TRAINING THE HAMSTRING MUSCLES IN INTERMITTENT-SPRINT SPORTS

A Primer for Coaches on Resistance-training, Flexibility-training, and Stretching

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PART I

RESISTANCE-TRAINING AS AUXILIARY-TRAINING

Introduction

The hamstring muscles are located on the posterior of each thigh with their common proximal origin on the ischial tuberosities, and their distal attachments on the proximal head of the fibula (*biceps femoris*), the posterior medial condyle of the tibia (*semimembranosus*), and the medial lateral condyle of the tibia (*semitendinosus*). The Biceps, as the name implies has a second, shorter head that arises from the *linea aspera* on the posterior surface of the femur and joins the long head for its distal attachment. Although the ischial tuberosities are anatomically below the hip joint, and do not cross this joint from above, they are part of the entire pelvis (*os coxae*), and as such are prime-movers creating extension of this joint whenever it is needed in a movement pattern. As the distal insertions of the hamstrings are all below the knee, they serve as prime movers for knee-flexion and inward rotation of the knee (*semitendinosus*, *semimembranosu*s), and outward rotation of the knee (*biceps femoris*). Human locomotor activities involved in intermittent-sprint sports require the hamstrings to work in concert with their antagonists the quadriceps to produce hip-extension and knee-extension at the same time, and this co-contraction occurs with virtually all whole body skills whether moving forward, laterally, or jumping.

This discussion will be limited to dynamic-movement sports that involve intermittent maximal sprinting, stopping, jumping, and direction changes (e.g., soccer, Australian Rules Football, basketball, baseball), and kicking (e.g., soccer, Australian Rules Football, rugby), rather than discuss every sport and the hamstring functions and injuries in them. The hamstrings are called into action on many diverse movement patterns performed in the land-based sports being considered:

i. With every stride taken, whether at low- or high-velocity, body-weight is absorbed at touchdown then propelled by the combined eccentric (to) isometric (to) concentric co-contractions of the two powerful thigh muscles, the hamstrings and quadriceps.
ii. After propulsion, the hamstrings are active as part of the recovery by concentrically contracting causing knee-flexion in concert with the psoas and iliacus of the same leg which bring about the hip-flexion bringing the foot to the next touch down.
iii. When kicking a ball is common (e.g., Australian Rules football, soccer), the hamstrings are called into action during any "*power*" kicks that take place by first flexing the knee during the preparatory phase, then by absorbing the momentum remaining in the thigh, shank, and foot after the ball has been propelled. This involves decelerating the limb via an eccentric hamstring contraction.
iv. Similar to iii, whenever the leg is thrust forward as the body is falling to the ground, the hamstrings are violently stretched and the weight of the body is brought down

upon the outstretched leg with possible injury occurring should the force be greater than the elastic properties of the hamstring tissues.

v. All jumping activities require high-intensity co-contractions of the thigh muscles of both legs to successfully propel the body upward.

The hamstrings perform a variety of tasks requiring the tissues to be conditioned to perform all actions without injury. Each muscle/fascia/tendon complex has to be capable of storing and releasing energy via high-intensity short-duration contractions, withstand high-tensile forces, and maintain sufficient elasticity to ensure that no disruption of tissue occurs. The durations of the hamstrings' functions are very short and typify speed of movement rather than strength or high-power movements like those often displayed in weight-rooms and gymnasia (Jenkins, 2005a).

It is the opinion of these authors that the occurrence of injuries to the hamstrings is much greater these days than in yesteryear (40-50 years ago). The reasons for the increased injuries are variously given as a lack of flexibility in the hamstrings, strength/power imbalances between the quadriceps and hamstrings, bilateral differences between the muscles of the hamstring group, and the dominance of the *biceps femoris* that receives two nerve supplies (one to the long-head and the other to the short-head) compared to the single supplies of the other two muscles (Jenkins, 2005; p. 344). Common opinion has it that hamstring injuries occur in high-intensity maximal exertions rather than in sub-maximal exertions.

Sprinting Demands on the Hamstrings

There are two principal roles of the hamstrings in intermittent-sprint sports when the athlete is sprinting. The first involves landing when they contract with the quadriceps to accept the body weight, store energy, and concentrically contract. In that role, both provide vertical forces to maintain body position, and to propel the body forward. The second is to flex the knee to shorten the moment arm creating a faster recovery. Neither role requires great application of strength, rather they involve short duration activations specifically timed for efficient use of available energy sources. These two roles employ the speed factor which should be preserved during various training activities. Other performance factors (e.g., strength,) that would interfere with the two main functions of the hamstrings should not be part of a conditioning protocol. The training effects of practice items that aim to develop unimportant capacities alter the nature of the function and structure of the hamstrings which increase the risk of injury.

In maximal sprinting actions, the duration of hamstring employment is in the range of hundredths of a second whereas hamstring strength-training activities, most commonly performed as isolated knee flexions against a relatively high resistance, only provoke adaptations associated with slow movements. To facilitate relevant trained states of the hamstrings, the most obvious activity is high-intensity sprinting and dodging that employs the hamstrings maximally across the roles they play in the sprinting and evasive actions. The employment of the muscles' capacities to the fullest is experienced in maximally-intense sprinting. Despite that obvious implication for the relevant training of hamstrings, conditioning coaches today employ a variety of isolated muscle-strengthening activities which do not result in sprint-performance improvements or injury prevention.

Resistance-training Relative to the Hamstrings

For coaches, athletic trainers, and conditioning coaches who believe that land-based or equipment-based strength-training is the vehicle through which performances are improved, there arises a problem. If strength gained from land training activities is not transferred to actual dynamic running, then strength-training is a waste of time for sprinting. The evidence against such transfer occurring is extensive (e.g., Clutch *et al.*, 1983; Morrisey, Harmon, & Johnson, 1995; Sale & MacDougall, 1981; Toumi & Best, 2004). The stationary isolated-muscle exercises used to develop strength do not replicate the activity position, posture, movement pattern, and contraction speed, type, and force[1] and do not mirror the muscular functions and coordinated roles of the muscles in dynamic exercises (e.g., sprinting, dodging, kicking, weaving). Strength-training and conditioning outside of the actual activity is supported by an industry and legions of adherents who believe in and perpetuate dogma and neglect objective evidence that is contrary to their beliefs. Trainers of strength activities will not be amused by this reality. Some of what is known, and it is not a complete list, about traditional strength-training and explosive training is bulleted below.

- There is no practical relationship between maximal force production and the ability to move the body, its limbs, and any piece of light equipment quickly (see discussion below and Figure 2). The current emphasis on improving strength to improve movement speed should not yield much change, if any, because the two capacities have so little in common (Gardner *et al.*, 2007). As well, the sports considered here involve fast directional and movement changes, features that are commonly associated with agility[2]. Greig and Naylor (2014) showed traditional strength measures are not associated with agility with relationships being task-dependent. Strength-training is not associated with maximum speed or agility development.
- The lack of transfer has been known for at least 50 years, as student studies have demonstrated (e.g., Promoli, 1978; Young, 1979). Whether training for strength or for power, or training isotonically with weights or using isokinetic devices, transfer to motor-performance tests such as vertical jumps was not achieved. In the (Promoli, 1978) strength-group training isokinetically, the post-test mean was three-quarters of an inch lower than the pre-test. Interestingly, for those who trained on an isokinetic "*leaper*" both the strength- and power-groups had most subjects complaining of back pain.[3].
- Another important issue when considering research is the dependent variables used to measure motor performance changes. Generally, there are one to three post-test trials, with either an average or the best trial chosen to represent the effect using the activity that was practiced. Many findings report the specific-practice effects and make the illogical generalization that those effects will affect true game-setting or game-simulation performances. Rarely, if ever do most studies actually test a real/simulated game performance in order to find the transfer effects of the training program.

[1] The movement parameters that need to exist to produce conditions that offer the remotest possibility of some practice-performance improvements being transferred to the target natural activity (Rushall & Pyke, 1991).

[2] Agility is not a global fitness component. There is little correlation between different tests of agility performance.

[3] Although popular, another non-specific device that should be avoided at all costs is one that places the resistance on the shoulders, while the force application is through the legs (e.g., jump-squats).

Intermittent sprint-sports usually involve hundreds of repetitions, and an auxiliary-training program might show positive effects on initial trials that serve as a quick post-test, but have a negative effect on the remainder of the efforts during a game. The training effect(s) of any out-of-context training-program should be tested in game-like situations before being considered for adoption.

- Strength-training does not improve fast movements of the same exercise. It is invalid to assert that slow resistance-training designed to improve strength, particularly when using machines or free-weights, will improve high-speed functional activities such as sprinting and dodging (Blazevich, 2012; Liow & Hopkins, 1998).
- The type of strength-training that is undertaken (light or heavy resistances, different contraction forms, degree of fatigue incurred, etc.) produces different training effects (Choi, Takahashi, & Takamatsu, 1997). Training for maximal and explosive strength were compared for effects (Tillin, Pain, & Folland, 2012). Maximal voluntary force increased in both groups, being significantly greater in the maximal-strength group. Explosive force at all time-points increased in the explosive-strength group by 13-54%, but were unchanged in the maximal-strength group. But, the gains in such studies only occur in the activities used in the study. In competent trained-athletes, explosive training does not transfer to "*real*" game-performances and has the potential to cause tissue damage that will be manifested as an injury in some maximum-effort skills in a competition setting.
- Heavy resistance-training before a specific sport training session will interfere with the response quality to specific training opportunities at the ensuing practice. Since the effects of concerted resistance-training last as long as 48-72 hours, the migratory and long-lasting affects of probably irrelevant-for-competition resistance exercises in the non-sporting environment of a weight-room, will compromise the opportunities and abilities of individuals to improve in specific-sport training activities (Doncaster & Twist, 2012; Hakkinen, Kraemer, & Gorostiaga, 2009).
- When power training is not highly explosive, its training effects are not much different to traditional strength-training effects (Lamas *et al.*, 2010).
- Actions requiring effort (strength or more correctly power) adapt specifically to the conditions and activities of training. The further removed from competition-specific actions are the exercises of strength and conditioning programs, the less valuable they will be for improving competition performances (Duchateau, 2009; House *et al.*, 2010).
- High-speed strength-training is better than low-speed training in high school athletes when performance goals involve fast and powerful movements (LeFavi *et al.*, 2010).
- Speed power training not only improves peak power, but it shifts the point at which peak power is produced to lower external resistance values, that is, an individual can move faster with reduced effort. Therefore, resistance-training at high speeds maximizes the ability to use movement speed to produce peak power (Sayers & Kyle, 2013).

Since the above statements contradict much of the dogma surrounding resistance/weight training and the claims of benefits for sporting performances, a more in-depth analysis of some research is warranted.

The Form of Strength Intensity for Developing Movement Speed

If resistance-training is to be performed with the aim to eventually improve movement speed (e.g., sprint velocity, direction-change duration), it should be maximally explosive and employ the force producing joints preferably not in isolation. Unless strength work trains the ability of the legs to generate forces in a very short time, that is, with maximum explosive force, slower training would not assist in the development of running speed (Young, McLean, & Ardranga, 1995). Less than maximally explosive movements are not related to maximal sprinting actions. Muscle strength and total work capacity are not related to sprinting (Neves, Barros, & Ribeiro, 1999). Delecluse *et al*. (1995) assessed the effects of high-resistance and high-velocity training on different phases of a 100-m sprint run. High-resistance-training programs did not improve sprinting performance. High-velocity training only improved sprinting performance by developing initial acceleration at the start of the task. Auxiliary-training programs of the two types used in that study caused a loss in the ability to maintain maximum sprint-velocity. In a study that reported benefits from added auxiliary-training, Newberry and Flowers (1999) evaluated three groups of 12 males following different training regimens: sprint training alone (12 x 40-yd, 25-second rest, three days per week), sprint training plus strength-training (5 x 12 repetitions of 50% 1-RM, two days per week), and no-training (control). Both training groups were significantly better conditioned than the no-training group. The resistance-training group displayed a significantly higher percentage of maximal velocity than the sprint-only group. There were no significant differences between groups in sprint speed. High-repetition strength-training added to sprint training increased muscular endurance, but not speed. That form of training would be best suited for activities that require repetitive sprints.

Clutch *et al.* (1983) compared the effects of weight-training-alone and jumping-alone, with weight training plus plyometric-jumping practices on vertical jumping performance and strength. Gains in strength-training demonstrated by the weight training group did not transfer to the dynamic activity of vertical jumping. Weight training produced no added beneficial effect on jumping performance over that gained from doing jumping alone. Young, Wilson, and Byrne (1999) opined that speed-strength is more important than maximum strength for influencing jumping performance/ability.

Rich and Cafarelli (2000) reported that isometric resistance-training produced a large increase in maximal voluntary contractile force and a small increase in contractile speed of the knee extensors. There were no accompanying changes in neural activation at a motor unit firing rate of 50% MVC. These results suggest that a short period of isometric training increased maximal force production but it did not result from enhanced activation of the whole muscle. Baseline motor-unit firing rates were already high enough to maintain precise control of sustained submaximal forces despite increases in contractile speed resulting from the resistance-training. Extended periods of high-load resistance-training that produce marked changes in voluntary strength may contribute little to the performance of activities that require submaximal strength levels. Such activities are sports that require fast movements (e.g., rowing, kayaking, swimming) where large-force generation does not have time to occur, or sports that require many submaximal repetitions (e.g., distance running, cycling, games requiring intermittent bursts of activity such as soccer). The energy misdirected into non-beneficial strenuous resistance-training could better be used for sport-specific training that involved whole-body functional and relevant tasks. Knight and Kamen

(2001) also investigated the effects of isometric contractile work and resistance-training on motor-firing rates in young and older men. Subjects were assessed for maximal knee-extensor torque and motor-unit discharge rate on four occasions. Progressive resistance-training using both isometric and dynamic 10-RM contractions began immediately after the second testing. Further tests were conducted after two and six weeks of resistance-training. Exercise training produced similar improvements (34%) in extensor torque in both age-groups. Motor-unit firing rates remained relatively constant during resistance-training. Motor-unit discharge rates were specific to the tasks requiring high levels of force. Resistance-training on different exercises did not affect the firing rates of the targeted muscles. Hoyle (1974) demonstrated that three motor-factors (nerve-conduction velocity, ballistic-movement capability, and body-agility) identified the fast speed athletes (elite badminton players) from competitive swimmers and non-athletes. Few people grasp the fact that movement speed is nervous-system dependent, and that laying down more myelin would be the way to enhance performance. They also do not appreciate that adding more muscle tissue actually makes it more difficult to move faster, requires more effort, which over the course of a game will ultimately cause earlier fatigue, generally resulting in lower or no change in performance outcomes. Strength-training increases tensile force capacity through the process of both enlarging the muscle/fascia/tendon units and stiffening those structures. In that process, elasticity is compromised.

Morrissey, Harman, and Johnson (1995) reviewed strength-training research. They concluded that there was not much hard evidence supporting strength-training as a viable or useful means for improving athletic (functional) performance. Dirr *et al.* (2014) showed that a regular routine of upper- and/or lower-body resistance-training performed in the two months prior to an international distance triathlon did not enhance triathlon performance time.

Because the hamstrings are long and built for fast contractions that overcome relatively light loads, it would seem that performing the actual activities of sprinting, dodging, and changing directions that are frequently executed and an integral part of field games would be the best activities to practice. Training effects would be evidenced in actual game settings. The emphasis on spending most of the practice sessions moving at game speeds is crucial, with the only exceptions being when an athlete is actually trying to learn a new skill, or when a 'set' plan strategy element is being learned and the initial attempts may be done at slower than game speeds until the flow of any element interactions is grasped by the athletes involved.

Intermittent-sprint sport athletes are required to produce propulsive forces as quickly as possible. To not focus on that capacity severely limits the benefits of training activities that emphasize other factors. Force is defined as:

Force = Mass x Acceleration

Since the mass of a highly-trained athlete does not vary extensively, in the context of this article, the only variable worthy of development to improve sprinting performance is movement acceleration. The faster a sprinter moves/accelerates in developing propulsive forces, the better will be the maximal performance[4].

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[4] It should be recognized that other factors (e.g., a reduction in active resistance and technique) can play an important role in producing faster maximal performances if technique is proficient.

The labeling of the various outcomes of resistance-training is confusing. In this article, explosive training is synonymous with "*fast acceleration-power training*". Traditional or heavy strength-training is synonymous with "*maximal-effort resistance-training*". Unless explosive acceleration is developed, no resistance-training will benefit performances in serious athletes. It is commonly reported that elite athletes embark on strength-training activities without any improvement in performances. Such is the case with American football players whose skilled movements were not improved by concerted resistance-training (Caterisano *et al.*, 1999; Harney *et al.*, 2001; Miller *et al.*, 1999). Often performances regress to be slower than in previous years when the emphasis on irrelevant resistance-training is given high priority in athletes' training programs.

A key to understanding why auxiliary-training (game-irrelevant protocols) brings about negative results is that the effects of the training go beyond the primary immediate training-focus and alter tissues to adapt to the need for more tensile strength (e.g., resistance-training) or more aerobic power (e.g., a common aim for using stationary/moving bicycles). A decrease in muscle and connective-tissue elasticity results in a decrease in the capacity to store and release energy continuously throughout a game and to move through the optimum range of movement that each athlete has developed for each game-skill.

Figure 1. The *RH-2 Rogue Reverse Hyper* machine that is used to strengthen the hamstrings.

A variety of machines have been developed with which to conduct hamstring strengthening. Many are also used for other activities. Figure 1 illustrates the *RH-2 Rogue Reverse Hyper* machine in strength-training mode [https://www.roguefitness.com/]. The advertising statement that accompanies the picture follows:

> *Manufactured and fully assembled in Columbus, Ohio, the Rogue RH-2 is a reverse hyper machine designed to meet the unique, changing needs of the athletes it serves. Widely utilized for physical therapy and back rehab exercises, the Reverse Hyper can also be used with light weights in everyday training to reduce lower back tightness and strengthen hamstrings, glutes, hips, and more.*

The recommendation to use light weights as resistance is a sound statement. Light weights are essential for muscle-injury rehabilitation. However, in the macho world of resistance-training and conditioning, the credo of *"more is better"* is followed more often than not. It often translates to the dangerous and unscientific belief that heavy-to-very-heavy resistances are more beneficial than lighter resistances for promoting changes in any muscles. Consequently, many strengthening programs are oriented to using the heaviest weights possible that facilitate some number of repetitions and sets of exercises for groups of muscles. The use of near-maximal or excessive resistances on isolated-muscle machines increases the likelihood of injury to the targeted muscles. As well, particularly in college and professional training facilities and commercial gyms, there often develop competitions between the resident conditioning coaches and trainers. One can frequently observe wall charts that list "record performances" on the various machines in the establishment. Equally as common is the tracking of athletes' progress to determine improvement statistics on weight-room exercises. Weight-room coaches often are intent on showing they can change their charges more extensively than other in-facility employees.

Strength exercises using very heavy resistances and high levels of effort damage muscles for as much as 48 hours (Dolezal *et al.,* 2000). Heavy exercises produce muscle damage in the form of "*minute tears or damage to contractile components with the accompanying release of creatine kinase (CK), myoglobin (Mb), and troponin I, the muscle-specific marker of muscle fiber damage*" (McArdle, Katch, & Katch, 2004, pp. 540). When coupled with extreme stretching and exaggerated ranges of movement, tearing of portions of a muscle's fibers and connective tissues also occurs (p. 540). It is highly likely that hamstring-damage occurs in heavy strength exercises that employ the hamstrings and other more powerful muscle groups in training activities.

Muscle damage through strength-training is not caused by the absolute forces created in an exercise but rather by the overall strain produced in the training session (p. 541). Large amounts of heavy resistance-training that produce significant fatigue in many muscle groups will be more damaging than will a few attempts at maximum lifts. Damage is often felt by athletes as post-exercise stiffness or soreness (*Delayed-onset Muscle Soreness – DOMS*), hamstring tightness, or general pain when moving, Damage occurs particularly when beginning training, attempting a new or altered exercise, or engaging in strength-training too frequently. The length of time needed to repair damage caused by weight training depends upon the extent of strain incurred in a training session. When strain is excessive, up to three days might be needed in normal individuals although individual differences exist and longer times have been recorded. When muscles are still exhibiting signs of damage, further training sessions will yield no benefits and likely will increase the amount of damage (Nosaka & Clarkson, 1995). Subsequent training sessions should be delayed to avoid compounding and extending the potential injury sites. Some individuals take longer than three days to recover from hard resistance-training. Testing important athletes for recovery durations is a necessary feature of a safe resistance-training program (McLester *et al.*, 2001). If strength-training occurs frequently, every one or two days is common in *"professionally-run"* establishments, the state of degradation of the hamstrings could be maintained or even increased with each succeeding workout session. In the latter possibility, injuries nurtured by strength-training might take some time to finally be exhibited which makes it difficult to attribute the actual cause of a hamstring injury because the problem only emerges intermittently. As well, through unknown quirks, there are some athletes who can tolerate heavy resistance-training and never suffer a hamstring injury. Such individuals further obscure the potential effects of heavy strength-training. It should be possible within a team to evaluate each athlete's participation in resistance-training, the involvement in hamstring-strengthening exercises, and the occurrences of hamstring problems. Results from such analyses should be considered on an individual basis and not combined to form team-statistics which could obscure a problem.

