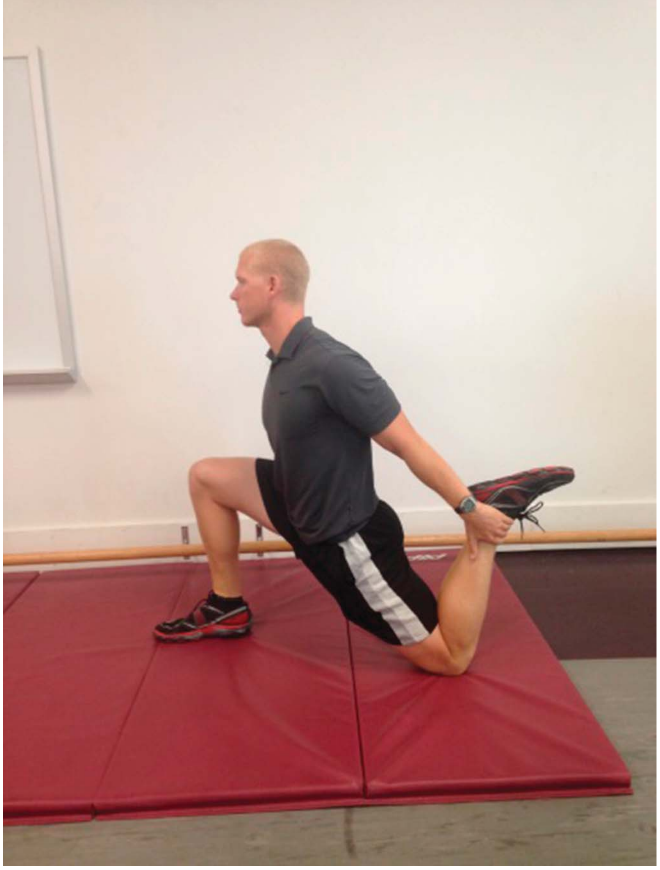

Figure 4. The individual is placing a greater stretch on his rectus femoris. The rectus femoris is the only quadricep muscle to cross both the knee and the hip. Therefore, the rectus femoris is both a knee extensor and hip flexor. Therefore, to facilitate the optimal stretch for the rectus femoris, the hip must be in extension, while the knee is being flexed.

well as several other neurological and muscular factors. However, would engaging in a chronic STR program impair RE? Considering it has been seen that lower levels of FLX are correlated with enhanced RE (20,25,34,54), should endurance runners avoid FLX training? To answer this, Nelson et al. (44) measured the effects of 10 weeks of FLX training on the lower-body musculature using 32 physically active college students. One group performed SS for 3 days a week for 40 minutes, whereas the control group did not engage in SS. Both groups were asked to maintain their normal training program during the study. After 10 weeks, Nelson et al. (44) noted that the group who performed the SS demonstrated a statistically significant improvement in their SR scores. However, neither the control group nor the SS group demonstrated statistically significant alterations in RE.

In addition to this, Godges et al. (27) studied the effects of 3 weeks of STR (totaling 6 STR sessions) on the hip flexors (HF), and its effects on RE. Although all of the members of the STR group increased their hip extension FLX, their RE at 4.0 or 7.5 miles per hour did not change after 3 weeks. One would suspect that perhaps more HF FLX sessions per week, or a longer duration of a study, could enhance a person's RE. It is known that tight HF can create an anterior pelvic tilt, thus pulling the hips out of alignment (55). This limits the ability of the gluteus maximus (GM) to fully contract during the push-off phase of running by not allowing full hip extension to occur (26). Furthermore, it has been stated that an increase in knee flexion during the swing phase of running enhances RE (2). The rectus femoris (RF) is both an HF and a knee extensor. If the RF is tight and overactive, this could decrease RE because this inhibits GM recruitment, as well as the inability to allow full knee flexion during the swing phase. Therefore, perhaps increasing FLX for the RF and the other HF through STR (Figures 1–7) could be advantageous in regards to RE. As of now, it seems that chronic STR will not impair RE. A more important determinant of RE is lower-body stiffness rather than lower-body FLX, which will be briefly discussed in the following sections.

Figure 5. If the athlete is unable to grab their own ankle, they can place a towel, band, tubing, and/or belt around their ankle to place a greater stretch on their rectus femoris. Note how the individual is not going into lumbar lordosis in the figures. Athletes with tight hip flexors often go into lumbar lordosis to compensate for a lack of hip mobility.

PRACTICAL APPLICATIONS

Strength coaches should try to enhance RE during the entire macrocycle of training. A 1% improvement in RE would lead to a 1% improvement in running performance, whereas a 6% improvement in RE leads to 6% improvement in running performance (2). In regards to FLX, more research is needed to determine whether long-term STR interventions should be avoided or implemented due to their effect on RE. A correlation seems to exist between lower levels of FLX and enhanced RE (20,25,34,54). However, Caplan et al. (13) showed that improvements in FLX increased stride length while running at 80% of an athlete's top velocity. Considering that the top endurance athletes have the ability to run at 92% of their $\dot{V}O_2$ max for extended periods of time (18), while maintaining relatively high running velocities, an improvement in FLX may be beneficial, and not limiting. Often times, endurance runners engage in higher running velocities as they near the end of the race, thus they increase their ROM at their hip during their final burst. The increase in stride length that was noted by Caplan et al. (13) was accompanied by a decrease in

Figure 6. If the athlete is unable to grab their own ankle, they can place their ankle on a bench, chair, and/or table to emphasize the stretch for their rectus femoris. The athlete should be encouraged to go far into hip extension without arching their back.

stride rate, thus, more energy would be preserved, which would result in an increase in RE.