Current thinking, which has yet to be verified fully, is that excessive high-stress strength-training can keep muscles in a damaged state. In the actual sporting activities for which the strength-training is supposed to benefit, the damaged muscle areas are predisposed to more extensive injuries. That is the explanation used to question the value of an obsessive focus on strength-training for sports improvement and its resultant effect of increased injuries, which is opposite to what it is supposed to do (i.e., muscle strength is supposed to improve resistance to injuries). Support for the "*strength-training-is-dangerous*" hypothesis is found in the attention being paid to methods to shorten the time that residual muscle damage exists after strength-training (Roy *et al.*, 1996). Muscle damage repair should not be confused with energy recovery, which occurs within two hours of strength-training (Henley, Irving, & Gaesser, 2004).

Heavy weight training takes considerable time for recovery. Residual fatigue from weight training could reduce the volume and quality of subsequent actual-sport training because of the fatigue that already exists and is carried into specific-sport practices. Because of the minimal transference of weight training benefits to whole-body activities such as sprinting and dodging, this detrimental effect on potentially beneficial sport-specific training must be considered (Scala *et al.*, 1987). Full resistance-training sessions should not occur before sport-specific practices and should be scheduled to allow recovery from their fatiguing effects to occur before a practice.

It is the muscle damage caused by heavy and/or intense resistance-training that heightens the likelihood of hamstring injuries in intermittent high-intensity sprinting/dodging activities. The following should be contemplated.

- Isolating muscle groups with machines that dictate particular movements often in postures that rarely arise in true-life activities is a very suspect approach to training. In Figure 1, it is hard to envision any activity where the hamstrings are exerted maximally in a similar body orientation (particularly with the hips anchored to the machine's supportive surface in a pronated attitude). The position in which strength-training effects are developed affects the nature and degree of training effects that occur in other postures/orientations. For example, Rasch and Morehouse (1957) reported that a training program that increased elbow-flexor strength in a standing position had a diminished effect on the same action when in a supine position.
- Movement-limited resistance machines load the hamstrings unnaturally because the muscles' contractions occur over a greater duration than that which occurs in normal settings. That extra time facilitates greater amounts of micro-tearing in the muscle structures and associated connective tissues than are experienced in free-standing normal activities (e.g., sprinting, direction-changes, high-speed accelerations). Post-training opportunities need to be provided for micro-damage to be repaired as opposed to the more common phenomenon of participating in full training sessions too frequently.

- Hamstring strengthening machines load the muscles to a much greater degree than normal toward the muscles' origins. The mechanical advantage of the sections of the muscles used in hamstring-strengthening exercises favors greater forces being exerted by the shortest lever-lengths. This feature is also an artifact of the position of the exercise, which in the case of Figure 1 fixes the hips in the machine exercise, something that does not occur in natural activities involving the hamstrings. The site of a hamstring injury provides a clue as to the cause of the injury. If an injury is deep in the hip or near the gluteus muscles, hamstring strength-training is a viable cause of the injury. Contrastingly, hamstring injuries caused by free-standing exercises are more frequently centered in the body of one or more of the muscles or even in the extensive tendons leading to insertions.
- The micro-tears/injuries that result from high-resistance strength-training activities stimulate repairs that thicken the muscle structures (e.g., fascia) causing the muscles and tendons to become stiffer[5]. Silva, Riebe, and Earp (2016) showed that increasing the stiffness of the quadriceps' tendons by using high-resistance strength-training did not result in performance or joint-kinematics improvements. Contrastingly, power training movement-centered activities did not alter tendon stiffness but did change performance and joint-kinematics in the practiced activities. Associated with increased muscle/tendon stiffness is a loss in muscle elasticity which reduces the potential of the hamstrings to function fully and normally. In a stiffened state, injurious tears to the muscle and connective tissues are more serious and demand longer rehabilitation periods than normal.
- Slower resistance-training exercises produce hamstring adaptations that have no benefit (only injury threats) to the muscles' integrities and functions in natural actions. Training-effects changes are incompatible with natural adaptations and could noticeably interfere with normal performances (e.g., some speed of running could be lost) as well as increasing the likelihood of injuries because of changed contributions/functions to coordinated complex movements when maximum exertions occur.
- When hamstring injuries occur repeatedly, the most common cause is that the rehabilitation exercises used are the same as those that heightened the likelihood of the initial injury. Coaches and athletes are well advised to be very skeptical of rehabilitation programs that use similar or the same training activities as those that preceded the injury.

The above consideration of the effects of dangerous strength-training on the long, narrow, not-particularly-strong hamstring muscles should lead the reader to conclude that intense resistance-training on isolated muscle groups that include the hamstrings is dangerous. Since none of the varied roles that the hamstrings perform in intermittent-sprint sports involve exceptionally high force production or isolated force production, the most obvious training

[5] To all intents and purposes, the increased stiffness renders the muscle structures more brittle. It is because of that loss in pliability that makes muscles tear and more often shear under extreme strain. One could argue that when one form of injuries occurs across a number of different sports, there are at least two common factors that could account for them: i) the high-level of exertion that produces the injury, and ii) an intense resistance-training program aimed at strengthening muscles to levels that are excessive for any demand within a particular sport. If exceptional strength was a very important factor for high-level sporting performances then more body-builders would be observed excelling in sports than the ultra-rare occurrence that currently occurs.

exercises would be game-speed (closer to maximal) sprinting, dodging, and direction changes, the latter two involving considerable skills that need to be practiced in game-simulation activities.

As was mentioned in the opening paragraph, the hamstring muscles function as agonists in knee flexion, and both inward and outward rotation of the knee when the knee is flexed; extension of the hip, and both inward and outward rotation of the hip joint when those movements are necessary. As well, with every stride taken, body-weight is absorbed at touchdown then propelled by the combined eccentric (to) isometric (to) concentric co-contractions of the two powerful thigh muscles, the hamstrings and quadriceps. To adequately prepare the hamstrings to perform efficiently in all those roles, activities that involve them in all their functions need to be experienced. Unfortunately, performing rigid knee flexes relatively slowly and powerfully on a machine such as that illustrated in Figure 1 does not stimulate most if not all the functional roles of the hamstrings in high-intensity intermittent-sprint sports. Because of that restriction, any belief that a machine exercise such as that illustrated is worthwhile for performance contribution is ill-founded and motorically incorrect. Relevant training for intermittent-sprint sports should contain movements that involve the hamstrings in all functions at high-intensity effort levels (i.e., game speed/simulation).

To further emphasize the multi-function role of the hamstrings involved in high-speed movements, it is worthwhile to consider a single activity and the varied roles of the hamstrings. In ballistic sport movements such as power kicking, the hamstrings are involved in both the preparatory movement of the kicking leg and the deceleration of leg momentum after the ball has left the foot/ankle. The former is a concentric contraction, the latter eccentric. In order to rapidly accelerate the kicking leg, the hamstrings are silent as the sequence of posterior pelvic tilt, lumbar flexion, hip-flexion, and finally knee-extension are performed. In the support leg the hamstrings and quadriceps co-contract isometrically rapidly decelerating the left leg from the foot to the hip adding to the acceleration of the kicking leg.

Machine and other auxiliary-training activities produce no beneficial training effects that are transferred to high-intensity locomotion sports but only serve to increase the likelihood of injury as well as consuming valuable training time that could have been used for specifically correct training experiences in natural settings.

Figure 2 illustrates the effects of two different resistance-training emphases on the exercise practiced[6]. Heavy training represents a traditional approach to strength-training, that is, maximum force development is sought without concern for movement speed in the training process. Explosive training represents accelerating as fast as possible against a resistance that does not impede movement velocity. Normally, the maximum load is less than 40% of force production (Rushall & Pyke, 1991) although Kraemer and Newton (1994) suggested 30%. Maximum strength is the maximum force that can be developed without movement, that is, isometric strength. The most notable feature is the maximum rate of force development (*"maximum RFD"*) that occurs with each type of training.

[6] The author of the study from which Figure 2 is adapted, is unknown to these writers. The figure was obtained from a colleague and is believed to have been in a book. Should anyone know the source of this figure, it would be appreciated if that information could be communicated to *brushall@cox.net* so that the full attribution of this work can be recognized.

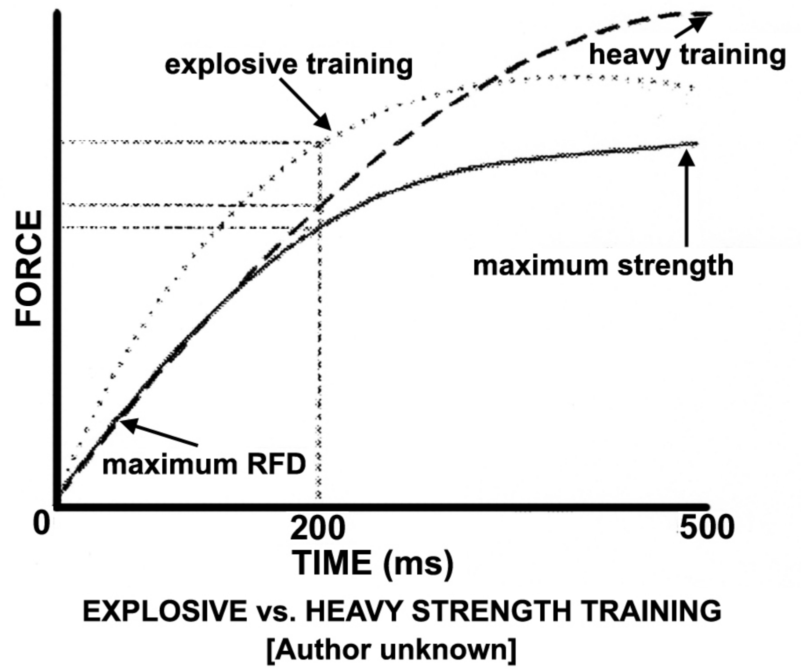

Figure 2. Movement characteristics of two types of resistance-training. It is contended that explosive training that does not hinder movement acceleration (it requires only light resistance) will produce the best training effect for the activity practiced.

The following features are gleaned from Figure 2.

- Explosive training stimulates movement acceleration resulting in greater force production in a shorter period than heavy strength-training. This is deemed to be the quality that should be developed in propulsive free-standing movements.
- Heavy training produces the greatest force development but it is developed slowly when compared to explosive training. Being very strong and slow to achieve the production of maximum force is not a characteristic that is desirable for intermittent-sprint athletes.
- The maximum-strength measure (isometric force) in Figure 2 is less than the force generated in activities in which movement (i.e., acceleration in heavy and explosive training) is involved.
- Explosive training with an emphasis on maximal movement acceleration is the form of auxiliary-training that would seem to be the most appropriate for sprinting if it must be performed. Moving fast is the most desirable capacity to develop.

It is proposed that explosive (maximum-velocity) training concentrating on movement acceleration is the most appropriate form of auxiliary-training for sports that have their outcomes improved by the development of movement speed. However, that proposal is limited. Training effects only occur in the activities overloaded/stimulated at training sessions. The beneficial effects of physical explosive training are only developed in the activities in which they are practiced. In auxiliary-training, it is the resistance-training activities (whether explosive or strength-oriented) that are improved, not the actual movements involved in the sport (in this case sprinting and dodging). A similar argument could be made for activities that improve kicking, sprinting, stopping, or direction changes in field-games. Those movements and their skill-components should be practiced in game-like situations at game-intensities. Whole sport-specific movements have to be performed so that the hamstrings can be stimulated in concert with other muscles' functions and structural position changes to enhance game-performance and reduce the likelihood of injuries that could occur in contests.

Maximum-velocity Training

In sports where high resistances need to be overcome, the power generated is largely dependent on the amount of force that can be exerted. Strength is an important factor in accelerating heavy objects or body-weight (e.g., rugby scrummaging, sprint starting, weightlifting) particularly from stationary positions. When light resistances are encountered, such as when the athlete is already moving, the speed factor dominates and great strength is not required or useful. This is the case in intermittent-sprinting sports such as Australian Rules football, soccer, field-hockey, lacrosse, etc. Muscular power is dependent on the coordination of both the fibers within muscles and groups of muscles. The relationships between force, speed, and power are shown in Figure 3 (Rushall & Pyke, 1991). Large forces cannot be exerted at high speeds. Thus, athletes in sports that require very fast movements do not need unusually high levels of strength. Sports requiring athletes to overcome high resistances quickly should do power training towards the higher end of the force-velocity curve while those requiring faster movements would work closer to the lower end of the curve. Running and sudden direction changes require fast movements with low resistance. Once an athlete is moving at or very near maximum velocity, forces are only needed to sustain the velocity, an exercise demand that requires high movement speed and only a minor level of force. That is a major consideration when considering the enhancement of the hamstrings and other very-fast contracting muscles involved in the types of leg propulsion developed in intermittent-sprint sports.

The development of maximum leg-propulsion movements should only begin after an adequate basic-preparatory phase of training. Such training can involve not quite sport-specific experiences. The sports considered in this discourse are played on a flat surface. To prepare the hamstrings for repeated maximum stimulations, moderate- to high-levels of effort running uphill and downhill could also be included in basic preparatory training. Once specific training commences, flat-running and direction changes need to dominate physical training so that training effects are relevant and maximal. The irrelevant features of the other two forms of incline running are useful for basic preparation and only need to be practiced occasionally once specific work commences so that their minor related training effects can be maintained.

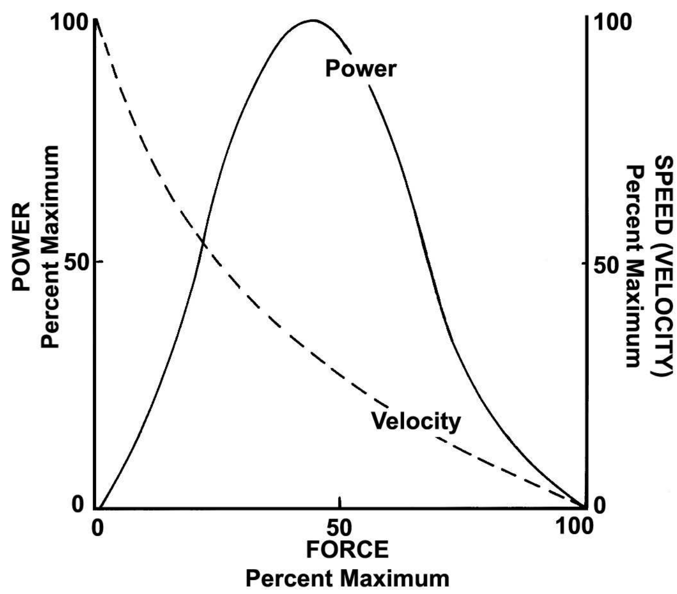

Figure 3. A Stylized Curve Illustrating the Relationships Between Force, Velocity (Speed), and Power.

Maximal running and direction-changes are features that should occur in the skill and position activities of game practices (*"interval skill drills"*; Rushall & Pyke, 1991, Chapter 17). As a competition season progresses, the physical factors involved in the muscles used in propulsive movements will approach a maximally-trained state. Thus, specific training activities for physical capacities, such as dedicated sprint-repetition sets and agility shuttle-runs, will gradually become less important/valuable as the trained-states of the muscles involved in the cyclic activities cannot be improved further. At that stage, they can be largely replaced by greater volumes of specific- and positional-skill game-relevant activities. In that approach to training, the hamstrings will be adequately developed and trained/conditioned.

There are three major features of the graph in Figure 3.

(a) When speed is very high the percent of maximum force that can be exerted is very low.
(b) When maximum forces are to be exerted the speed of movement should be very slow.
(c) Maximum power (the best combination of force and speed) is achieved at speeds which use 30-40 percent of maximum force.

These relationships have obvious implications for the emphases of training items that are planned for power and speed development. For sprinting and direction changes, the movement velocity will be high and the applied force very low. The only times larger forces, but still in a moderate- to low-range and for very short periods of time, are needed is when a player accelerates from a low velocity.

The case for maximum-velocity training has been made largely through de-bunking the dogma associated with common strength-training. Performing maximum-effort sets of sprinting, shuttle-runs to practice direction changes and quick-stopping, etc., should be part of the physical training regime of serious and elite teams throughout pre-season and particularly in-season training in the sports for which they are frequently executed and particularly appropriate. Those activities will allow players to develop their individual skill-needs for each activity. Few coaches recognize the major importance of developing and refining the skilled coordination and timings of the whole-body sectors that are involved in running, stopping, and rapidly changing movement directions. Those activities will adequately stimulate and physically train the hamstrings. The training of isolated muscle-groups outside of game-simulation practices will have little benefit for improving game performances because they develop partitioned movements that are distinctly different to those of the same muscles and joints being used in free-standing whole-body activities. They are irrelevant for the needs of developing game-movements and skills. If those irrelevant activities are approached excessively, the likelihood of injuries in game-settings will increase. Such is the case with developing the hamstrings to accommodate the stresses of games and game simulations. The import of relevant research is clear; the claim that auxiliary strength-training as additional in-season activities provides benefits for game performances is unsupported. That clarity is obscured by the strength-training industry and those involved in strength-training programs (ostensibly to maintain employment and/or make themselves indispensible to the "*team*") that perpetuate the dogma and pseudo-scientific argument that strength-training is part of any modern training program for any sport. The opposite is actually true.

The Neural and Psychological Bases of Human Movements

That the popularity of auxiliary-training renders it a necessary part of elite and professional athlete training should be disturbing to scientists who are familiar with the functioning of the human body and how it responds to various forms of exercise stimulation. A perpetuating influence is the industry involved in manufacturing *"new and improved"* devices that are supposed to directly alter performance levels and health status. Another influence is the legion of individuals who practice the activities for no other purpose than it is their form of exercise in an increasingly mechanized and natural-activity-deprived world. As well, there are individuals who are schooled in exercise science with its heavy bent on explanatory exercise physiology and then go on to a professional position as a conditioning coach, personal trainer, exercise specialist, etc. Proselytizing that auxiliary exercising is good for other forms of exercise is accepted and promoted unashamedly by individuals and even institutions.[7]

Holt and Holt (2010) spoke about the belief-based approach to auxiliary-training for golf:

> *A number of fallacious inferences, betraying a sometimes merely superficial and sometimes hopelessly flawed understanding of the body and how to improve its skilled performance, are lurking in the background. One such fallacious inference is to reason that a certain outcome (say, driving distance) will be improved by increasing a certain basic physical capacity (say, strength), even though the athlete may already have an optimal level for that particular skill, that is, a level beyond which performance will not be further enhanced by increasing the capacity. Another fallacy is reasoning that other desirable capacities (say, flexibility) or outcomes (say, accuracy) will remain unaffected if not enhanced by increasing other capacities in certain ways (say, strength by lifting heavy weights). Yet another fallacy is to reason that an increase in one's general fitness will yield better performance in an activity like golf. One more fallacy can be captured by the slogan "More is better": if some conditioning is good, then more frequent, longer, and more demanding conditioning is presumably better, and the more demanding the better, even though there is clearly a point of diminishing returns beyond which tissues, worked harder and harder still, eventually break down.*

It is not the purpose of this discussion to delve into the evidence-based scientific literature compared to belief-based pseudo-scientific literature (Rushall, no date) that refutes much of the auxiliary-training literature. However, it is assumed that resistance-training and conditioning of the hamstrings is undertaken because of the mistaken belief: *"any muscle group will benefit from auxiliary-training and those benefits will transfer to game-situation or simulation activities."* Another belief is that since an auxiliary-training facility has a

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[7] Several years ago, a Southern California college built a new Athletic Department and training facility. A large space was made available and equipped to provide opportunities for resistance-training and conditioning activities. Appropriate specialist coaches were hired. Rumor has it that in excess of one million dollars was invested in the space/facility/staff. The Athletic Director at the time decreed that all representative teams of the institution were to use the facility and staff ostensibly to justify its cost, whether or not its activities were supported by a specialist-sport coach. Such a display of ignorance about human movement and sports performance was somewhat supported by the academic offerings of the college whereby students could earn an undergraduate degree specializing in athletic/exercise conditioning and/or training. It is believed that the elevation of the dogma and myths of the *"value"* derived from auxiliary-training to academic status is replicated in many institutions in the USA and Canada.

machine that might be useful for injury rehabilitation, it might also be useful for a *"complete resistance-training program"* and so the hamstrings are ineptly trained/abused.[8] Not all performance qualities benefit from physical stimulation through auxiliary-training programs. In order to explain that statement, it is necessary to digress and develop the fact that not all physical movements, if any, are best served by conditioning coaches/athletic trainers and their auxiliary-training programs.

Some Historical Elements in the Development of the Specificity of Neuromuscular Patterning[9]

The most impressive early discussions (~110 years ago) mostly involved Frank Gilbreth's recount of Sperry's work, which disputed *Poppelreuter's Law*. That work showed when an arm was extended vertically downward and the index finger slowly traced a 12-inch circle, a pattern of sequential firing of the shoulder muscles was displayed with most muscles assuming a propulsive (agonistic) function at one time and a control (antagonistic) function at another. However, when the same circle-tracing was sped-up, the sequence and functions of all the muscles were totally changed despite an observer seeing the "*same action*" done at a faster velocity (Arthur Slater-Hammel, personal communication, October, 1967). The complete difference between submaximal and maximal efforts doing the *"same"* activity is still being verified (e.g., Elmer, Peterson, & Marshall, 2014). Using arm-cycling, which is somewhat allied to the upper-body work of sports such as kayaking and swimming, the change in effort levels showed maximum efforts recruited major muscles that were not used in the lesser-intensity work, had different muscle coordination patterns, peak EMG activity occurred in some major muscle groups, and the extent of muscle activations were also increased. When training at less than competitive-setting intensity, the technique bases (i.e., how and when the muscles work) do not train anything associated with contest-specific work. It does not prepare individuals to compete in the games.

Frances Hellebrandt (1958, 1972) summarized much of the main implications of the research on motor-learning specificity that existed before the late 1950s. There has been little new information on this topic since then. Some of her conclusions and their implications are listed below.

> *If muscles participate in more than one movement, as most do, they must be represented diffusely in the cortex. Presumably different centers connect via internuncial neurons with groups of peripherally disposed motor units. . . . motor units are activated in a definite sequence which varies with the movement elicited. As the severity of effort increases, those involved primarily in one movement may be recruited to assist in the performance of others* (Hellebrandt, 1972, p. 398).

Movement patterns, not muscles[10], are represented in the cortex. Patterns are learned and those patterns are peculiar to every movement. Skilled performance improvements are

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[8] This manifests one of the frequently observed weaknesses in physiotherapy training programs: That the principles of physical rehabilitation are equally applicable to the auxiliary-training programs of elite and professional athletes (although such programs also are very often incorporated into age-group and high-school athletic training programs).

[9] Much of this section is a repetition of the appropriate part of Rushall's (2011) paper *Swimming energy training in the 21st Century: The justification for radical changes (Second Edition).*

[10] The common term *"muscle memory"* is nonsense.

continual refinements of the details governing the skill intensity, velocity, type of muscle contractions, the provision of energy, and locus of movement. They are represented in the brain. No serious athlete would improve performing in a contest without practicing repetitions at game-intensity in situationally-specific settings (for the sport of swimming see de Jesus *et al.*, 2010). To practice at another velocity would practice something different. Techniques are peculiar to each varied velocity for each movement classification.

> *. . . reflexes evoked under similar conditions are extraordinarily consistent. Indeed, they are so repetitive as to warrant designating them patterned movements. . . the fundamental unit of action may be thought of as a total response in which agonists and antagonists, synergists and fixators participate in balanced and harmonious activity. Partial patterns emerge secondarily, by virtue of special training, . .* (p. 399).

Total actions (e.g., those to be used in a competitive setting) need to be practiced. The partial or isolated training of movement segments (e.g., drills, land-training exercises, auxiliary-training exercises) would not replicate the unit function in a desired total competitive action. Thus, once techniques (total response patterns) are being refined, partial practices would serve no purpose other than to learn another movement pattern. There would be no integration of the partial practice movement into the total response movement once an individual-determined level of movement-skill competency is reached. The only way a highly-skilled athlete can improve performances, is to specifically practice those performances. No auxiliary-training activities would contribute to skill enhancement once a skill has achieved a reasonable level of proficiency. It is possible that the auxiliary-training and/or partial-skill activities could degrade the target-skill performance.

> *. . . the sensory feedback coming from muscles, tendons, and joints greatly affects movement patterns. Central excitations have a tendency to flow always into stretched muscles. Thus, every change in body positioning alters the configuration of the next succeeding efferent response. It affects not only the muscles stretched, but all functionally related muscle groups as well. This means that a change in the responsiveness of one component of a movement-complex spreads autonomously to the other constituents* (p. 399).

When a patterned movement is changed by conscious effort to alter at least one aspect of a technique (*aka* style), the whole action is altered, usually to perform worse[11]. The practices of isolated drill elements or use of training equipment and then consciously implementing the experiences from the drills and equipment use into the established pattern would disrupt the pattern in its entirety. Thus, the changed element may be performed "*better*" but the other, previously acceptable movement characteristics will be altered for the worse. This is the conclusive argument against auxiliary-training that is supposed to "*strengthen*" an athlete and/or increase performance velocity. Claims to produce beneficial changes in serious athletes by doing something other than game-specific simulations should be treated with great skepticism.

> *. . . willed movements which are new and unfamiliar always demand cerebration. They are performed at first with more or less conscious attention to the details of their*

[11] To improve/alter an established technique, competent performers have to be prepared to perform worse for a period of time before they perform better than before the change. That leads to the adage; *"An athlete has to perform worse to get better."*

> *execution. Once mastered, they operate automatically. Conscious introspection at this stage may even disrupt the nicety of an established pattern. After an act has become automatic, . . , it is less well performed if it must first be considered and analyzed* (pp. 399-400).

Conscious attention to details of an automated action will reduce the efficiency/economy of that action. There is a time before an important competition when conscious attention to details of techniques at practice needs to cease so that preparation can be perceived by an athlete as consisting of "*good feeling*" techniques that are performed automatically. At some stage in an athlete's career, the emphasis should switch from "*changes for the better*" to refinement of newly established skill elements and skills. When refinement is approached, it should involve mental preparation and recognition, specific-skill practices, and evaluation of athlete-generated feedback against objective feedback (e.g., video analysis).

If competing movement patterns are learned through conscientious practicing of contra-specific water (e.g., in-pool running) and land activities (e.g., weights, yoga, isokinetic machine work), conscious attention in a game could switch to a less-efficient pattern of movement learned through the counter-productive activities, particularly if attention is on one segment of a complete movement technique[12]. As attention then switches to other different skill elements, the economy of a performance is degraded. In games/races and at practices, a great deal of emphasis should be placed on the total activity technique. If change is desired, then skill segments will have to be changed requiring both the coach and athlete to endure and tolerate a decline in performance until the change is incorporated successfully and the whole altered pattern, which is a new technique, is practiced sufficiently to surpass the level of learned performance of the previous form of the activity. With young people, altering established skills is possible. However, with mature individuals there comes a time when no alterations of established skill patterns should be contemplated because there would be insufficient practice time in an athlete's sporting career to successfully incorporate the change and return to or better the previous performance level.

However, when fatigue is incurred, conscious attention to performance details produces a more efficient movement form than one that is executed automatically. Thus, there are times when the conscious control of performance movements is detrimental (e.g., in non-fatigued states) and times when it is beneficial (e.g., in states of high fatigue). A loss of technique control should be used as the index of detrimental fatigue, recognizing that the fatigue could be physical, neural, mental, or combinations of all three.

Through practice, many activity patterns are learned. More often than not, families of movement patterns are learned to accomplish the same functional outcome. While a set of repetitions is executed in an interval-training format, movement patterns will be evoked in series to avoid unnecessary fatigue in the central nervous system mechanisms and the skeletal structures used. In fatigue and stress, the recruitment of extra responses and neural patterns will be more extravagant because of learned facilitation. Much training is performed in fatigue and thus, more than restricted efficient movement patterns are learned to dominance. That mirrors what happens in a competition. As a game/race progresses,

[12] Of particular importance is that if a change in a technique element is attempted, in accord with Newton's Third Law there will be a counterbalancing change in a technique element somewhere else in the movement pattern.

techniques change (Oxford *et al.*, 2010; Seifert, Chollet, & Chatard, 2007). If specific limited training had only occurred, that is, the body only knew a narrow band of efficient movements, then the recruitment (irradiation) would be minimal and movement patterns would center on efficient movement. Adequate rests during practice should be provided to prevent an athlete trying very hard to perform well when tired because too much fatigue inhibits the attainment of practice goals, reduces learning potential, and sensitizes the brain to new counter-productive/irrelevant experiences and neural representations.

Practice does not make perfect. Only practice that yields feedback about the correctness of responses can generate advances towards perfection. If practice-activity content is largely irrelevant for competitive situations and/or feedback is inadequate or non-existent, practice time largely will be wasted. However, individuals without external correct-coaching feedback do improve in performance but only to a certain level. Without instruction, individuals tend to adopt expedient strategies for movement control, which quite often are not the best or most economical movement patterns. This is why an individual can participate in serious recreational sport for 20 years, never having had a coach, and not improve year after year and even worsen in accordance with the aging process. The expedient patterns that have been learned and perpetuated limit performance to that of a mediocre level.

For efficient and maximum performance ". . . *the kinesthetic acuity we should strive for is not enhanced general body awareness, but rather, a more sharply defined and specific sensitivity to what is happening in those key maneuvers upon which the success or failure of complex movement patterns may depend*" (Hellebrandt, 1972, p. 407).

The skill content of practices has to mimic that of competitive requirements if beneficial training is to be experienced. It is wrong to practice something with good intent (e.g., "*I hope it will benefit the performance*") without being able to justify and demonstrate correlated transfer to a competitive skill and performance. It is wrong to practice a sporting activity if the skill amplitude and rate do not reflect the intended competition-specific qualities (Robb, 1968). If this dictum is not adhered to, much practice will be wasted and/or will be counter-productive. It is quite possible that movements practiced could be so irrelevant that their impact on hoped-for game-specific movements would be so destructive that performance would be worse than if no practice had occurred.

There is a tendency in modern sport for "*gurus*" to advertise their services for greatly increasing sporting performances for anyone willing to pay for the services. Mostly, such services offer one specific tactic, experience, or device for achieving remarkable claims. The theoretical and evidentiary reasons for the claims usually are not in accord with the known principles of human performance, and more specifically, motor learning.

In recent years, brain activity when performing or imaging a skilled movement has been viewed through the use of functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) scans (e.g., Ehrsson, 2001). Ehrsson showed:

i. Power and precision movements of the index finger and thumb of the right hand were controlled by different areas and patterns of activation in the brain. A power grip was associated predominately with contralateral left-sided activity, whereas a precision-grip task involved extensive activations in both hemispheres. Figure 4 contains a section of the illustrations provided by Ehrsson (2001) which demonstrates the advancement in technology since Hellebrandt's work. The visual confirmation of the measured brain activity increases the reliability and understanding of the Specificity Principle in skilled and exertional movements. This work was also published by Ehrsson *et al.* (2000).

ii. Distinctive brain activity was also shown for the movement skills of synchronous and alternating finger tapping.

iii. The fontal motor areas of the brain are stimulated by both an illusory limb movement stimulated by vibration stimuli and imagined movements of the fingers, toes, and tongue. The patterns of stimulation are movement-specific.

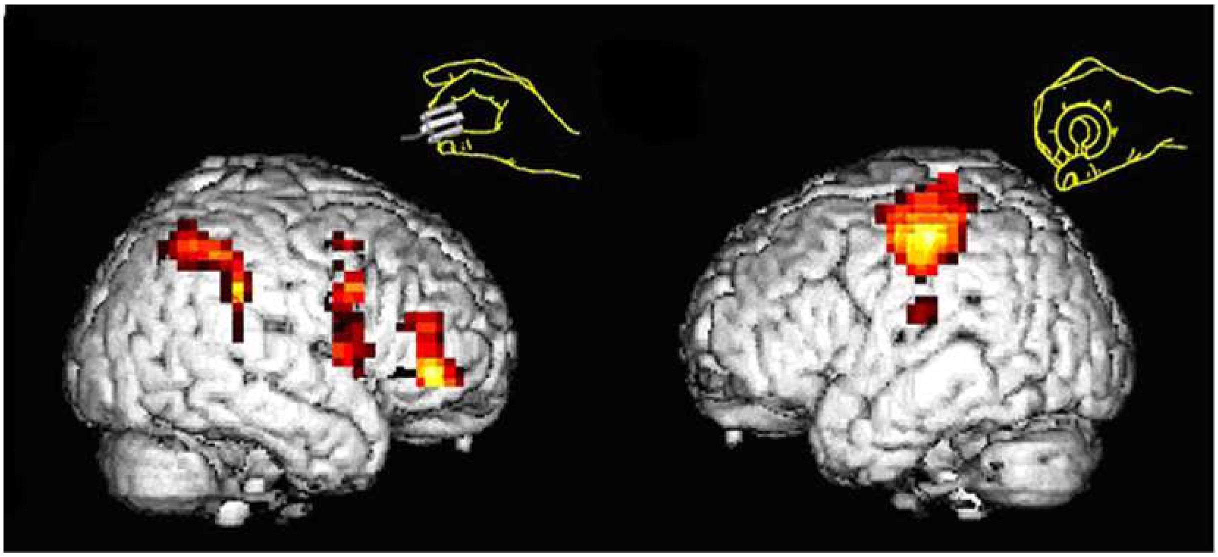

Figure 4. fMRI images of part of the specific brain activities associated with the precision index finger–thumb movement (leftmost upper line image) and power-grip movement of the same digits (rightmost upper line image). [Reference: Ehrsson, 2001. Permission granted for reproduction in this article (personal communication November 11, 2016): Image – H. Henrik Ehrsson; and copyright Karolinska Institutet.]

The latest research technology demonstrated by Ehrsson supports the specific movement representations in the brain for activities that are much alike. When movements are very different, brain activity is even more dissimilar. Further, athletes commonly perform their skills in a practice-environment and augment those skills with land-training (auxiliary-training). Often land-training activities aim to increase muscle group strength by performing activities in a postural orientation and gravitational experience, and loci of movements, speed and nature of contractions, effort levels, and performance outcomes that are distinctly different to the competitive experience. How one could believe that isolated-muscle land-work augments and benefits whole-body movements in games is baffling.

The following quote from one of the world's foremost motor learning/control scientists, Dr. Richard Schmidt, author of *Motor learning and performance: From principle to practice,* is most pertinent.

> *A common misconception is that fundamental abilities can be trained through various drills and other activities...For example, athletes are often given various 'quickening' exercises, with the hope that these exercises would train some fundamental ability to be*

> *quick, allowing quicker responses in their particular sport. There are two correct ways to think of these principles.*
>
> *First, there is no general ability to be quick, to balance, or to use vision...Second, even if there were such general abilities, they are, by definition, genetic and not subject to modification through practice...A learner may acquire additional skill at a drill...but this learning does not transfer to the main skill of interest* (Schmidt, 1991, p. 222).

The specificity of movement patterns and control is a scientifically established principle of human exercise. It is the encoding of patterns in the brain that establishes the uniqueness of movements. There has been no wavering on this scientifically validated phenomenon over the past half-century, although minor theoretical incursions have been attempted. Yet, auxiliary activity practitioners persist in violating this basic principle of performance with dubious arguments, false premises, and distorted facts. It is too well proven to concede that the scientists might be wrong. It is time for the practices and programs of coaches to be brought into line with established facts. The training of sporting skills and energy provision and its variants has to be specific and whole. If effective technique-change work is not achieved at practices, athletes will persist with undesirable faulty movement-patterns which compromise performance efficiency (Schnitzle *et al.*, 2008). The programming of appropriate transferable-to-game practice activities in an enriched milieu of correct sporting training is a challenge for modern coaches.

Neuromuscular Pattern Specificity

The concept of all movement patterns being separate and specific has existed for a long time. In this day, little confirmatory research is conducted on the patterning of movements in the brain. It has become an accepted motor-learning principle that all movements are specific and that the higher the level of proficiency of an athlete, the more refined will be the neuromuscular patterns. It is the neuromuscular patterns that govern high-level performance even in activities where physical effort is extreme (e.g., Grabe and Widule's 1988 study on weightlifting). As evidence of the universal acceptance of this concept, Luttgens and Hamilton (1997), in their valuable book on kinesiology, did not justify the principle of neuromuscular specificity but simply referred to it as follows:

> *Skillful and efficient performance in a particular technique can be developed only by practice of that technique. Only in this way can the necessary adjustments in the neuromuscular mechanism be made to ensure a well-coordinated movement* (p. 507).

The two authors repeated their acceptance of the specificity of neuromuscular patterning in their discussion of muscle strength.

> *Strength or endurance training activities must be specific to the demands of the particular activity for which strength or endurance is being developed. The full range of joint action, the speed, and the resistance demands of the movement pattern should be duplicated in the training activity* (p. 465).

Many auxiliary-training activities are advocated, many driven by the profit motive of manufacturers and inventors rather than scientific fact. They need to conform to the *Principle of Specificity*. In this paper, only a few works in the historical literature that led to this principle were considered. While reading this section, one must consider how can today's popular commercial aids (e.g., weight-machines, free-weights, elastic-band resistance devices, large balls for *"core exercise"*, etc.) promote activities for any sport that conform to this principle? If they cannot, then they must be wrong/irrelevant for serious training athletes.

The *training paradox*, if ignored, is another factor that introduces irrelevancy into auxiliary-training programs.

1. *Beginner participants* benefit greatly from doing drills and part-exercises as activities in their instructional process. They allow the learner to focus on an action-part that might be difficult to do if it were first attempted imbedded in a full complex whole-body action. Similarly, an unfit individual might start jogging as a way of improving fitness to find that at that time the running also makes riding a bicycle easier. Part of the learning or initial adaptation challenges that occur when beginning a new activity shows that there is some partial transfer of training benefits from quite often dissimilar activities.

   As a new participant builds familiarity with an activity and develops some competency, the transfer effects of non-specific activities no longer are so obvious. With complex movements like those involved in any intermittent-sprint field or court game, within the same individual some parts of an action might still be at the beginner stage while others have forged ahead to have a recognizable level of competency. When learning to dodge an opponent, as a previous beginner improves stepping to the left which might be of an average acceptable form, stepping to the right could still be at the beginner level. The effectiveness of part-skill activities (i.e., drills) would vary with the competency levels of the parts of a total movement pattern. Newly serious athletes who have progressed from beginner programs are likely to show differential responses to program items because of the varied competencies of the elements in their relevant skilled movements.

2. *Competent athletes* (e.g., those in serious training) will gain little from performing parts (i.e., drills, resistance exercises) of a complex movement in isolation. Similarly, the early fitness gained after entering a serious training program will have only slight transfer to other activities. As experience with training improves, the value of part-learning experiences or *cross-training* for fitness diminishes.

3. *Advanced* or *elite athletes* need to be exposed to training experiences that directly comply with the *Specificity of Training Principle*. Techniques need to be altered and those alterations practiced while performing the whole action. Physical training needs to be applied to the actual muscle-part and muscle-group activations that are of the same velocity/intensity as those which would occur in competitions. The vigorous debate of more than half a century ago over the part versus whole learning strategy[13] showed that for cyclic activities (e.g., dodging, running, cycling, etc.), when

[13] Perhaps as much as 50 years ago, a popular topic for motor-learning research was *whole versus part learning*. The question being asked was: *is it better to teach activities in parts or as the total activity*? There never was a definitive principle developed from such research because too many variables (e.g., a subject's familiarity with the activity; for a novel activity all subjects were beginners; the degree of complexity of the activity; etc.) modified the nature of the practice item for it to become relevant for beneficial training effects. Despite Professor Fanklin Henry's clear demonstration that motor skills were specific and that generalized factors did not exist between movements, the demonstration of ignorance in exercise-related activities still is consistently shown by conditioning coaches, among others, who claim their programs will benefit performances in remote competitive settings.

technique modifications are needed they should be attempted while performing the total action. Specific changes attempted in competent/advanced performers require modifications in the neural patterns of activation in the brain associated with the full action.

The point behind the above long digression is to present an aspect of coaching that is mostly ignored or simply paid lip-service. When one considers the great diversity of activities that comprise competitive sports, there is not one activity that does not have a significant element of skill involved when performed at the highest levels. Also, as a participant moves through the participation-ranks of beginner to competent to elite/professional, much of the progression is determined by the advancement in appropriate skilled movements. Unfortunately, that necessary emphasis is obscured/replaced by a physiological emphasis which usually provides irrelevant training experiences for the sport. In this paper, an attempt is made to draw readers' attention to the need for the skill elements of movements to be developed eventually in full-movement form in game-situations/simulations. A conscious effort has to be made to discard irrelevant physical training and the detrimental fatigue and training effects that it generally develops, and to embrace the *Principle of* [*Training*] *Specificity* so that as much training time as possible will yield performance improvements that will transfer to competitive environments. The neural component of movements is more important than isolated partial-movement training aimed at generating exercise fatigue and deserves a more extensive emphasis than that given to auxiliary and flexibility training.

Neural Factors in Strength/resistance-training

Rapid increases in strength develop during the first two to eight weeks of training (Fleck & Kraemer, 1988; Thorstensson *et al.*, 1976). Those marked improvements occur without any increase in muscle size or muscle-fiber morphology. Strength-training effects first occur at the neuromuscular level. The first response to strength-training is the harnessing of existing capacities and resources to perform the exercise. Training a group of muscles in a particular exercise will increase strength in that exercise but will not generalize to any appreciable degree to another exercise involving the same group of muscles (Sale & MacDougall, 1981). The neural adaptations that occur are very specific. There are four responses that produce strength increases without any anatomical (morphological) changes: neural adaptations appear first and improve technique; the firing rate of motor units increases; additional motor units in the muscle are recruited; and the synchronization of the motor units is improved. It also has been suggested that inhibiting the self-protective mechanisms of the body (e.g., golgi tendon organs) allows for a more forceful contraction (Ikai & Steinhaus, 1961). Morphological adaptations occur after neural adaptations are exhausted (Bosco, Rusko, & Hirvonen, 1984; Fleck & Kraemer, 1988; Moritani & de Vries, 1979). Even with the inclusion of physical adaptations after extensive strength-training, the performance of strength is significantly governed by neural stimulation and excitability (Lepley *et al.*, 2013). Neural excitability predicted nearly half of the variance in quadriceps strength providing evidence that neural pathways and stimulation are essential in maintaining and increasing quadriceps strength. To increase neural drive and excitability, exercises should be performed with maximum explosive effort with an emphasis on speed of movement rather than excessive loads that slow movement execution. Neural drive is stimulated to the highest level by highly explosive training rather than maximum effort slower-moving strength-training (Folland & Fry, 2012).