To improve RE, a strength coach can target several modifiable factors to improve RE over a training program. Strength training, plyometrics, hill running, and high-intensity running all have their place in a runner's program. According to Anderson (2), an improvement in a runner's technique will improve RE. Therefore, strength and conditioning coaches should be aware of the optimal running technique. If the strength coach chooses not to implement a chronic STR program into a long-distance runner's protocol due to either time or preference, the reader should note that resistance training with a full ROM can improve FLX (43,50). At this point in time, we the authors feel that moderate volumes of STR designed to enhance FLX should not reduce RE. However, more research on STR over a training period is needed to fully conclude this. Emphasis should be placed on increasing lower-body stiffness. Lower-body stiffness has been shown to positively impact running performance (3,21,31). Male runners have demonstrated increased leg stiffness compared with females (28), which may help explain why some studies have shown males to have better RE (10,22).

It is known and agreed on that individuals should avoid SS before exercise since it is associated with impaired physiology and performance, such as a decrease in MTU stiffness. Muscle-tendon unit stiffness is associated with a greater transference of energy during the contact phase of running, thus increasing propulsion (36,52). Rather than using SS before competition, a DWU should be implemented.

Future research is warranted to determine whether long-term STR programs affect RE in athletes of different sports, ages, and levels of competitiveness. Most research assessing FLX and RE measures the compliance of the hamstrings. It makes sense that less-compliant hamstrings might generate more elastic energy with small ROMs compared with highly compliant hamstrings. However, future research needs to be conducted regarding the FLX of the HF, quadriceps, and/or plantar flexors (PF) in regards to RE. Tight HF could limit the ROM achieved while the hip is being extended in the gait cycle, thus decreasing GM recruitment and rate of force development, especially at higher velocities. The GM has the potential to be a powerful hip extensor and is most recruited in the final ROM of hip extension. Therefore, it may be advantageous to focus on FLX of the HF over the hamstrings to increase RE, as well as to improve maximum running velocity (37). Furthermore, tight HF could promote certain injuries, such as sport hernias, osteitis pubis, and groin pain (55). Figures 1–3 describe stretches for the HF muscle group. To promote a greater stretch on the psoas muscle group, the torso should be laterally bent (Figure 3) (40).

The same can be said about the quadriceps, especially the RF. The RF is the only quadriceps muscle to originate on the hip, and therefore, serves as both a knee extensor and hip flexor. The RF is known to be overactive and tight, thus pulling the pelvis out of alignment. It has been seen that an increase in knee flexion during the swing phase can improve RE by decreasing the length of the lever (i.e., distance from the hip to the ankle) of the leg (2). Therefore, it would make sense that more compliant quadriceps, especially the RF, could enhance RE. Furthermore, those who cannot produce optimal hip extension while running may compensate by going into lumbar

Figure 7. Another variation to emphasize the stretch of the rectus femoris is to have the athlete place their ankle on a glute ham machine (or something of a similar height). To increase the stretch of his rectus femoris, the individual would flex the knee of his stance leg while avoiding lumbar lordosis.

lordosis (27), which causes stress to the lumbar vertebrae. Stretches that emphasize the RF can be seen in Figures 4–7. Since the RF is both a knee extensor and hip flexor, the best approach to stretch the RF would be to place the hip in extension with a flexed knee.

Finally, a lack of FLX of the PF could impair running performance and RE. An increase in FLX of the PF would allow an increase ROM of dorsiflexion at the ankle joint during the gait cycle. This could promote the shin to be in a more positive angle during the initial contact with the ground. A positive shin angle promotes acceleration, whereas a negative shin angle promotes deceleration (17). Therefore, strength coaches may only want to stretch certain muscle groups and certain joint angles. However, to date, there is insufficient research to verify this claim. The best advice would be to determine the limiting factor for an individual athlete. If the athlete is lacking hip mobility, greater emphasis should be placed on improving hip mobility, whereas if an athlete has subpar leg stiffness, they should engage in strength and plyometric training. To assist the reader on topics briefly mentioned in this article, the reader can find more information on lower limb stiffness (41), plyometrics (49), resistance training (35), and stretching/flexibility (29) from articles referred to in this sentence to improve running performance and RE.

SUMMARY

In summary, SS before exercise will impair several aspects of performance, including RE. Therefore, SS and/or proprioceptive neuromuscular facilitation stretching should be implemented after exercise or in separate training sessions. As long as MTU stiffness is preserved, improving FLX will most likely not impair RE. However, the strength coach may want to place greater emphasis on improving FLX of the HF, quadriceps, and PF than the hamstrings to improve running mechanics, thus increasing RE. In general, stretching activities should be implemented ≥2 days per week, ≥2 sets per muscle group per session, held 15–60 seconds per stretch, held at the point of discomfort, and involve all the major muscle groups (33,53). However, if FLX is a limiting factor for performance, STR interventions could be performed every day with greater volumes and intensities. The strength coach could prescribe SS, dynamic STR, proprioceptive neuromuscular facilitation STR and/or partner STR to elicit the optimal outcome.

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