The major factor for the practitioner to understand is that the initial response to strength-training is one of skill acquisition. Morphological adaptations only occur after skill levels have been developed and training focuses on the build-up of strength through heavy resistances in blocks of low repetitions. Conditioning coaches usually assert that resistance-training is the only avenue for increasing muscle size (i.e., hypertrophy). However, the recent emphasis on high-intensity interval training, where the training stimulus is closer to game-intensity rather than one that mainly stimulates aerobic adaptation through sub-maximal training intensities has shown that it too alters muscle size in untrained young males (Losey *et al.*, 2013).

Sporting exercises that are technique dominant will have a greater chance of improvements if the training emphases are on one or more skill factors that enhance the proficiency of the sport's movements rather than one or more minor physical factors or capacities. When physical training, such as resistance-training, is performed conscientiously and frequently, the movement patterns developed in the brain are specific to that exercise and do not influence contest-relevant performances. Groups of neuromuscular movement representations in the brain do not migrate in part or in whole to other exercises. What is trained in a gym or weight-room stays in the gym or weight-room. Thus, skill-dominant sport training should emphasize skill-development and not over-emphasize physical training (Kearney *et al.*, 1994).

There are two other considerations that need to be contemplated when deciding what are the best training activities for competent to elite athletes in a particular sport.

1. When the *Principle of Overload* is applied to a contest-relevant activity, the performance technique varies during the time the activity is attempted. As fatigue enters into repetitive executions, movement alterations occur, the degree of alteration rising with the degree of fatigue up to a point[14]. Consequently, although one training block of correct movement execution is performed, the brain develops a family of movement pattern representations, most of which lead to the same performance outcome/result. In a similar manner, in a resistance-training exercise that is performed to exhaustion, a family of movement patterns for the exercise is also developed. Neither of the two *"families"* of representations will migrate to nor influence the other. Even when the general activity is the same (e.g., running), by changing environmental features (e.g., up-hill, pulling a sled, tethered-running, treadmill-running, etc.) will result in quite different neuromuscular representations deeming each activity to be specific (Town & Bradley, 1991).

   Some auxiliary-training adherents and coaches will claim that research shows that cross-training, resistance-training, etc. do transfer to other forms of performance (e.g., Loy, Hoffmann, & Holland, 1995), although the amount of transfer is only quite small when one considers the amount of effort and energy expended. When the Loy, Hoffmann, and Holland article is used as scientific justification for cross-training or transfer of training effects, apparently the readers have not read the literature review fully. What those authors showed was:

[14] As the acidity of body fluids increase with fatigue, the ability to learn (i.e., to form neuromuscular pattern representations in the brain) diminishes and eventually stops. Learning is halted before total exhaustion is achieved.

With cross training, several modifying factors have to be considered. The fitness level of the individual will alter training sensitivity and the nature of effects.

- For particularly unfit individuals, any overloaded-exercise experience is likely to increase physiological indices and performance in any activity.
- For moderately fit individuals, for example, those interested in fitness, any overload exercise is likely to marginally increase central measures of cardiorespiratory fitness, but effects on performance are likely to be inconsistent.
- For extremely fit individuals, cross-training overloads usually will not influence specific fitness because it already is likely to be maximal. In very demanding training programs, cross-training experiences might be a respite from excessive overloads and stimulations and could act unwittingly as a minor safeguard/rest activity. On the other hand, a case could be made to assert that target performance could be affected detrimentally by cross-training because of its fatigue and competition for resources.

The research evidence that exercise learning and training are specific and eventually do not facilitate movement or energy-resource sharing/generalization between activities is much more abundant than that which supports auxiliary-training dogma.[15]

2. Conditioning coaches have expanded the dogma of their influence. Hard auxiliary-training sessions are touted to improve, among other factors, psychological characteristics. *Mental toughness* is commonly claimed to be a weight-room outcome. Slogans, such as *"Winning starts in the weight-room"* are often posted on gymnasia walls. Coaches shouting at athletes as they push a resistance-exercise to voluntary exhaustion frequently call forth a slew of claims (*"feel the good you are doing yourself"*; *"this will be with you in the fourth quarter"*; etc.) to propagandize the dogmatic value of the irrelevant experience for a particular sport. There is little to no evidence in acceptable research fields that transfer benefits in the psychological domain occur although some mood characteristics are altered for a brief period from a bout of exhausting auxiliary-training.

The requirement of sport coaches to realize and understand the message of this paper was clearly espoused by Holt and Holt (2010) in their discussion about golf.

> *A philosophy of skilled human movement must be sensitive to the various ways in which skills can be performed, what the performance of those skills actually requires, and variations among the bodies performing those skills. Pursuing optimal performance must not gloss over these varieties, from body characteristics to skills types and means of execution. At the same time, attempts to optimize performance should not be infected by overtraining or inappropriate cross-training or general fitness conditioning, which will at best leave performance unaffected and at worst be extremely counterproductive. False theories of skilled movement, together with the fallacies that subtend them, must be abandoned on pain of undermining the very goal at which they aim. Achieving the*

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[15] For example see: http://coachsci.sdsu.edu/csa/vol12/table.htm; http://coachsci.sdsu.edu/csa/vol21/table.htm; and other *Coaching Science Abstracts* issues concerning movement specificity, strength-training, and training in general.

> *optimum, in golf as in life, requires an awareness of what really matters hand in glove with a sensitivity to differences among people and ways of getting things done.*

Neural-training Emphases are Required for Serious/elite Athletes

Hoyle and Holt (1983) provided an early justification for a neural training emphasis for human ballistic movements. The neural features involved also pertain to the maximal cyclic activities that are the basic requirements for competency in intermittent-sprint sports. Almost 40 years of laboratory testing and independent studies (Holt, 1970–2006) on this type of phenomenon conducted at Dalhousie University's Sport Science Laboratory has consistently and invariably supported this training emphasis with a view to elevating it to be the most important physical training emphasis for the sports considered in this presentation. The Dalhousie University research has repeatedly demonstrated that those who excel in activities requiring extremely fast movement patterns, including sports such as badminton, table tennis, Australian Rules Football, field hockey, etc., possess the following neural characteristics (Hoyle & Holt):

1. *Very fast nerve conduction velocities to the prime movers (muscles) involved in the patterns of movement performed in the sport (Huang, Chang, & Hsieh, 2005). For the sports mentioned above, this would involve most of the peripheral nerves to the four limbs. As an example, the above athletes' ulnar nerve conduction velocity was 65–75 m/s, whereas non-athletes, or athletes involved in other sports might conduct at 35–55 m/s.*
2. *High-velocity limb movement capability on simple, non-skill dependent uniaxial, single joint rotational movements (simplified human ballistic movements rather than three or more segments). They can simply move a limb through space at higher speeds than normal. This means that they have the capacity to recruit more of the available fast-acting motor units (Hoyle, 1974; Hoyle & Holt, 1983).*
3. *Greater movement speed and agility of their bodies. When given simple, non-practiced agility tests, they scored significantly faster than other athletes and normal individuals (Sievert, Backus, & Wenger, 1995).*

All three of the identified factors involve high-speed conduction along the large motor nerves. Interestingly, although it is intuitive to think that these athletes would also have faster reaction times, they did not (Hoyle, 1974).

Having the required neural components is one of two necessary ingredients for producing fast well-executed skills. The other is having the capacity to sequence and repeatedly execute precise fast movement patterns. The approach to training fast high-intensity activities (i.e., repeating, being provided with feedback, and changing the skilled-movement form) is infrequently discussed and not well-known.

In keeping with this presentation's focus on including neural/psychological training for performing maximal speed activities in the sports considered, the mental content of preparation for each task repetition is an element that must be contained in all repetitive training exercises of game-simulation form. Behm and Sale (1993) showed:

> *At the highest speeds of movements, it is thought that adaptations are neural, that is, movements with the greatest speed and effort are developed as a learned response. Their training is neural and does not involve physiological changes in the muscles.* (p. 359)

Very seldom are the thought processes and psychological variables associated with changing performance capacities considered in physical training programs in serious sport environments. Behm and Sale showed that movement was unnecessary but movement-intentions were for speed-performances to change through practice. At training, maximum sprint runs should be accompanied by conscious attempts to move quicker than before. The intent-belief that this can be achieved is a major determinant of improving movement speed.

Another variable that governs the level of activation of muscles in human ballistic or speed movements is the form of physical training involved. Folland and Fry (2012) showed that neural drive was greater during explosive actions than in maximal voluntary contraction exercises (e.g., strength-training/weight training exercises). Greater stimulation is provided by explosive exercises than maximal conventional concentric contraction exercises. Consequently, to develop ballistic and/or speed movements, the exercises of training should be maximally explosive, that is they should be performed as fast/explosively as possible. To do that, exercises should be accompanied by intentional content to move faster, jump higher, kick further, etc. than on the previous exercise attempt. Each training repetition should be executed with the intention of improving performance foremost in an athlete's mind.

Edwards *et al.* (2008) reported that after two months of traditional strength-training for arm-sprint power, the introduction of explosive arm-sprint training produced further increases in arm-power performance. As well, the explosive training produced desirable improvements in several biochemical factors. Gardner *et al.* (2007) verified the work of Edwards *et al.* by showing there is no practical relationship between force and the ability to produce force quickly. Moving quickly and producing force quickly may be related, if at all, to only a small degree. The current emphasis on improving strength to improve movement speed should not yield much, if any change because the two capacities have so little in common. Some subjects in strength-studies do show some transfer of training effects, albeit in minor amounts. The greater proportion of subjects do not demonstrate any effects. Thus, if a coach decides to include rigorous weight-room training activities as physical training for an intermittent-sprint sport[16] the returns for the time spent in such training will be meager to non-existent. One has to question if time allotted to training could be better used by substituting one or more different activities.

A further training strategy for improving performance speed is to vary the resistance load while doing the game-intensity performances. Particularly in baseball, the use of under- and over-weighted balls to improve pitching speed, under- and over-weighted bats to improve bat-speed are common and perpetuated by a significant equipment market. However, studies within baseball show that the varied resistances offered by the different objects do not produce any significant skill-performance gain (Mills & Rushall, 2006, Rushall, 2009a). Bauer *et al.* (1995) demonstrated that doing an activity with reduced-load to increase speed or heightened-load to increase strength, was not supported as a sound training-stratagem. Since the activity (elbow-extension) was ballistic in nature, it can be asserted by analogy that using heavy and light bats for batting practice, light or heavy balls for throwing/pitching, etc., will not produce beneficial results over those that would be obtained by using the exact game equipment. For ballistic exercises, training is specific in its effects (i.e., the movement representations in the brain). Supplemental work as part of training does not increase the

[16] Indeed any sport.

nature of the desirable specifically trained-response. Rather, it simply develops other skilled movements. If the under- and over-levels of stimulation used at practices are very close to the desirable skill, there is a possibility of an incorrect movement pattern migrating into the correct pattern domain, particularly with athlete-recognizable increases in fatigue. Variable training resistances are used in a number of sports without confirmatory evidence of improved performance levels over that achieved by game-specific loads. Sprinters run up and down hills, or pull parachutes; swimmers are subjected to assisted and resisted elastic-band training (Maglischo *et al.,* 1985); the main effects of such exercises being technique changes that distinguishes them from *"normal"* correct techniques. They offer no practical value for an athlete. The resistance added to a ballistic movement will place a greater stress on the soft tissues that will produce the "*propulsive*" phase, where the limbs and objects involved transition from preparatory to propulsive movements. This transition phase is where a great many injuries are produced to the muscle/fascia/tendon units.

While there are other spurious reasons that coaches adopt particular activities for their programs (Rushall, 2009b), one more will be described and then this paper will proceed with other topics. For want of a better label, this faulty action will be called *"the superstition gambit"*. When a team/program is successful and that team employs an activity that is no part of any other organization's activities, many usually make a great leap of faith and assume that the unusual activity was one of the causes of the success. Then follows the decision to include that activity in their program so that the successful team's advantage will be neutralized in the future. The attribution of cause to the unusual activity for the team's success is irrational which defines the reasoning as a superstition. Not only do coaches copy spurious pursuits for their own program least they are disadvantaged in some way, similar reasoning is also common in auxiliary conditioning programs. Conditioning coaches implement new equipment and activities on an almost yearly basis so that a team/program will be participating in the latest conditioning activity. Few head coaches assess whether rolling on large inflated balls to develop *"core strength"* or using new resistance machines, etc. are correlated with a team's performance. There simply is a faith-based belief that conditioning programs are helpful for top teams and performers despite the evidence being to the contrary and such programs having the potential to promote injuries.

Training Models

Rushall (no date) described the procedures adopted by many coaches and sports administrators that structure sporting programs on belief-based premises. That no longer is necessary because of the extensive volume of research based on evidence that now exists in man's knowledge repository. In the sport of swimming, Rushall (2011) completed an extensive review of evidence-based research to determine what principles exist to guide the conditioning of technique-specific forms of competitive swimming. The model that evolved used the ultra-short (short work, short rest) work pattern and the *Principle of [Training] Specificity*, to meet a significant proportion of particular race demands in a vastly greater proportion of training than that usually experienced in traditional swimming programs. The model was labeled *Ultra-short Race-pace Training* (*USRPT*). Despite extensive derogatory resistance from entrenched swimming coaches and their organizations, the training method has seen steady growth and acceptance by open-minded swimming coaches. Although the model was first described for swimming, it was proposed as being applicable for any conditioning activity where high-intensity effort levels need too be performed in volumes.

When that model is applied to whole-body game-simulated conditioning activities it is labeled *Ultra-short Game-pace Training* (*USGPT*). Fattah and Fahmy (2017) showed USGPT to be superior to traditional basketball conditioning activities in female Egyptian upper-echelon players. This model of training is claimed to be superior for conditioning athletes who participate in high-intensity activities for an extended period (i.e., it involves the development of an activity-intensity specific-form of endurance). There is little doubt that the USRPT model could be adapted successfully for beneficial gains to all sports requiring endurance performances at specific high-intensity work.

In swimming, there are very short races (50 m) that require swimmers to swim their absolute fastest for the duration of the events. To improve in those events, swimmers need to improve the magnitude/quality of the swimming, that is, they need to go faster. Training for those events required a different training model that placed performance magnitude as the target of training. Sprint-USRPT was developed (Rushall, 2017). Intermittent-sprint sports have similar demands on their athletes. When running with a ball, chasing an opponent, dodging around defenders, etc., the performance levels are maximal. Athletes run as fast as possible, often kick as quickly as possible, and evade defending opponents with moves so fast that the defender does not have time to fully process the attacker's movements and thus misses a tackle, block, hinder, etc. Sprint-USRPT programs aim to develop the skill elements associated with maximal exertions so that athletes will perform consistently, with little likelihood of injury, and to the best of their abilities in games and game-simulation activities. Conditioning programs in intermittent-sprint sports should have most of their training of this nature so that players will improve up to their inherited limits in the activities that are crucial for effective game-performances. Sufficient repetitions of the short-duration maximum-level skill attempts will increase the endurance capacity for performing that way in each athlete.

The point behind the above discussion is that both training models are evidence-based. The premises upon which they are formulated are true, a characteristic that cannot be attributed to belief-based dogma and myths that permeate sports so extensively. Both training models allow skill/technique to be practiced with each repetition of the selected exercises. Further, the models aim to develop athlete self-monitoring which affects motivation and performance understanding. One might ask: *"What have the previous pages of discussion to do with the hamstrings?"* They explain the rationale for making a change from traditional conditioning-exercises that are irrelevant for improving game performances. Also, toward the end some forms of erroneous coaching decision-making are offered and finally two factually-based coaching models are proposed as being the models for changing the trained state of the hamstrings in all the roles in which they could be engaged in a game or simulated-game environment. The considerations of what is right for the hamstrings are the same considerations that are required for any other group of muscles that might be stressed in a competitive setting.

Each muscle/fascia/tendon (MFT) unit has specific attachments, and when stimulated in isolation brings about specific movement patterns particular to its anatomical design, which is consistent among human beings. However, the make-up of fiber types and connective tissue characteristics vary considerably from person to person, which explains some of the variances in the performance of sport skills. To achieve a conditioned state, enabling the athlete to perform at his/her best throughout the competition, each MFT unit should be subjected to specific contraction intensities and types of activation, and not be forced to work intensely through excursions and intensities not found in the skill set within the sport. To maximize the function of an MFT, it needs to be stimulated exactly in accord with the timing and activation demands of each skill needed during competitions. It is erroneous to assume all muscles are the same and then train them using the same program, muscle-isolation strength devices, and inappropriate frequencies of stimulations within and between training sessions. For example, the stimulus appropriate for the thigh MFT's (both hamstrings and quadriceps) whose co-contractions in the sports of importance to this paper are brief (~100 ms in full use), would be very different to the movement speed and resistance incurred for these same MFT's when training for and competing in Power Lifting and Body Building. Very different training programs would be required for all the leg musculature in order to properly apply the *Principle/Law of Specificity*. Therefore, the best training program is to perform whole-body activities that cause all MFT's to act as they would in a competitive situation. For example, high-velocity running distances often encountered in game situations would be an appropriate conditioning and functional stimulus. For sports that require twisting actions (e.g., evasive movements in rugby football, dodging in soccer), practicing game-simulations where those movements are required to be performed maximally (in terms of speed) would also be appropriate for the hamstrings/quadriceps and all other muscles. With strength and most stretching protocols, the one-form-of-training-fits-all doctrine is a poor, erroneous, and often injurious path to follow when conditioning athletes. For practices to be maximally beneficial, the muscles of concern need to act exactly (movement pattern) as they would in a game/contest, at the movement speed (velocity) of the intended action, use the same contraction type as in the intended movement, and produce the same contraction force(s) in the role(s) to be played (i.e., antagonist, stability, agonist) throughout the total movement. With serious athletes, those training parameters can only be achieved in game simulations that allow for movement repetitions so that movement efficiency can be improved. If the above factors cannot be accommodated in a training activity for the hamstrings and all other MFT's, then any other training form would be irrelevant and probably increase the likelihood of injury when under game/contest stress.

Gender. Because females are structurally and hormonally different to males, the possibility of gender causing different responses to strength-training arises. Bosco *et al.* (2000) compared trained athletes of both genders on hormonal and power responses to resistance-exercises. Low-repetition, fast-twitch fiber-dominated exercises reduced serum testosterone and power output due to fatigue. High-repetition, slow-twitch fiber dominated exercises increased serum testosterone levels. These characteristics occurred only in males, the female response being much less and significantly different. Lemmer *et al.* (2001) showed that metabolic changes occur in males as a response to strength-training but not in females. Foley, Carswell, and Mier (2014) found that for strength-training programs males can interchange groups of exercises (e.g., push-up and bench-press) and achieve similar results, whereas females do not display such generality and to all intents and purposes respond to every exercise with differentiated dynamics and effects.

Mazetti et al. (2000) examined the hypothesis that *"explosive"* strength power resistance-training (3-8 RM) would result in greater improvements in peak and mean upper body power than hypertrophy resistance-training (8-12 RM) in untrained women. It was found that explosive resistance-training produced superior upper-body strength and power gains than did heavy resistance, calisthenics, or aerobic training experiences.

Auxiliary resistance-training programs for females should take a different form to the commonly designed questionable-value programs for males, although they too will be of equally questionable value for female free-standing activities. Females are better suited and served by explosive exercises that emphasize movement speed rather than effort levels. To develop similar auxiliary-training programs for both genders (most commonly using the very questionable "*male model*") will place female athletes at a disadvantage for experiencing the most-productive training effects possible.

Any non-specific exercise used in a conditioning program must not interfere with the skill/neural factors nor impede an athlete's capacity to repeatedly store and release energy that is needed to perform each and every movement throughout the game being played without injuries. A progressive-resistance exercise regime that successfully causes a change in elements of the musculoskeletal system, making them bigger, stronger, and stiffer, also detracts from maintaining movement speed throughout an entire game. This is due to the added amount of energy required to repeatedly move a heavier body. That alone should be enough to justify elimination from conditioning programs.

The most common resistance-training approach to conditioning (e.g., isolated muscle-groups, equipment-determined actions, varying movement velocities and forms, a disregard for the *Principle (Law) of Specificity* for transferring training effects to real-life performances, etc.) is unacceptable, it makes no positive transfer to sport performances, and by altering the very foundational structures predisposes athletes to injury. If the hamstrings are resistance-trained in isolation from other complicated patterns of movement, a similar effect can occur to that which happens to the other biceps muscle, that being the *biceps brachii*. Shortening of this and other elbow flexors can result in a contraction, a shortening of the flexors that cross the elbow anteriorly resulting in permanently flexed elbow joints.

As bad as the above is for training the hamstrings, when this is coupled with other forms of training, the results are even worse. Conditioning experts, in their quest to maximize each and every physiological capacity often prescribe stationary or moving bikes in order to increase and maintain aerobic capacity. And it certainly accomplishes that goal for stationary-cycling. However, as with the bigger, stronger, and stiffer body from heavy resistance-training, there is a real negative effect that goes along with the aerobic increase. That is the entire exercise, done over many long periods, with the hips, knees, and ankles always moving in a constrained limited range of movement, causes an adaptation that restricts the hamstrings from ballistically elongating during actual sport play, often leading to injury.

The above two factors are examples of just how far the *"sport-fitness industry"* has ignored the basic *Principle of Specificity* and failed to recognize the negative effects of the above approaches to conditioning athletes.

Applying the Principle of Specificity to Auxiliary/resistance-training

These authors have advocated throughout this paper that any conditioning used in sport must first and foremost do no direct harm, nor predispose athletes to harm as they practice and play. This concept is applicable to all components within the athletic experience; psychological, anatomical, physiological, biomechanical, and technical. One way to ensure that this happens is to follow the *Principle of Specificity* whenever structuring a practice or competition. Each exercise and drill should, in some identifiable manner, contribute to the development of an athlete's capacity to perform his/her role within a team, which includes being in the best physical condition possible.

On-field drills, working at game speed, performing the patterns that will bring success in competitions, are not only beneficial, but necessary. This approach is more easily accepted as a reasonable application of the *Principle of Specificity* since those practices are exactly the required behaviors for success in competitions.

Auxiliary-training, exercise protocols that are non-specific to a particular sport, must be evaluated by determining exactly what "*effect*" they are bringing about to the athlete's mind and body, and whether or not that effect is desirable. Do the effects enhance performance or perhaps even more importantly do they detract from performance or cause injury? This paper has discussed the indiscriminate misapplication of exercise protocols to virtually all modern team sports without justification based on sound scientific evidence.

Does this in fact mean that all non-specific exercises are to be avoided? No. It just means that those in charge of designing and implementing the "*conditioning*" of the athletes must look at the outcomes from each exercise objectively, measuring when possible, the effect of such activity on each individual. If an exercise adds muscle tissue, strength, body weight, and stiffness and this either diminishes performance or causes injuries, it should be avoided. If an exercise has neither a positive or negative effect on sport performance but has a positive effect on general health, is it worthwhile to devote practice time to it? Most would opine "*yes*". If an exercise protocol improved, then maintained an important physiological characteristic needed within these sports to perform the repertoire of movements without injuries, it would seem justifiable to also include that exercise.

By being able to perform the required skills that are needed for competitions, an athlete would already have many of the required physiological capacities that will contribute positively to team play. Some responsibilities within a coaching role follow.

a) To refine and improve each athlete's ability to produce the desired movements at the right time during play. This comes from intelligently designed drills, performed in a manner and speed that is similar to game pace, together with a thorough analysis of available videos that permit the players to see and then understand just how successful plays occur.
b) To prevent/minimize the chances of injury during practice sessions and competitions, keeping in mind that injuries often happen when athletes are either over-tired or from overly repetitive accumulated trauma. A few quality repetitions (with focused feedback) of intelligent drills offers greater learning than merely repeating drills up to, and going beyond fatigue.
c) To ensure that each athlete's conditioning program includes exercises that maintain or improve their physiological capacities to perform movements of the same quality throughout the game without sustaining injuries. This would require that "*conditioning*" sessions prepare each athlete to maintain the quality of their movements at a high level throughout the entire competition, that is, the capacity to move at desired speeds where fatigue would not render a performance inadequate as a game progresses. Additionally, conditioning should include protocols that will maintain the necessary elasticity and resiliency of the soft tissues, and the movement ranges needed for all actions performed in competitions.

Auxiliary/strength-training

Strength-training is needed when an athlete is rehabilitating from an injury or illness that has caused atrophy of the soft tissues rendering them unable to perform the basic movement-repertoire of a sport. Bringing the athlete back to "*normal*" levels of strength is obviously one of the necessary parts of conditioning during this phase of preparation for a return to full-training. A second and rare need for strength-training would occur if an athlete seriously lacked the capacity to overcome resistances encountered in competitions in one specific location of the body. However, if individuals lacked the general body strength to reach an elite level in any given sport, perhaps they have chosen the wrong activity and should engage in a sport that better matches their physical characteristics.

PART II

FLEXIBILITY AND STRETCHING

Introduction

Flexibility and stretching are perhaps two of the most confused concepts in coaching and sports science. The terms are often used interchangeably and much of the research assumptions underlying both concepts is inconsistent, the researches themselves are poorly controlled, and expected rigor for measuring both dependent and independent variables in many cases is absent. For clarity and consistency, this paper will attempt to consider the concepts critically and the evaluation of published researches will be relatively rigorous.

Definition of Flexibility

Holt, Pelham, and Holt (2008) reviewed various definitions of flexibility. They were categorized as: i) a few-words or one-word definitions, ii) range-of-motion definitions; and iii) ability definitions. All suffered short-comings in the scope of their meaning. Because of the dissonance and inconsistency of implication in the various definitions, it was concluded that one definition implying a definitive scope would be the best alternative to produce a scientifically verifiable entity.

The definition of flexibility should imply a physical property, that is, a structural disposition or physiological capacity. Holt, Pelham and Holt proposed the following definition:

> *Flexibility is the disposition of body tissue to allow, without injury, excursions at a joint or set of joints.*

- Disposition is a transient state that is amenable to change because age, gender, injury, and/or life-style factors can affect how much a joint(s) can function in a particular circumstance at a particular time. Temporary increased movement ranges are possible when restriction is due to soft-tissue tension. A short-time after completing one-time or seldom-occurring modifications because of the intrinsic elasticity in the soft-tissues, the qualities of the normal resting state are reclaimed.
- Tissues include the modifiable soft-structures (muscles, fascias, tendons), which are often referred to as connective tissues, soft-tissues, and more generally as muscles. The fixed structural elements of a joint, namely joint-capsules, cartilage, ligaments, bones, and various components of the nervous system (e.g., neuromuscular spindles) are referred to as joint-tissues and no attempts should be made to modify them.
- In a joint(s) there is a restorative capacity or preserved functionality that dictates the extent of safe movements (i.e., movements that do not cause injury or injuries). To move beyond the normal tolerable range of a joint(s) movement may lead to soft- and/or joint-tissue damage, joint dysfunction if the joint-tissues are altered/damaged, pain, and/or a protective swelling response of the region. Flexibility limits the scope of movements.
- Each joint or group of joints has a definitive function that allows specific movements to occur. Limits to excursions may include soft-tissue contact, bone-to-bone contact, ligament-tension, and soft-tissue tension.

When considering flexibility, two components are fundamental to the concept: the joint-tissues and the soft-tissues. The stability and function of a joint(s) is mainly determined by the relatively fixed joint-tissues, particularly the joint-capsule and surrounding ligaments, while the soft-tissues, most notably the fascia and musculature elements influence the movement range[17]. When flexibility is a target of training, that is the joint movement needs to be increased or even maximized (e.g., as with dancers and gymnasts), only the soft-tissues should be modified. Modification of the joint-tissues is most likely to cause injury or increase the likelihood of injury during a game or sporting performance. Even if altered safely, the change would contribute little, if any, to performance enhancement and depending upon the stretching protocol used, may even degrade performance.

The most common descriptor associated with flexibility is range-of-motion (ROM). When discussing a ROM, it should accommodate not only single-joint but multiple-joint movements. Commonly, it refers to a joint in that the more flexible the joint, the greater is the range of motion. However, that single descriptor is incomplete when discussing all that is involved with flexibility and joint-movements.

Flexibility is specific to each joint (Fleishman, 1964, Harris, 1969), differs between each athletic group (Song, 1979), and is specialized between individuals and sports. The combination of the needs of each athlete, the activities in which they engage, and the state of training, are individual and need to be determined by flexibility testing before developing a training program. The flexibility needs of sports vary considerably. Some activities, such as gymnastics, figure skating, and diving, require the greatest range of flexibility to be developed and maintained in some joints for adequate performance. Team games do not usually require extreme flexibility even when a joint could be forced beyond a normal range of movement. However, programs aimed at extreme flexibility are often included as part of conditioning and warm-up programs. For endurance sports, flexibility work is often included in a restoration process. Stretching of the *Achilles* tendons and calf muscles after a distance-running workout is supposed to facilitate recovery in the lower leg muscles and reduce soreness. Today, those reasons for performing considerable stretching are questioned (based on the evidence available).

Flexibility is a defined state of movement. Activities and sports that involve extreme movement extents (e.g., gymnastics, dance, ballet, etc,) attained through deliberate training, attempt to facilitate the greatest movement ranges possible usually across the whole body. Deliberate training involves frequent repeated stretching actions that target the desirable forms of movement. An indication of an individual's flexibility at any given time might be that which exists after a period of inactivity, after engaging in free and varied play, or after a deliberate stretching routine. Those three occasions would yield different values for each joint(s). Each is a transient state of flexibility. Consequently, when talking about a person's flexibility characteristics, to understand such values it is important to know the situational circumstances that preceded the observations. One might assert that flexibility is situationally-dependent recognizing that the amount of change that can be safely obtained (i.e., without injury) is ultimately limited by the joint-tissue structures of the joint(s) involved. Attempts to achieve an even greater movement range beyond that which is structurally blocked nearly always results in serious injury or incapacity. The daily or frequent activities of a person develop a pattern of habituated joint-flexibilities. When an infrequent stretching

[17] There is conjecture about what produces the increased range. Rather than one element being involved it is definitely a multi-factorial causation. These authors consider the fascia and muscular elements play a big role in the phenomenon.

routine is performed, the routine should change the flexible extents of joint-movements for a brief time (possibly 20 minutes or less). If no further stretching is involved, the movement ranges revert back to the pre-stretched state(s). To change an habituated flexibility level, stretching routines need to be frequent, consistent in training stimuli, and be used for at least the duration in which the flexibility-change is sought or needed. Transient infrequent stretching only produces a temporary state. If that altered-flexibility level is important, then the activity for which it was undertaken needs to be performed up to the commencement of the pursuit.

Stretching programs are normally the procedures to alter an existing flexibility-state. Guissard and Duchateau (2004) assessed what happened after 30 sessions of static stretching (duration not communicated) on the characteristics of the plantar-flexor muscles. Increased dorsiflexion resulted mainly from reduced passive stiffness of the muscle-tendon unit and tonic reflex activity. Maximal voluntary contraction torque and the maximal rate of torque development were not affected by the training. Changes in flexibility and passive stiffness were partially maintained one month after the training program while reflex activities had already returned to control levels indicating that the underlying neural and mechanical adaptation mechanisms showed different time courses.

Consequently, the terms *flexibility-training*, *stretching-routines*, and *stretching* (depending upon the context), are normally synonymous. The majority of research articles that focus on flexibility and stretching mainly involve stretching. Research that focuses solely on flexibility is relatively uncommon or uses the term incorrectly.

Joint mobility is restricted by bony and fleshy masses that block movement in the end position and by the skin, muscles, tendons, ligaments, and capsules that act as ties and are put on stretch in the limiting position. The shape of bones, the elasticity of ligaments and muscles, the strength of the antagonist muscles, and the effort of movement also determine a maximum range of movement. A variety of external factors also affect flexibility: heat treatment (Grobaker & Stull, 1975), preliminary exercise, short-wave diathermy (Asmussen & Boje, 1945), hot showers (Carlile, 1956), muscle soreness, tolerance for pain, ability to relax, and room temperature (Scott & French, 1959). These factors could cause day-to-day variations in flexibility in athletes and need to be considered before exercising. Extended sports participation over a considerable period, produces an habituation of movement ranges that facilitate the actions in the sport. Specific physical activities, such as weight-training and calisthenics (Denk, 1971, de Vries, 1962), dance (Campbell, 1944), yoga (Meyers, 1971), basketball (Turner, 1977), and ice-hockey (Chevrier, 1981) produce changes in flexibility because of long-term habituation. Each sport appears to generate a range of flexibility in its participants that suits the majority of activities performed. Conscientious training and participation in a sport will eventually produce an habituated level of flexibility that will meet most of the usual demands of the sport. The adaptations alter the sensitivity of the often-used joints (Dover *et al.*, 2003). Joint position sense is affected most in those joints. On the contrary, McNeal *et al.* (2006) found no change in joint-position sense. The sensitivity of joints is altered when they are sore or injured (Safran *et al.*, 2001). Habituation is specific to the position played in a game (Baltaci, Johnson, & Kohl, 2001; Cook & Strike, 2000). Further, joint laxity increases as sporting careers develop (Ellenbecker *et al.*, 1998; Pomianowski *et al.*, 2001). Someone who has participated for a number of years, and particularly during the maturing years of adolescence, will "*grow*" the ranges of movements that facilitate frequent movements associated with their playing. Any attempts to develop greater ranges of movement are unlikely to yield benefits because the actual range of movement needed for effective performance has been developed through the specific activities of the sport. The belief that extra flexibility-training is necessary to accommodate unusual circumstances when limbs are forced beyond a natural participation-developed range appears unnecessary for full-time mature athletes and in a general sense is a belief that should be questioned.

A myth about flexibility implies that the greater the range of flexibility, the greater is the performance potential. Sporting activities develop movement ranges that facilitate the skills of the sport. There can be too much flexibility. Henry *et al.* (2006) investigated the relationship between running economy (an important predictor of running success) and flexibility in females. Running economy was inversely related to flexibility, the relationship increasing with the velocity of running. Jones (2002) found a similar inverse relationship between running economy and lower-body flexibility in international standard male distance-runners. Long-distance running efficiency involves establishing a highly refined and restricted ROM that is repeated throughout the major portion of the event until the final sprint to the finish. Programming long-distance runs for intermittent sport athletes may not be advisable since they rely on a variety of intense locomotor activities throughout the game including sprints, jumps, and dodging movements that place higher tension demands on the musculature of the legs. The athletes envisioned in this paper must develop the capacity to function in a variety of ever-changing and extensive demands on the soft tissues of the legs.

Definition of Stretching

Stretching is a procedure used to increase or maintain flexibility (Jenkins, 2005b). The soft-tissues contained in one or a group of joints are viscoelastic[18] and therefore can be stretched to gain more extensive movement capability[19]. The elastic elements of the soft-tissues enable recoverable deformation, that is, after the joint(s) is stretched, the soft-tissues will return to the initial position. The viscous elements facilitate permanent deformation. Modification of the viscous elements is required for an alteration of flexibility within safe (injury-free) bounds. A variety of stretching procedures have been advocated in a very loose manner. The adoption of a strict procedural course for stretching is virtually non-existent and has confounded the published literature. Perhaps *Proprioceptive Neuromuscular Function* (*PNF*) comes closest to stipulating a set of procedural steps. Exactly what happens when muscle is stretched is still a point of contention (Jenkins, 2005b, p. 304).

The performance outcomes of stretching exercises should always conform to one movement principle: *an individual should assume a position(s) that takes the targeted tissues to the safe limits of their movement potentiality* (Holt, Pelham, & Holt, 2008).

Stretching has several uses. It can be part of a concerted program to facilitate the normal situation of joints being very close to the extreme of flexibility. Dancers, gymnasts, figure

[18] Viscosity is a measure of a fluid's resistance to flow. Elasticity is the tendency of solid materials to regain their shape after forces have been applied to them and altered their shape. Viscoelasticity is the property of materials that have viscous and elastic characteristics such muscles. One of the features of viscoelastic body structures is that they generate and dissipate energy as heat when subjected to deformity.

[19] In popular opinion. Now that neuromuscular patterning is recognized, only movement potential is altered by stretching. The effect is not visible until the new ROM is incorporated into an altered movement representation.

skaters, and a host of sports which have that need require the assumption of extreme positions while performing stunts (e.g., surfing, snowboarding half-pipe, aerial skiing, cheerleading,[20] etc.) and usually employ stretching routines to constantly visit the near- or maximum ranges possible for single and multi-joint movement components. Stretching can also be used as a single bout of activity as part of a warm-up/preparatory routine before and/or after practices and competitive efforts. In the latter role, flexibility normally is not expected to change and the value of some stretching protocols is questionable for that purpose.

Short-term habituations occur in a game. As periods are played and fatigue is encountered, movement parameters change. Murray *et al.* (2001) found that decreases in ranges of movements of joints occurred in baseball. Chevrier (1981) found ice-hockey players failed to maintain warm-up-developed movement ranges apparently because the joints never experienced those ranges in games. It has been suggested that short-term habituations could be caused by fatigue, the adoption of protective mechanisms, or a failure to experience expected ranges of movement in competitive settings.

Flexibility and Stretching Research

An adequate dependent variable to indicate a change in joint position is difficult to institute. Range-of-motion (ROM) is the most popular measure reported in the literature but it reflects only a part of the change in a joint's movement capability. At best, ROM for single-joint movements is a measure of the angular change about that joint. The sit-and-reach and stand-and-reach are linear measurements that involve many soft tissues, hamstrings, trunk extensors, outward rotators of the hip joints, plantar flexors, and scapula-humeral tissues. Without separately testing each of the above the score recorded does not permit a complete understanding of the tissues that actually determine the final position. When a stretching research report assumes single-joint ROM, or combined linear measurement such as sit-and-reach to be satisfactory indices of movement capability they do not present the complete picture of what might or might not have occurred. Thus, the understanding of what happens with stretching exercises and programs is less than complete.

When the independent variables in research reports are inadequately defined, those reports fail to conform to a basic requirement of acceptable science. A research report should contain sufficient descriptions so that the conduct of the research can be fully replicated by another researcher to assess the reliability of the findings included in the original report. That inadequacy is a feature of much flexibility and stretching research. For example, a statement of *"hip flexion was held for 30 seconds"* is inadequate to describe a static-stretching procedure that might be used to stretch the hamstrings. More information needs to be provided. For example, the following are some unanswered questions:

- What was the angle at the hip? Different angles require different muscle involvements within an individual. Not only does the activity vary within a subject, but the between-subject's variation also varies inflating the statistical yard-stick of sampling

[20] See https://www.youtube.com/watch?v=NIdnTlQc3iA where a 13-year-old aspiring cheerleader is forced into a leg-splits position and cries out in agony. The coach and some cheerleaders force the young girl into a position that she is incapable of assuming through self-directed activities. This is an example of what is covered later in this paper as *"abusive stretching"*.

error. The compounding of within- and between-subject's variations could obscure positive findings (Type II error).

- How was the initial position assumed? How fast was the flexion? Was the movement to the treatment position from a standing or sitting position? Did the assumption of the position involve various degrees of flexion as the body segments were being positioned? Those are just some of the extraneous variables that could affect the way hip flexion is assumed and held. They could cause variation in the amount of stretching involved at the hip joint.
- If the stretching exercise was repeated, how were the repetitions restricted so that there would be no variations between trials? A failure to control the replication of repeated activities could inflate both within- and between-subject's variance.
- How was between-trials variability controlled across the subjects? If control was achieved with one subject in one manner but in another subject using a different procedure, then variance within the data in the study could be inflated. Researchers commonly ignore variations in the treatments afforded subjects by assuming any such effects are random and therefore will have a minimal effect on a statistical analysis. Such an assumption involving humans as subjects and treatment controllers have too often shown that experimenter-bias influences a study's results. At present, that realization has been recognized in exercise physiology to the point where double-blind research procedures are the norm for such works. No such bias has been evaluated in flexibility or stretching research but needs to be prevented because most studies heavily involve human manipulations and interactions.

One could go further and delve into more inadequacies of the description of hip flexion (e.g., age, gender, physical-fitness state, matching of subjects, etc.). To further illustrate the imprecise manner in which research is related, another example would be beneficial. Moe and Aune (2009) explored the acute effect of *Proprioceptive Neuromuscular Facilitation* (PNF) stretching on maximal voluntary contraction, rate of force development, and power in both isometric and dynamic contractions of the hamstring muscles in male kickboxers. Ss were tested randomly with or without stretching over two days. The day without PNF served as a control condition. Each experimental condition included a 10-minute warm-up on a treadmill at 60% of a subject's HR_{max}. Immediately after warm-up on the day without stretching, the dependent variables in both the isometric and dynamic contractions of the hamstrings were tested. After warm-up on the stretching day, subjects underwent a controlled PNF sequence of the hamstrings that was followed immediately by a test of the dependent variables. Consequently, the time of testing differed between conditions. A better procedure would have been to have an irrelevant activity in the control condition that lasted the same duration as that required for the PNF execution. A subject's hamstring flexibility was assessed by the *"sit-and-reach test"* after warm-up both days of testing, and after the PNF experience. Only the dominant leg was tested. PNF increased hamstring flexibility, but negatively affected maximal voluntary contraction, rate of force development, and power in both isometric and dynamic contractions of the hamstring muscles.

This was one of the very few studies that reported negative effects of PNF stretching. Could the results have been caused by a minor but significant alteration in the standardized procedure for conducting PNF stretching? When evaluating stretching research, and in particular PNF stretching, it is helpful to consider the following factors:

- What was the method used?
- What controlled PNF sequence was used?
- What were the tests used and the delay of time between exercise and testing?
- How were the tests related to the stretching technique, that is, were the tests truly valid? Is it clear when one or two legs are involved in stretching and/or testing?
- Was there a follow-up with a second test after a delay period to measure the duration of the effect?

Despite the various forms of PNF stretching that have been developed deliberately or by a failure to adhere to the original protocol standard for use in sports and exercise (Holt, 1973), there still is a substantial body of evidence that supports PNF stretching as being the only safe and beneficial form of deliberate stretching work (see below).

Of particular importance for research assessment is the consistency of research findings. For example, do studies employing stretching of a particular form overwhelmingly produce the same results? When a treatment is employed and a certain result almost always occurs on different occasions, there is a strong likelihood of causal association between the two phenomena (Mills' *Direct Method of Agreement* - *https://en.wikipedia.org/wiki/Mill%27s_Methods*). When a treatment is not employed and a certain result almost always does not occur on different occasions, there is a strong likelihood of causal association between the two phenomena (Mills' *Direct Method of Difference* - *https://en.wikipedia.org/wiki/Mill%27s_Methods*). Although Mills' Canons of inductive reasoning were stated in absolute terms, in the real world of human field or applied laboratory research are the experimental manipulations ever precise enough to produce certain outcomes from well-defined and specified research procedures?

When a field of sport science research is analyzed for principles of movement that might become strong predictors of performance outcomes, the large majority of the researches need to be consistent in the implications of their findings. The main problem is when assessing a field or topic when there are frequent contradictory findings. Several studies show an effect and other studies show no effect. Is either group of studies to be believed or disbelieved? The causes of inconsistent research findings could be several. The variables being manipulated were inadequately described and/or controlled to the point of making studies so different that they actually reflected different treatments and thus, produced different study outcomes. Sometimes, what is being studied is expressed so imprecisely that study outcomes vary greatly[21].

It is generally recognized that there are three classes of stretching protocols: dynamic (ballistic) stretching, static stretching, and Proprioceptive Neuromuscular Facilitation (PNF). It is contended below that each class is distinctly different in effects, popularity, and value. Kokkonen *et al.* (2000) reported on the effects of weight training with or without *"stretching"*. When *stretching* was added to weight work, the benefits of the combined training exceeded those of weights-alone training. It is not clear if the *stretching* undertaken was a mix of more than one class of stretching. If the *stretching* was only one class but stretching was part of a general discussion, then the observed effects of the study could be attributed to a form of

[21] This paper generally asserts that the variation in treatment methods and procedures used in research is rife in the fields of flexibility and stretching.

stretching that is not similarly effective. It is important that the class of stretching used in research be stipulated so that misapplications of findings from stretching studies are avoided.

Meta-analysis is a structured method for assessing the status of findings in defined areas of research. Both meta-analyses and general personal reviews have been conducted for the field of stretching. Decoster *et al.* (2005) reviewed the literature regarding the most effective positions, techniques, and durations of stretching to improve hamstring muscle flexibility. Data-based studies were reviewed according to specific inclusion/exclusion criteria. Overall, methodological quality was poor, with only 6 of 28 studies satisfying the inclusion criteria. The majority of reviewed publications were rejected because of poor research protocols. It was difficult to identify confidently the most effective hamstring stretching method. Hamstring stretching increased range of motion with a variety of stretching techniques, positions, and durations used in the acceptable researches. The literature does not clearly affirm if any method is dangerous or produces undesirable side-effects.

The conclusions of researchers in the fields of flexibility-training and stretching are guarded at best and rarely show any support for the benefits of either pursuit for attaining the popular claims that they reduce the incidence of injuries, accelerate activity recovery, enhance performance, and/or are a valuable part of any auxiliary-training program. What is most alarming is the number of *"pseudo-research"* articles that have found their way into the general scientific discussion about flexibility-training and stretching publications and meeting proceedings. When objective scientific criteria, as occur in meta-analysis, are applied to the large majority of flexibility and stretching articles most are discarded for being inadequate.

Research on stretching has yielded mixed and contradictory results. Some have shown stretching as helping an athlete's performance while others have found no such benefits (Chevrier, 1981). Those that propose the no-benefits claim likely would acknowledge that a lack of flexibility would be a severe setback. Travers (1973) stated that poor flexibility has three consequences: it is impossible to perform skills properly, there is an increased risk of muscle injury; and there will be a loss of power in the ROM. On the other hand, having extreme ranges of movement also does not produce the three outcomes attributable to limited movement ranges. Cureton (1941) suggested that flexibility exercises, if employed in sufficient dosages, may condition muscles, tendons, ligaments, and bones to a greater tensile strength and elasticity. On the other hand, excessive flexibility may cause problems because adequate joint stability cannot be provided, for example, the shoulder in the rugby scrum (Cureton, 1941, Davis, Logan, & McKinney, 1961) and throwing activities. Generally, the effects of a lack of flexibility on performance are confined to opinions rather than research. In the *"aesthetic sports"* (e.g., diving, gymnastics, figure-skating, rhythmical gymnastics, etc.) elite levels cannot be achieved without having already demonstrated the dynamic flexibility necessary to perform the required movement patterns. In those sports a maintenance program of stretching is all that is required.

When research results are inconsistent about flexibility-training or stretching, not only could the inconsistencies be produced because of similarly labeled but varied treatments but also because of the tendency for practitioners in the field to invent treatment modifications usually based on the belief that if the intent is *"to do good"* then the aberration is acceptable despite it never being evaluated by objective research to establish the altered method's acceptable validity and reliability. In this paper, the authors will produce topic classifications and present samples of acceptable publications. Endeavors will be made to make some sense out of the confused field to produce useful guidelines for coaches, athletes, and sport-science students.

Forms of Stretching

Active and Passive Stretching

To conduct a stretching movement in a joint(s), usually one part of the body needs to be fixed so that it will not move or at most, only move a little during the activity. The other part of the body about the joint is moved so that the soft-tissues about the targeted joint(s) are stretched. The stretching of those tissues can be achieved by two general but distinct sources of force.

1. *Active stretching*. The dynamic forces used in the stretching exercise are caused by and under the control of the individual. In some moves, gravitational forces assist the movement while in others it adds to the resistance applied to the moving limb(s).
2. *Passive stretching*. The forces applied to move the limb(s) are supplied by an external agent or device. Some examples are partner stretching, but not PNF, stretching machines, abusive stretching (dangerous partner stretching routines - see below, and also https://www.youtube.com/watch?v=NIdnTlQc3iA), stretching bands, and surgical tubing. The control of the stretching process relies upon the external entity (i.e., person or device) heeding the directives of the person being stretched. Many persons involved with passive stretching (e.g., athletic trainers, masseurs, etc.) think that they are only effective if they elicit patient responses indicating a notable sensation of pain. Because of that cultural bent, many external stretchers are dangerous. The upper limit of any stretch, passive or active, should be the tolerable threshold of a painful experience.

Surprisingly, the amount of stretching research that contrasts active with passive stretching is sparse. Seemingly, one would only need to use one form of stretching modified to be passive on several occasions and active on others. For clear scientific investigations, only one variable should be manipulated while all others are constant within contrasted conditions. Comparing active with passive stretching or forms of stretching is sparse. There has been more evaluation of passive stretching in research while active stretching seems to have been afforded the default form of implementation of stretching protocols. Usually, when a form of stretching is described it is left for the reader to assume that it was the active form. Mixed forms, where both active and passive attributes exist in stretching protocols, are commonly reported (e.g., Cramer *et al.*, 2004; Nelson & Kokkonen, 2001).

Esposito *et al.* (2009) investigated the effect of passive stretching on maximum aerobic power and time to exhaustion. Active males performed a maximum incremental test on a cycle ergometer to determine VO_{2max} and a test at 85% of VO_{2max} (high-intensity submaximal exercise) to exhaustion. Tests were carried out on different days without (control condition) and with a preceding stretching routine. When compared to the no-stretching control condition, stretching produced the following results: power output was 5% lower; VO_{2max} was similar; the maximum exercise cardiorespiratory variables and blood lactate concentration were not significantly different; time to exhaustion was shorter; and VO_2 and blood lactate concentration at minute 4 of the high-intensity submaximal exercise were higher but similar at exhaustion. Acute passive stretching significantly reduced maximum power output but not VO_{2max}. Time to exhaustion was significantly shorter when the exercise was preceded by stretching maneuvers. Passive stretching detrimentally affected both power and aerobic performance. One implication of this investigation would seem to be that passive stretching should not be part of a performance preparation routine. However, without knowing what the form of stretching was used in the study, the understanding gained from this investigation is quite limited.

McHugh and Johnson (2006) examined whether the hamstring muscle length at which strength was measured affected strength loss following passive stretching in males. For isometric strength-testing and stretching subjects were seated upright (90º trunk flexion) with the test thigh flexed 15º. Two maximum isometric contractions were performed at 80º, 65º, 50º, 35º, 20º and 5º of knee flexion. Passive stretching of the hamstrings occurred by straightening one leg to full extension and holding that position for 90 seconds. The stretching was repeated five times. Stretching resulted in an 8% decrease in resistance to stretch at the end (5º) range of motion. It also led to a decrease in peak isometric torque with the muscle in a shortened position (-15% at 80º) but not in a lengthened position (+7% at 5º). The practical significance of these findings is that stretching did not appear to have a detrimental effect on hamstring strength at muscle lengths where muscle strain injuries are thought to occur (i.e., in a stretched position). The results of this study are not particularly obvious. Although stretched hamstrings remained strong, other variables (e.g., isotonic and isokinetic strengths) need to be evaluated before suggesting full stretching of the hamstring muscles is a worthwhile activity for activities that require very fast contractions, such as those that occur in the sprinting, evading, and kicking functions of the sports considered in this paper.

Several studies have investigated the effects of passive stretching on strength and power.

- The time course of strength deficit following an acute bout of maximal passive stretch was monitored. Subjects engaged in maximal stretching of the plantar flexors of the ankle joint (14 stretches over 33 minutes). They also experienced a control condition of no-stretching for the same period. It was found that repeated maximal passive stretching decreased voluntary strength for up to an hour (Fowles & Sale, 1997).
- Ryan *et al.* (2007) examined the time course for the effects of eight minutes of passive static-stretching on isometric peak torque, percent voluntary activation, electromyography, and mechanomygraphy of the plantar-flexor muscles. Subjects performed 16 consecutive 30-second passive stretches (time under stretch was ~8 minutes) on an active isokinetic dynamometer. Isometric peak torque, percent voluntary activation, electromyography amplitude, and mechanomygraphy amplitude were assessed before, immediately after, and at 10, 20, and 30 minutes post-stretching. Passive static stretching reduced plantar-flexor strength immediately after the stretching, however, most of the force deficit recovered within 10 minutes. The stretching-induced force deficit was not accompanied by decreases in muscle activation or changes in mechanomygraphy amplitude. Force production parameters were not enhanced by passive stretching.
- Ryan *et al.* (2008) reported a variation of the above study. They examined the time course for the effects of two, four, and eight minutes of passive static stretching on musculotendinous stiffness of the plantar flexor muscles. Healthy subjects performed the musculotendinous-stiffness assessments before, after, and at 10, 20, and 30

minutes following the passive stretching treatment. Four randomly-ordered trials were separated by 3-7 days: (a) control, (b) two minutes of passive stretching, (c) four minutes of passive stretching, and (d) eight minutes of passive stretching. For the passive stretching trials, several 30-second consecutive passive stretches of the plantar flexors were completed in a dynamometer where the lever arm passively dorsiflexed the foot to the point of discomfort, but not pain. Each 30-second stretch was separated by 20 seconds of rest until the total time under stretch for each trial was completed. The control condition was quiet resting for 15 minutes. To assess musculotendinous stiffness, the dynamometer lever-arm passively dorsiflexed the foot at 5° per second until the maximum tolerable stretch was achieved and held for five seconds. Musculotendinous stiffness was decreased but only during the first 10 minutes of stretching. Stiffness was greater for men than women across all angles and it increased further at each larger joint-angle. It is possible that distinct characteristics of the ankle joint produced the short-lived detrimental effects.

- Behm, Button, and Butt (2001) evaluated force loss after prolonged static and passive stretching. Tests were conducted before and 5-10 minutes after 20 minutes of static or passive stretching of the quadriceps. Six of the twelve subjects also experienced a no-stretching (control) condition. Following stretching, maximal voluntary contraction force decreased by 12%, while muscle activation increased by 2.8% and inactivation increased by 20.2%. It was suggested that strength loss after stretching was affected more by muscle inactivation than changes in muscle elasticity. Too much stretching appeared to decrease force production.
- Nelson and Kokkonen (2001) tested male and female physical education students for knee flexion and extension strength (1 RM) on two days. One test was preceded by quiet sitting, while the other was preceded by active and passive ballistic stretching of the hip, thigh, and calf muscles. Stretching increased hip flexibility as measured by a sit-and-reach test. Knee extension and flexion strength were significantly less after stretching than after no-stretching. A thorough bout of stretching reduced the strength of the muscles stretched. A notable characteristic of this study was that both active and passive approaches to ballistic stretching were combined. It was not possible to discern if either or both forms produced the effect.

Although the studies reported above are not an exhaustive representation of the work in this field, they all showed that passive stretching and passive-active stretching affected performance or musculoskeletal factors negatively. As well, the variation in observed time periods of the lasting effects of stretching ranged from 10 minutes to at least one hour.

Worst-case Passive Stretching – *Abusive Stretching*

For some reason athletic trainers and conditioning "*experts*" have developed methods of stretching that are excessive and injurious. This is probably due to the misguided belief, that when exercises are performed in exceptionally increased volumes and intensities they are more beneficial, which is a violation of the *Roux Principle*[22]. That false belief is extended further with stretching when a second person applies high external forces to movements at their extremes in a passive-stretching protocol. Muscles and joint structures in those positions

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[22] Roux Principle: *Small stimuli are useless, moderate stimuli are useful, and excessive stimuli are harmful* (Stegemann, 1981, p. 266).

are subjected to forces that damage the joint-tissues and result in micro-tears and more severe injuries.

Flexibility has limitations. In a very sane approach to flexibility-training, Holt, Pelham, and Holt (2008) defined and limited flexibility-training (stretching). A major concern was the avoidance of injury to both joint- and soft-tissues. Their work stimulated these authors to label the commonly observed phenomenon of an athletic trainer or conditioning coach using his/her body weight to apply excessive extra force to one or more joints in an athlete to produce a movement range that could never be achieved through self-controlled activity as *"abusive"*. Usually, warm-ups before major league baseball games display many million-dollar players being subjected to this dangerous/destructive form of exercise. It is best termed "*abusive stretching*" because it does pre-dispose athletes to injuries by interfering with the structures that support joint integrity (Yang, Im, & Wang, 2005). Holt, Pelham, and Holt warned against such a possibility. Consequently, in the literature are some research studies that evaluate sane stretching practices while others employ harmful or potentially harmful stretching practices without differentiating the two. Because of this discrepancy, any athlete or coach should be cautious about "*equating*" studies on stretching. Comparing the results of abusive stretching studies to those related in sane-stretching studies should be avoided. This leaves the field of flexibility-training and stretching in a confused state. Reading the literature and reviews on stretching and flexibility-training is a treacherous path because of frequently poor research methodologies (Gremion, 2005). The original *Scientific Stretching for Sports* (*3S*) publication (Holt, 1973) and its most recent affirmation (Holt, Pelham, & Holt) set the parameters for obtaining beneficial effects from stretching exercises.

Extreme hamstring stretching is a common activity in many sports. If abusive stretching is focused on elongating ligaments and joint capsules, excessive forces are created on structures that should not be part of a stretching program. If focused on forcefully elongating soft-tissues, such as muscle/fascia/tendon units, micro-tears can occur predisposing the athlete to injury during practice or a game. Askling *et al.* (2008) studied the injuries incurred in activities that forced the hamstrings to function in extremely lengthened positions. All injuries occurred during movements reaching a position with combined extensive hip-flexion and knee-extension despite the strength of the extended muscle being retained (McHugh & Johnson, 2006).

Figure 5 illustrates a very common stretching exercise that places the hamstring muscles in the region of consideration in the above cited articles. It is an instance of abusive stretching. The trainer forces the passive player into a position that could never be achieved voluntarily (i.e., without additional outside force). The position is one where the joint-tissues are being stressed. It should be easy to imagine what this exercise is doing to the player's groin and hamstring muscles' origins. The athlete has even put his right hand on the muscle origins as an involuntary reaction to potential or actual harm being experienced by the player and caused by the exercise.

Figure 5. Abusive passive stretching of a professional player's hamstrings and hip joint.

The following comments can be made about the partner-assisted stretching exercise illustrated in Figure 5.

> *The most important observation is that by pushing on both legs the partner is creating something analogous to the "rack". Simply by forcing the left-hip extensor attachments apart, the trainer is creating excessive tension and will either cause or predispose this athlete to a possible tear.*
>
> *Neither the athlete nor partner is in a correct position. The athlete is not lying flat, the non-exercised leg is off the ground (a protective maneuver), and the head and upper trunk should be against the ground without tension. The flexed right hip and tendency toward posterior pelvic tilt is the athlete's way of trying to minimize the tension on the left hamstrings created by the trainer.*
>
> *The entire protocol is unacceptable*.

One has to ask: *How many injuries in sports are caused by trainers and their stretching routines that entail the type of dangerous and nonsensical abuse like that pictured above?* Not only are the exercises wrong but usually they involve static holding in extreme positions. Consequently, the detrimental aspects of extreme passive static-stretching are added to the injurious effects of forcing athletes into unnatural positions. Abusive stretching might well be a very common source of musculoskeletal injury in professional and serious sports, particularly when individuals attempt to justify their importance to an organization through overt activities that depend upon their dominant [questionable] function in such dangerous manners. There is no research or scientific evidence that supports any procedure whereby the added partner in the extreme stretching exercise contributes beneficial force.

The message about abusive stretching is clear: If a trainer, conditioning coach, or other person participates in a stretching protocol by exerting additional forces to a limb that take the applied forces beyond that which the athlete alone can voluntarily develop, then the activity and other-person participation should be terminated and removed from the sporting program.

Proprioceptive Neuromuscular Facilitation (PNF): The Best Flexibility/Stretching Protocol

Jenkins (2005b) categorized three types of stretching activity; *Proprioceptive Neuromuscular Facilitation* (*PNF*), *dynamic stretching*, and *static stretching*. Both authors of this paper have used *PNF* since 1971 when Dr. Holt introduced Dr. Rushall to the PNF procedure. Dr. Holt has used, taught, and researched PNF stretching since 1967 (Holt, 1973). While it is admitted that both authors favor PNF stretching over the other forms of stretching, this paper is produced with careful recognition of the need to observe independent research findings in an objective way. The reader will be the judge of whether that need has been satisfactorily observed. In the early days of PNF use, Holt coined the sporting use and adaptation of PNF as *Scientific Stretching for Sport* (*3S*).

The 3S-PNF protocol was originally designed as a manual, partner-assisted stretching technique; a partner was needed to provide a fixed resistance against which the lengthened muscles are isometrically contracted at or near maximum (in order to use spindle facilitation). Holt (1973, p. 2) related that:

> *The 3S stretching method is a relatively new approach to increasing range of motion for athletes and dancers. Justification for its use in sport, dance, and physical education is founded on theoretical, experimental, and practical evidence.*
>
> *(1) It is the only sport stretching method based on Herman Kabat's* [1952] *PNF (proprioceptive neuromuscular facilitation) therapeutic principles, and as a result is firmly based on accepted neurophysiological factors.*
> *(2) It has been tested experimentally and shown to be superior to both traditional methods of stretching* [fast-stretching (ballistic) and slow-stretching (now termed static stretching)] *for sport.*
> *(3) It has proven itself repeatedly to be the most efficient means of increasing flexibility in practice situations.*

Over the 44 years since the first sporting publication of 3S-PNF (Holt, 1973), further justification for the value of the stretching method has been repeatedly presented. The terms PNF and 3S have been replaced by the label *"Reversal of Antagonist Method"* which better describes the uniqueness of the most current method in sporting domains. The reason for the change is that originally Herman Kabat attributed the changes in movements that resulted from PNF to be caused by neurological factors. However, after 50 years, carefully controlled research and in particular experimentation by Dr Holt and his associates at the Sport Science Laboratory at Dalhousie University in Canada have found that the new movement extents of Reverse of antagonist method largely involve the elongation of the fascia of the muscles being stretched. Despite *"Reversal of Antagonist Method"* being a better label of what is involved in the latest protocol for PNF, for this presentation 3S-PNF will be used. PNF and 3S-PNF will be used interchangeably.

- Modern 3S-PNF is the only stretching protocol that has been thoroughly researched with full disclosure to the public over the past 47 years. This method now consists of the evolution of a specific protocol that will result in the best possible improvements in ROM, with the lowest probability for either causing harm or predisposing an athlete to future harm while practicing or competing.

- It is the only stretching protocol that addresses tissue elasticity by gently causing an elongation of the muscle/fascia/tendon (MFT) complex during a low-force isometric contraction with the complex in a pre-lengthened position to start the protocol. This isometric contraction with the body segment immobilized gently stretches the fascia sheaths that envelop the individual fibers (endomysium), the smaller to larger bundles of fibers (perimysium), and the fully enveloped muscle-tendon unit (epimysium). Static stretching, yoga (an adapted form of static stretching), or dynamic stretching do not affect this mechanism. That is why when hamstrings are stretched using the various methods, 3S-PNF has 3-4 times the improvement of the other methods.
- Modern 3S-PNF does not require maximum or near maximum effort isometric contractions, but is performed with the least amount of effort that elicits the desired elongation effects. It is never used to alter joint and ligamentous tissues but, if performed correctly, is always applied where the limitation to movement is the soft tissues of the MFT units.
- Three studies have been found that reported what might be construed as negative results for PNF on bodily functions and performance. When reading the summaries of those works below, one should remember it is possible that inappropriate variations of the PNF protocol were used which suppressed the positive outcomes that should be expected from the true employment of 3S-PNF.

    i. Moe and Aune (2009) [see discussion above under the heading *Flexibility and Stretching Research*] using male kickboxers for subjects, showed that a PNF protocol increased hamstring flexibility, but negatively affected maximal voluntary contraction, rate of force development, and power in both isometric and dynamic contractions of the hamstring muscles.

    ii. Church, Wiggins, and Moode (2001), using female subjects, compared the effects of warm-up alone, warm-up plus static stretching, and warm-up plus PNF stretching on a vertical jump test. It was reported that the vertical jump was decreased only in the warm-up plus PNF condition. How the warm-up was controlled on each occasion, the effect of familiarity that could have been produced by the warm-up alone, the control for equality of the warm-up, and other factors are not known. The addition of the warm-up most likely was a confounding factor. What might have been a better test could have been to compare no-stretching, static stretching, and PNF stretching on vertical jump performance.

    iii. Johnson *et al.* (2012) determined the effects of static and PNF stretching on knee peak torques in aerobically trained female athletes. Post-static stretching and post-PNF stretching knee extension and flexion peak torques were significantly lower when compared to no-stretching values. The reduction in peak torque values for both knee flexion and extension may possibly negatively compromise athletic performance in females.[23] The study report indicated that all subjects performed the same amount of stretching, which is a violation of the *Principle of Individuality* (Rushall & Pyke, 1991), and that amount was arbitrarily chosen

[23] The reader should be aware of the hypothesized different responses to stretching between the genders. At this time, there is insufficient clear and properly defined research to reliably indicate the nature of exact gender difference(s).

which further raises the possibility that both forms of stretching and the way they were applied did not fairly represent the procedures. From the description of the time allocated to stretching: *three stretching sets of 30 seconds each (10 seconds rest between sets) for knee flexors and extensors (six sets total for both conditions)*; it is difficult to picture how 3S-PNF could be implemented correctly under those time constraints.

The Current 3S-PNF Procedure. This section primarily is a summary of the work contained in Holt, Pelham, and Holt (2008).

Although the original 3S form of PNF was articulated by Holt (1973), there have been some modifications to that initial exact protocol for performing PNF and are now mostly contained in the Holt, Pelham, and Holt book. As PNF has become familiar to many, a number of variations in procedures have been developed, mostly without appropriate substantive research supporting the alterations. Consequently, not every variation of PNF is equally effective.

> *Common PNF varieties include: (1) hold-relax (isometric contraction in a lengthened position, without a following concentric contraction of the antagonist); (2) contract-relax (in a lengthened position, concentric contraction of antagonist followed by relaxation and passive hold; (3) slow-reversal-hold-relax (isometric contraction in a lengthened position, then relaxation and concentric contraction of the antagonist followed by relaxation and passive hold); and (4) 3S, or (repeated) reversal of antagonists (placing the agonist in a lengthened position, contracting isometrically against an immovable object, then contracting the opposite muscle group concentrically to further lengthen the stretched tissues)* (Holt, Pelham, & Holt, p. 53).

To the satisfaction of these authors, the latest 3S-PNF (reversal of agonists) protocol is the most effective protocol for increasing flexibility, lowering the probability of injuries, promoting relaxation in the muscles employed, and for use in sporting and clinical rehabilitation settings for any age-group. Adherence to the protocol components described below is required otherwise both injury risks and ineffectiveness are likely to increase. An example of stretching the hamstrings is provided next (see Figure 6). In this example, the hip-extensor muscles, of which the hamstrings are an important part, are the agonists. The hip-flexor muscles that are shortened in the procedure are the antagonists. The roles are reversed when the hip-flexors contract (in that movement they are the agonists). Then the extensors are the antagonists to hip-flexion.

Steps in the 3S-PNF Protocol

1. *The beginning position* (*the athlete lying on his back*). The participant assumes a properly aligned posture (reclining, sitting, or standing) for the joint(s) to be exercised. Only the joint(s) to be stretched should be moved during the complete process.

   In Figure 6, the positions of all body segments are posturally correct in the two protocol stages represented. The head, shoulders, hips, arms, and left leg are flat on the ground. The right leg is straight with the knee fully extended. Those orientations should be compared to the positions of the same elements in the abusive-stretching example provided in Figure 5. By keeping the hips flat and the right leg straight, the hamstrings will be subject to stretching because no other joint other than the right hip will be adjusted. It is assumed that the reader will be able to reverse this and adapt the descriptions for the left-leg hamstring muscles.

Keeping the right leg straight, particularly at the knee, the right hip is slowly flexed as far as possible to attain the starting position for the procedure. In this position the right-leg hamstrings are in the maximum voluntary lengthened position.

The beginning position (the trainer providing an immovable resistance). The trainer is responsible for producing an immovable resistance against which the right leg will push. After it is apparent that the joint(s) no longer can flex, the trainer places the most immovable part of his/her body flush with, but not pushing on, that part of the joint to be contracted.

In Figure 6 Frame A, the trainer assumes a kneeling position. His shoulder is placed in contact with the athlete's right-leg upper calf muscle and the trainer's left hand is placed just below the knee to signal to the athlete that the whole leg has to be straight throughout the exercise.

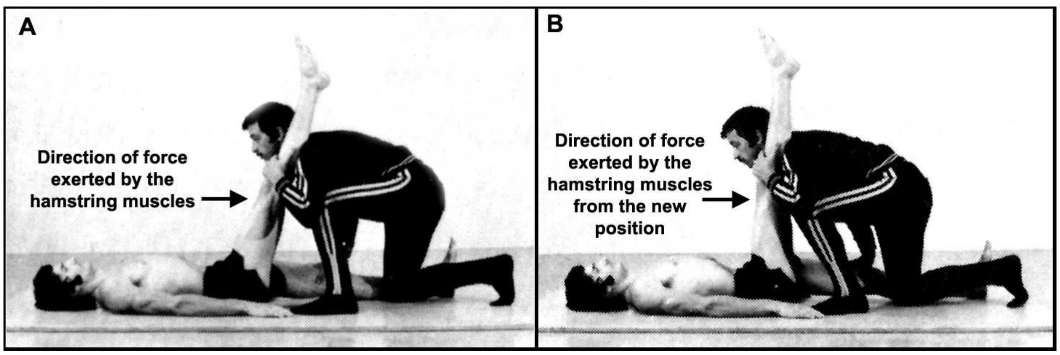

Figure 6. Two stages of the 3S-PNF method for stretching the right-leg hamstring muscles.

2. *The isometric contraction* (*the athlete*). When the joint(s) is flexed and the trainer is in position, the athlete attempts to extend the joint(s) which involves contracting the extensors. Since the trainer should prevent any leg movement, the contraction of the extensors is isometric. That isometric contraction begins with a four-second build up to a level of noticeable effort, although that level is not maximal but submaximal to avoid any possibility of injury being caused by a maximal contraction. After the four-second build-up, an isometric contraction of the right hip-extensors is held for six seconds. Thus, the hamstrings are contracted in the lengthened position. The four-second build-up and six-second contraction phases are dictated by these authors' familiarity and experimentation with different combinations of phase durations. Other authors might recommend different times. In the Dalhousie University Sport Science Laboratory, the four- and six-second phases are deemed long enough for the athlete to execute fully controlled contractions without rushing which was one of the observed drawbacks of the shorter-duration phases in earlier protocols.

   Performing an isometric contraction with the hip-extensor muscles produces an often overlooked phenomenon of muscle function: *when a muscle contracts, upon relaxing the muscle it returns to a lengthened state*. Thus, the fully lengthened extensor muscles in Figure 6, of which the hamstrings are part, will be lengthened further after the isometric contraction. Since those extensors are antagonists to hip flexion, after relaxation the hip flexors should be able to flex (concentrically contract) the hip more acutely before the antagonists restrict the range of motion again.

Of particular note is the effort used throughout the isometric contraction. In the Dalhousie Sport Science Laboratory, it was found that 100% and 80% isometric contractions yielded the same level of effects. As well, isometric contractions of 50-80% effort levels all produced similar beneficial effects. The need not to exert 100% efforts was verified by Feland and Marin (2004) who found that PNF stretching using submaximal contractions was as effective as when maximal contractions were used.

The isometric contraction (*the trainer*). The trainer should conscientiously prevent movement in the body segment to ensure that an isometric contraction occurs while the extensor muscles remain fully lengthened.

3. *The post-isometric contraction relaxation/release* (*the athlete*). After the isometric contraction is complete, tension in the muscles associated with the contraction should be relaxed/released over two or a few more seconds. During that stage of the exercise, the trainer should move away slightly to allow the athlete's limb to move for a short distance. From that slightly extended position, the athlete enters the next reposition-contract-relax sequence.

   The post-isometric release (*the trainer*). As the athlete releases tension, the trainer should allow some movement in the body segment without letting any more joints move. In the Figure 6 Frame A example, the trainer's hand would still remain close to the knee and contact between the trainer's shoulder and the athlete's leg maintained while minor movement space is yielded to the athlete.

4. *Re-positioning to a new beginning position in the next repetition of the procedure* (*the athlete*). After the two-second relaxation, the athlete hip-flexes (concentrically contracts) the joint(s) again to a new maximally flexed position. The move to the next flexion phase should be smooth and controlled and should last approximately three seconds. It should be noted if the position attained is new or similar to the previous flexion limit.

   Figure 6 Part B, illustrates the new hip flexion position occasioned by the lengthened hip extensors. When hip-flexion is maximal, the next phase begins.

   Re-positioning to a new beginning position in the next repetition of the procedure (*the trainer*). When the athlete can flex the hip no more, the trainer assumes a position similar to that in the first phase of the contract-relax sequence. The trainer should resist the temptation to apply further force to the leg when it is in the fully flexed position.

5. *The next isometric contraction* (*the athlete*). With the joint in the new position, the hip extensor muscles are isometrically contracted against the trainer's immovable resistance. The characteristics of the first contraction should be repeated: the build-up to the final contraction force should take approximately four seconds and the actual isometric contraction held for six seconds.

   The next isometric contraction (*the trainer*). The resistance provided the second and all subsequent contract-relax sequences should be immovable. The principal role of the trainer is to ensure the contraction of the hip-extensor muscles always occurs isometrically with the muscles in the newly lengthened state.

6. *Repetitions*. The repeated voluntary flexion of the antagonist muscles in the 3S-PNF sequence, eventually reaches a terminal stage where no further flexion is possible in the exercise set. Determining the terminal flexion for the exercise is why it is important to compare every new flexed position to the previous position. Normally, both the athlete and trainer agree that such a position has been reached. Once terminal flexion is noted, the exercise set should be terminated. For most exercises, four repetitions usually is sufficient to reach the terminal position for the exercise set.

   The trainer should resist applying added force to the limb/body part when the terminal position is repeated. In a practical setting, the cause of the position limitation is not known and well could be the flexibility limit of the joint(s). Attempts to *"improve"* the position further by the trainer applying an added external force could increase the likelihood of injury when the joint is used near its extreme movement range and/or in high-intensity movements (e.g., sprinting, jumping, kicking, dodging) in a game.

   When a 3S-PNF exercise is first instituted it should be repeated at least daily. As the athlete's confidence in the procedure increases with each trial/set, it is likely that the effort level of both the flexion and extension phases of the sequence will increase. There is no value gained by an athlete attempting to execute a maximal (100%) contraction effort at any stage in the protocol. The athlete should always be aware that the contraction levels always should keep some effort-reserve unused. That caution avoids causing an injury or a state that is a pre-cursor to injury.

   Daily execution of exercise sets are warranted for normally active individuals. However, for very serious athletes, Holt, Pelham, and Holt (p. 62) opine the following:

   > *Several factors must be considered in determining the appropriate number of stretching sessions per day and per week: (1) the flexibility status of the individual at that particular time; (2) the nature of the physical activity trained for; (3) the objectives of the fitness program; (4) the volume and intensity of training at that point in the cycle; (5) the interactive training modes (e.g., strength, aerobic, speed, skill and so on); and (6) the specific needs of the subject. For those in serious preparation for sport or dance, we recommend at least two sessions per day, one before and one after each workout, practice or game. A more extensive stretching regimen may be helpful if the activity involves significant time delays in practice or competition (e.g., track and field), or if the activity is repetitive and so tends to cause tightening or cramping of the exercised muscles (e.g., cycling, jogging, soccer).*

   With repeated sets of the exercise, improvements in the final position will occur in the early group of exercises. However, there will come a time when one day's terminal position is no different to that of the previous session's limit. When that occurs, the frequency of dedicated daily exercise sessions should be lowered to a *"maintenance schedule"* of perhaps once every two or three days. When each

> execution of the set that adheres to the strict protocol described above repeats the terminal position, that indicates the maintenance schedule is *"just right"*.

Jenkins (2005b) reported that there are two forms of PNF stretching. The first is *active PNF* where the athlete controls both the flexion and extension contractions without any outside augmentation. The second is *passive PNF* where the flexion movements are altered with the trainer providing most of the force to reposition the joint(s). Because of the often misguided enthusiasm that results in the excessive force application of athletic trainers, conditioning coaches, etc., these authors recommend that only active PNF be entertained specifically in the 3S-PNF protocol.

One of the most important features of 3S-PNF is the contract-relax sequence in each repetition with the muscles being stretched in a progressively lengthened state. Wallin *et al.* (1985) compared a form of contract-relax stretching with ballistic stretching. After 14 experimental training-sessions over 30 days, the ballistic stretching group switched to contract-relax stretching. Once a week contract-relax stretching was enough to maintain flexibility. Training three to five times per week was necessary to increase flexibility. Ballistic stretching improved flexibility, but was not as effective as the contract-relax method. When the ballistic group changed to contract-relax, flexibility improved further and the group caught up to those who had only performed contract-relax activities from the outset of the study. The value of a procedure that involved contract-relax cycles was supported.

3S-PNF is rarely touted as a performance-enhancement procedure. Holt, Pelham, and Holt (2008) limited the scope of contributions of the procedure to increasing flexibility, lowering the probability of injuries, promoting relaxation in the muscles employed, and for use in sporting and clinical rehabilitation settings. It is hard to reconcile how a training procedure for improving flexibility could directly affect a performance in a negative or positive way. It is the altered flexible state that has the potential to change performance if the changed ROM is believed to be more desirable and employed correctly in the technique aspects of a physical activity. In altering a person's state of flexibility, some further benefits have been shown. Kokkonen and Lauritzen (1995) observed male and female groups in a college aerobic-fitness class performing PNF. Flexibility, strength, and muscular endurance improved by similar percentages in both gender groups but no changes were recorded in a no-stretching control group. Sheard, Pierozynski, and Paine had a mixed-gender group train with PNF on one leg in a correct hamstring-stretch manner but with a strap rather than a partner as resistance. They assessed if any spillover effects of PNF exercising on the contralateral limb were exhibited. In the exercised leg, PNF produced ROM increases while a control group performing only leg-raises did not. In the PNF group but not the control group, the range of motion in the unstretched contralateral limb increased indicating that some degree of neurological crossover occurred. PNF stretching on one limb could cause some training effects in an immobile injured limb.

Ryan *et al.* (2006) investigated the effects of a Contract-Relax-Antagonist-Contract form of PNF stretching, with and without a warm-up intervention, on anterior/posterior and medial/lateral whole-body stability. The treatment conditions were warm-up and stretch, stretching only, and a control condition with no treatment. CRAC-PNF of the hamstrings, plantar flexors, and hip flexors were performed during the two treatments. A six-minute treadmill warm-up was added to stretching in the warm-up and stretch condition. After treatment, warm-up and stretch scores improved 8% and were significantly different from the scores of the stretching-only and the control conditions, those two conditions being no different to each other. Conley *et al.* (2007) compared the effects of no warm-up (control), weighted-jump, submaximal-jump, and PNF warm-up methods on vertical jump performance in NCAA Division II female volleyball players. The average vertical jump height using the PNF warm-up method was significantly greater than no warm-up but was not different to the weighted-jump or submaximal-jump warm-up methods.

Conley *et al.* (2006) compared the effects of none, static, light-ballistic, and PNF stretching methods on 1 RM bench-press performance. PNF targeted the triceps and chest muscle-groups using two separate exercises. The average 1 RM bench-press values were significantly greater for the PNF condition than in the other conditions. Since the subjects experienced all conditions, PNF enhanced strength whereas the other treatments did not. When PNF isometric contraction-effort levels are at a relatively high level, there is the strong possibility of strength gains as well as flexibility gains. Gains in strength have been observed in untrained young to old subjects who employed PNF as part of a regular exercise program[24]. No evaluations have been performed on this factor in trained or highly-trained athletes. Two-minutes of PNF and static stretching were compared for effects on the quadriceps and hamstring muscle strength and knee-joint range of motion (Davis & MacConnell, 2007). Short-duration static stretching was found to have a detrimental effect on muscle strength but short-duration PNF had no detrimental effect on strength.

Dynamic (Ballistic) Stretching

Dynamic (ballistic) stretching has a history in sporting activities. It is perhaps the oldest form of stretching and is used appropriately when time is restricted or the athlete is alone. It should not be used for increasing flexibility. The classic form of dynamic stretching is ballistic (bounce) stretching but mental and movement restraints have been introduced to prevent injuries or increases in injury potential. Exercises are performed to repetitively contract the agonist muscles to stretch the antagonist muscles. When performed fast with movement ranges approaching the limit of flexibility for a joint(s), injury is possible in the soft-tissues of muscles and even the joint-structures. Today it is often possible to see potentially-injurious ballistic stretching performed in conditioning programs (e.g., in military training and professional sporting team warm-ups). For example, all levels of baseball players typically warm-up in the on-deck circle swinging a weighted bat or heavy bar at game-speed velocity. Another example is often seen at training for sports that involve maximum jumping (e.g., ski-jumping, long-jumping, volleyball, and basketball). A series of continuous bounding movements are performed. If athletes are instructed to touch the ground with flat hands at the end of each bound, extreme ranges of crouching will result and muscles will be forced to function at their extremes with high levels of force/effort. A further common example is toe-touching. Individuals are instructed to bend forward and downward at the hips with the legs straight and feet shoulder-width apart. They are encouraged to use gravity and hip flexion to achieve the desired range of movement quickly and in few trials. Because of poor/dangerous execution, some authors resist advocating any use for dynamic stretching in training or contest settings (e.g., Jenkins, 2005b).

Dynamic stretching is possible over a wide range of movement speeds, varied demands on energy, and varied changes in kinetic energy during each exercise repetition. It can be done

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[24] Personal communication, L. E. Holt, October 17, 2017.

gently at relatively slow speeds, moderately at various intermediate speeds, or violently at very fast speeds. The body may be used as its own resistance, or resistance may be added in the form of extra weights, bars, or vests. Added resistance, especially when coupled with high velocity movements, often leads to injury. There is no set standard for such oscillations, which may vary in speed and force even within a given repetition. The speed of execution, slow, controlled/intermediate, and controlled/fast, is a rough classification of forms of dynamic stretching. Normally, those three movement intensities serve as a progression for learning to stretch or injury rehabilitation.

A characteristic of any sane stretching form or routine is that when at movement extremes the athlete should experience a discomfort level of 80%-or-less in each repetition. Stretching bouts should be terminated when the 80% level is reached even if the individual believes he/she could have extended further with more effort. By observing the 80%-or-less rule, injuries or injury pre-cursor states should be avoided.

1. *Slow dynamic stretching*. This is the first stage of a progressive dynamic-stretching program. This form of dynamic stretching is most popular with older persons because it also demands controlled balance. *Tai Chi* has much of its characteristics. The flexion and extension movements about the joint(s) are executed slowly and under full control. The velocity of the movements is supposed to be constant across the range of the action. As with any stretching form, the degree of stretch experienced should not exceed 80% discomfort. Usually, lower than the 80% threshold is advocated so that discomfort is experienced in very tolerable amounts. Repetitions of the exercise are performed with each attempting to extend the range of movement without increasing the discomfort level. The stretching routine is terminated when the individual determines two successive exercise-trials have reached the same limit for that bout of stretching. Athletes might conscientiously perform this form of dynamic stretching when in the early stages of rehabilitating from injury. It is not viewed as being a worthwhile/relevant activity for training healthy sports people.

2. *Controlled/intermediate dynamic stretching*. The velocity of the flexion-extension movements is faster than the slow version of dynamic stretching but still not maximal. The movements are constant in speed, only reach an 80% or less threshold of discomfort, and are terminated when two successive trials reach the same movement-limit in the exercise-bout. Essentially, this form of dynamic stretching is similar to the slow form except that movement velocity is increased. It is commonly used as the next phase after the slow form seems to have reached its usefulness. It is the second stage of progressive increases in movement velocity as an individual transitions from slow to intermediate and eventually fast dynamic exercise forms. When part of a progression, it is commonly observed that movement velocities increase as the athlete gains in confidence for performing the exercises. Only when an athlete rehabilitates at this level should participation in low-intensity levels of the sport be considered.

3. *Controlled/fast dynamic stretching*. This is the final stage of progressive dynamic stretching. The requirement is to move fast so that movement velocities approximate the velocities of sporting movements for which the exercises are best suited. However, fast movements develop considerable kinetic energy and if not monitored/controlled could approach the range of movements outside of a *"safe range"*. The 80%-or-less rule is particularly appropriate for this movement form and requires individuals to

> concentrate on adhering to that criterion. A failure to concentrate and control the extent of the movement ranges makes this a potentially dangerous activity with regard to developing the potential for injuries at the movement limits. Athletic trainers, conditioning coaches, coaches, and exercise-partners should be charged with the responsibility of assessing what is happening at the extremes of fast movements.

There are some activities that require maximal intensity/velocity explosive movements (e.g., hurdling in track; sprinting, dodging, kicking, etc. in the sports considered in this paper). Controlled/fast dynamic stretching as a specific-performance preparation activity could be too risky for inclusion in a warm-up routine or for the transition stage from completion of a warm-up to the start of a contest. With dynamic stretching the 80%-or-less discomfort rule is paramount. Participants need to be appraised of the dangers and/or injury-outcomes that could result from disregarding that controlling factor. If athletes are schooled in the need and procedures for the cautionary execution of the method, controlled/fast dynamic stretching could be performed as a "*feel-good*" activity, an activity that would contribute to the benefits of a warm-up, possibly contributing to the maintenance of an elevated central core temperature produced by a warm-up, and/or sustaining an athlete's concentration on contest preparation.

In the role of a time-filling exercise or a stretching routine that is appropriate for situations in which an exercise partner is unavailable, dynamic stretching is used most effectively to prepare already-stretched muscles for movements specific to a sport. It can sustain the changed viscoelasticity of the soft-tissues that resulted from a more beneficial stretching routine such as 3S-PNF.

A significant proportion of research concerning dynamic stretching has focused on its performance-enhancement potential. The association between dynamic stretching and performance is likely due to the fact that it is used in both the warm-up and pre-contest transition phase of contest preparation. Wunderlich *et al.* (2013) found that 15-minutes of eight different lower-body dynamic stretches that were repeated twice improved a 5-km running time-trial performance but did not alter hamstring flexibility or running economy. Pius *et al.* (2009) found that dynamic stretching as a warm-up did not alter soccer kicking-skills in females. Van Gelder and Bartz (2009) showed that dynamic stretching produced significantly faster times on an agility test when compared to a no-stretching treatment. Wright *et al.* (2006) reported that a 10-minute jogging warm-up was significantly better than dynamic stretching for increasing the range of motion of the hip although both had a significant positive effect. The warm-up and dynamic stretching performed before a trial increased vertical jumping performance. Costa *et al.* (2011) found that dynamic stretching caused hamstring concentric peak torque and the conventional hamstrings:quadriceps ratio to decrease to a greater magnitude than a sitting-only control condition. In addition, dynamic stretching decreased eccentric hamstring peak torque and the functional hamstrings:quadriceps ratio. Sommer *et al.* (2009) reported that dynamic stretching increased the caloric intake of male runners performing a 30-minute run at 65% VO_{2max} workload. On the other hand, Zourdos *et al.* (2009) observed that dynamic stretching and no-stretching had similar non-effects on a 30-minute run for distance. Given that there was no consistency between these studies with regard to how dynamic stretching was defined, two investigations reported stretching forms that could be labeled *dynamic stretching* and they seemed to be associated with enhancement in the performance factors and activities that followed their execution.

A number of studies have compared dynamic to static stretching. Pius *et al.* (2009) reported that neither dynamic nor static stretching influenced the performance of a soccer kicking-skill in females. Van Gelder and Bartz (2009) found that a dynamic stretching treatment produced significantly faster times on an agility test when compared to static stretching and no-stretching treatments. There was no difference between the static stretching and no-stretching conditions. Sekir *et al.* (2010) showed that concentric and eccentric quadriceps and hamstring muscle strength at two isokinetic speeds displayed a significant decrease following static stretching in elite female athletes. In contrast, a significant increase was observed after dynamic stretching suggesting it may be an effective technique for enhancing muscle-performance during pre-competition warm-up routines in elite females. Wright *et al.* (2006) reported that dynamic stretching before a trial significantly improved vertical jumping performance whereas static stretching was detrimental in its effect. There was no difference between the two forms of stretching for increasing the range of motion of the hip. Herda *et al.* (2007) found that static stretching reduced hamstring strength at two short-muscle lengths but hamstring strength was unaltered by dynamic stretching. When dynamic stretching is compared to static stretching it is both more beneficial and effective for ensuing performances and performance factors.

Flexibility is generally proposed as being different between the genders. Whether forms of stretching also differ in effects depending upon gender has not been substantiated. Pius *et al.* (2009) reported that dynamic stretching did not affect soccer kicking-skills in females. Sekir *et al.* (2010) found that dynamic stretching could be an effective technique for enhancing muscle performance during the pre-competition warm-up routine in elite women athletes. Costa *et al.* (2011) showed that leg extensor and flexor concentric peak torques, leg flexor eccentric peak torque, and the conventional end functional hamstrings:quadriceps ratios during isokinetic muscle actions were affected negatively in women. Nelson and Kokkonen (2001) tested a mixed-gender group of physical education class students' knee flexion and extension strength (1 RM) on two days. One test was preceded by quiet sitting, while the other was preceded by active and passive ballistic stretching of the hip, thigh, and calf muscles. Stretching increased hip flexibility as measured by a sit-and-reach test. Knee extension and flexion strength was significantly less after stretching than after no-stretching. Submaximal running factors were not affected by dynamic stretching in female distance runners (Henry *et al.*, 2012). More studies need to be conducted and evaluated to establish firm gender differences associated with the effects of a dynamic stretching experience.

Several studies have reported the effects of dynamic stretching on the hamstring muscles. Everett and Beekley (2012) found that a dynamic exercise routine that progressed in intensity produced improvement in hip-flexor and hamstring flexibility. However, the observed effects dissipated over the first 20 minutes of post-exercise recovery. After dynamic stretching, concentric and eccentric quadriceps and hamstring muscle strength at two isokinetic speeds displayed a significant increase in strength parameters (Sekir *et al.*, 2010). Dynamic stretching increased ROM more than static stretching but a 10-minute jogging warm-up was not significantly different from either stretching condition (Wright *et al.*, 2006). Hamstring strength was unaltered by dynamic stretching (Herda *et al.*, 2007). Dynamic stretching of the leg muscles including the hamstrings did not affect a 30-minute running performance

(Zourdas *et al.*, 2009). Costa *et al.* (2011) reported that dynamic stretching caused hamstring functioning, particularly force generation, to decrease. The inconsistencies between the above studies suggest that until dynamic stretching is established as an exact protocol, research findings will vary in accord with possible variations in stretching methodology.

Controlled dynamic-stretching designed to guard against exercise extents and intensities that could cause injuries or pre-dispose muscles to injuries in competition settings, has a place in sports when partners are unavailable, during the latter stages of warm-up routines, and during the transition phase between warm-up completion and the beginning of competing. It could also be useful during delays at practices (e.g., when waiting for a turn, after inactively listening to a coach's instructions, etc.). It is recommended that it be used for situations when an athlete would otherwise be inactive. Progressive dynamic stretching routines could also be used in injury-rehabilitation programs but should not replace effective methods for developing flexibility, particularly 3S-PNF.

Static Stretching

Static stretching involves the stretching of muscles to the point of *"slight discomfort"* or *"slight stretch"* (Jenkins, 2005b). Once the muscles around the joint(s) to be stretched reach that cautionary limit, the position is held statically so that the tension within the muscles is gradually reduced. Most static stretching routines involve a series of 3-5 repetitions, each usually lasting from 10-30 seconds. The static technique requires a relatively slow and controlled continuous movement to the end-range, which can be assisted by gravity or some other external force, a concentric contraction of the antagonists, or a combination of the two. At the end-range, the participant holds the terminal position for the designated time then releases the hold slowly. Unfortunately, there are many variations of static stretching involving practitioners' innovations which often render the technique of no value or harmful. As with PNF and dynamic stretching there are publications that state, at a minimum, the duration of the static hold while others refer to static stretching without any performance qualifiers. One should expect variations and contradictions in the research reporting the use of this form of stretching.

This form of stretching has the potential to be injurious particularly if the positions held are: i) at the maximum discomfort level that is tolerable by the athlete; ii) the positions exceed those that would be voluntarily sustained by the athlete (as in *abusive stretching*; see above); iii) the approach to the stretch position and recovery from that position are fast or explosive; and iv) the length of time the position is held exceeds the maximum recommendation of 30 seconds (Jenkins, 2005b; Holt, Pelham, & Holt, 2008). However, as with any human response factor there is considerable interindividual variation in hold-time. The length of the static contraction at the stretch (end-range) position is best determined by the wisdom of the athlete.

Research involving static stretching is the most voluminous and has entertained many more variables and modifications than the other two general classifications of stretching procedures. Research interests have included the effect of static stretching on performance and basic performance factors, gender-specific responses, strength and force development, and associations with warm-ups. For each of those topics, the research can be categorized according to the duration of the static hold (e.g., <31 seconds; 31 - <60 seconds, 60+ seconds, and investigations where no hold-time was reported).

The three methods of stretching do produce changes in ROM of one or more joints. If programmed stretching is entertained as a training program for extending a range of flexibility, ballistic stretching is likely to be the least effective, but nevertheless a contributor to establishing a new ROM. Consequently, in the studies reported below, seldom will it be mentioned that the ROM of flexibility was improved. That is a reasonable assumption of effect for the three classes of stretching activity when only performed on a few or irregular occasions.

Static Stretching and Performance

Performance is considered to be a movement that involves the whole body and yields some duration or magnitude of the movement in a form that is readily understood by most athletes and coaches (e.g., time for a 5 Km time-trial; the weight lifted in a bench-press; the height attained in a standardized vertical jump, etc.). Performance also involves a notable level of skill. It is currently believed by many coaches that increasing flexibility before performing will promote better performances and reduce the incidence of injury. Those beliefs need to be questioned in light of recent evidence (Nelson & Kokkonen, 2001). Why one would expect a stretching routine, normally most suited for increasing the range of motion of a joint(s) at a particular time as a temporary phenomenon, or as an often repeated routine designed to produce a permanent change in flexibility, to improve performance does not reveal a sound understanding of the physiological function of joints in isolation or as part of a complex movement. However, it seems that many believe static stretching has a role of directly altering performance potential at a specific time.

Hold-time of less than 31 seconds.

- Donkin *et al.* (2012) examined the effect of pre-exercise static stretching (25-seconds hold) on cycling time-trial performance. The warm-up protocols were static stretching, warm-up (15 minutes of sub-maximal cycling), and no-stretching. No significant differences were found in time to completion between the three treatments. Static-stretching in a warm-up role had no unique effect on endurance performance.
- Claeys *et al.* (2012) examined the effects of static stretching (30-second hold) compared to motor imagery and quiet rest (sitting and reading a student newspaper) on anaerobic performance in trained cyclists of both genders. Both manipulations were similar in the absence of effects to quiet rest. Neither static stretching nor imagery enhanced anaerobic cycling performance.
- Mosey, Mosey, and Otto (2007) evaluated the effect of static stretching (30-second hold) on maximal anaerobic performance. Following two warm-up protocols, female softball players performed maximal 30-yd and 100-yd sprint trials as well as a maximal leg press. A no-stretching warm-up consisted of seven minutes of jogging, while the stretching warm-up included identical jogging plus 30 seconds of static stretching of the calf, hamstrings, and quadriceps repeated three times with 30 seconds of rest between each stretch. The static stretching group ran significantly slower at both distances and was significantly weaker in the leg press.
- The effects of short-duration (15-second hold) static stretching on 100 m sprint performance in elite college sprinters were evaluated by Tsai *et al.* (2012). The muscle groups of the hips and lower legs were stretched after ~20 minutes of a

specific warm-up). Overall sprint performance was not affected by static stretching although the last 20 m of the run was altered detrimentally.

- Possible performance enhancing effects of static stretching on vertical jump performance were studied in males and females. Stretching focused on the lower body and shoulder regions as they were the areas that were used in a vertical jump performance. Vertical jumping performances remained unaltered after the intervention (Moneghan, Bemis, & Fradkin, 2010). Although that implication is not remarkable, this study did not demonstrate jumping performance depression as has been reported in other studies.
- Subjects performed a training routine of static stretching immediately after 10 minutes of a jogging warm-up. Another five subjects performed the same stretching routine after a 20-minute rest period. Static stretching consisted of four bilateral 30-second passive static stretches of the quadriceps femoris, hamstring, adductor, and calf muscles, twice per week for five weeks. Vertical jump performance and calf and adductor flexibility did not change. Hamstring flexibility improved significantly and was similar for both groups. The lack of effect of a static stretching routine did not appear to be affected by a prior jogging warm-up (Wittman, Babault, & Koussai, 2005).
- Henry *et al.* (2012) compared the effects of three stretching routines: i) no-stretching control, ii) very brief static holds (1-2 seconds), and iii) static stretching (30-second hold) on submaximal running economy in female distance runners. The three forms of stretching prior to submaximal running did not alter VO_2, lactate, or stride-length in females.

No stated duration of static hold.

- High school athletes were tested for bench-press (1 RM). In two other sessions, a general and exercise-specific warm-up, and a maximum velocity bench-press at 85% 1 RM were performed. Static stretching was randomly implemented immediately before the tested lift in either session 2 or 3. Static stretching significantly impaired bench-press mean power and mean velocity (Fry *et al.*, 2003).
- The technical leaping ability of female rhythmic gymnasts was evaluated after static stretching and a usual warm-up as a control condition. Static stretching before a competition negatively affected rhythmic gymnasts' leaping performances (Di Cagno *et al.*, 2008).
- Power *et al.* (2004) observed no significant changes in jumping performance after static stretching.
- Christiansen and Heise (2006) determined the effects of static stretching on bipedal hopping. Active dorsiflexion was increased in the static-stretching group when compared to a no-stretching control group. There were no differences between groups in the variables or the performance of hopping.
- Sayers *et al.* (2007) determined if the acceleration and/or the maximal velocity phase of a 30-m sprint is impacted by pre-performance static stretching in elite female soccer players. A no-stretching condition yielded significantly better performance characteristics of acceleration, maximal velocity sprint time, and overall sprint time than the static stretching condition.

- Young and Behm (2003) found that running and practice jumps in a warm-up had a positive effect on subsequent explosive force production (concentric jump and drop jump) whereas static stretching had a negative effect.

Not one of the above references reported that static-stretching favorably affected any physical performance. Effects were either non-existent or detrimental to the dependent variables employed.

Static Stretching and Performance Factors

Performance factors are subsets of movements and structures that comprise part of a total skilled activity (e.g., knee extension as part of a kicking action). Performance factors should only be considered when they function at the same velocity as that which occurs in the full movement. Often, performance factors interact with other factors to produce a beneficial contribution to the total skill while, when taken in isolation, are not associated with performance of a total skill.

Hold-time of less than 31 seconds.

- Power outputs every ~1 km and VO_2 of a cycling time-trial were not significantly different between treatments (static stretching, 15 minutes of sub-maximal cycling as a warm-up, and no-stretching) or time. Heart rates and ratings of perceived exertion were not significantly different between trials, but increased significantly over time within trials (Donkin *et al.*, 2012).
- Gergely and Austin (2009) determined the effect of two different warm-up treatments over time on driver clubhead speed, distance, accuracy, and consistent ball contact in male competitive golfers. The treatments were an active dynamic warm-up with golf clubs and a 20-minute total body passive static stretching routine plus an identical active dynamic warm-up. Passive static stretching significantly decreased clubhead speed, distance, accuracy, and solid contact when compared to the active dynamic warm-up condition. It was inferred that passive static stretching should be avoided as part of a warm-up before highly-skilled high-velocity activities such as golf.
- Performance of prolonged intermittent exercise was monitored after active rest, passive rest, and static stretching (30-second hold). Lactate was significantly decreased by all treatments but did not differ between conditions. Peak pedaling frequency and mean power were not altered by any treatments. Mean power rate significantly increased after static stretching whereas passive and active recoveries produced no changes. Static stretching may increase prolonged intermittent exercise performance but offers no extra facilitation in lactate removal (Miyahara, Mieda, & Ebashi, 2009).
- Changes in joint-position sense following an acute bout of static stretching (30-second hold) for the shoulder musculature were evaluated in healthy adults of both genders. Shoulder-flexion range of motion improved due to a static stretching intervention. No significant difference in joint-position sense followed the stretching intervention at any angle (McNeal *et al.*, 2006). Static stretching did not affect joint-position sense contrary to the conclusions of Dover *et al.* (2003).
- Male cyclists were observed to determine if bouts of static stretching affected peak and mean anaerobic power output on two Wingate cycle test trials. One trial followed static stretching and the other was no-stretching. Both preparations were preceded by

a conventional warm-up on the cycle ergometer. Static stretching significantly decreased both peak and mean power output. The conventional no-stretching warm-up was superior to the one that contained static stretching (Ramierz, Williford, & Olson, 2007).

Hold time of between 31 seconds and less than 60 seconds.

- Cannavan, Coleman, and Blazevich (2009) examined the effects of a moderate duration bout of static stretching (45-second hold) on peak active and passive ankle joint movement, neuromuscular activity (EMG), and gastrocnemius tendon stiffness in a group of men and women. Static stretching did not impair the plantar-flexors' ability to generate force or affect gastrocnemius' tendon stiffness in either men or women.
- Behm *et al.* (2004) investigated the effect of lower-limb static stretching (45-second hold) on balance, proprioception, and reaction and movement times. Subjects were tested on two occasions; i) before and after static stretching of the quadriceps, hamstrings, and plantar flexors, and ii) after a similar duration no-stretching control condition. There were no significant differences in the decrease in maximal voluntary isometric contraction between the stretch and control conditions or in the ability to match submaximal forces. Balance scores decreased significantly after stretching but increased significantly (i.e., they improved) after the control condition. Reaction and movement times decreased significantly after the control condition which differed significantly from stretch-induced increases in both factors. A bout of static stretching impaired balance and reaction and movement times when compared to a no-stretching condition.

Hold time of 60 seconds or greater. The two studies referenced below answer the question about why others have found strength and power decrements following stretching, but always in reference to static contractions held for a good length of time. These studies are very important.

- Hoge *et al*. (2009) examined the acute effects of passive stretching on the electromechanical delay of the plantar flexor muscles. Very long holds (135 seconds) were used on the ankle joint. Electromechanical delay increased by 11.2% from pre- to post-stretching. Excessive static stretching reduced the responsiveness and elastic properties of muscles and their supporting structures.
- Kato (2009) investigated changes in the mechanical and architectural properties of the gastrocnemius muscle-tendon unit due to a six-week static stretching/flexibility-training program. Stretching and non-stretching groups were compared. Plantar flexion torque passively attained at rest (0 degrees of ankle joint) decreased significantly, while the fascicle length increased significantly at week 4 and later. Different changes of muscular and tendinous components were joint-angle dependent. Static stretching reduced the elastic properties of the muscle which could account for a significant portion of performance loss due to this type of stretching.

No stated duration of static hold.

- Besser *et al.* (2013) studied the effects of static stretching on metabolic efficiency during a graded cycling-test in experienced cyclists. The treatment was compared to a no-stretching treatment. Static stretching was found to significantly inflate metabolic cost and functioning at the highest exercise-intensity levels but at lesser exercising intensities metabolic efficiency was improved.

- The effects of static stretching and no-stretching on a 30-minute running time-trial performance were compared (Wilson *et al.*, 2008). Static stretching prior to an endurance event had a negative effect on the performance of trained runners whereas no-stretching had no effect.
- Pius *et al.* (2009) compared the effects of a standardized static stretching and dynamic stretching warm-up on the performance of a maximal instep-type soccer place-kick in female high school varsity soccer players. There were no significant differences between the treatments for any variable indicating that neither was preferable to the other. The actual effects of the treatments compared to baseline were not reported.

Static stretching appears to have no effect or a detrimental effect on physical performance factors. Only one dependent variable (low-intensity cycling ergometry) yielded a positive benefit of metabolic efficiency.

Static Stretching and Gender

Static stretching studies that reported observations on females only or compared males and females are reported in this section.

Hold-time of less than 31 seconds.

- Johnson *et al.* (2012) determined the effects of static stretching, PNF, and no-stretching on isokinetic knee peak-torques in aerobically trained female athletes. Both stretching treatments reduced peak torque values for both knee flexion and extension whereas not doing stretching did not change the values.
- Moneghan, Bemis, and Fradkin (2010) assessed if there was any performance enhancing effect of static stretching (15-second hold) on vertical jump in two gender-different groups. Both groups failed to exhibit any improvement indicating that the response was not gender specific.
- Henry *et al.* (2012) compared the effects of three stretching routines on submaximal running economy in female distance runners. Stretching routines were randomly assigned and included: i) a control consisting of a 10-minute sit; ii) brief static stretching involving two sets of 30-seconds of five stretches that were held for 1-2 seconds and repeated for the 30-second period; iii) extended static-stretching involving two sets of 30 seconds of five stretches that were held for the 30 seconds; and iv) dynamic flexibility involving a series of 10 running-specific drills repeated for two sets of 30 seconds. The submaximal running task was for 10 minutes at 80% VO_{2peak}. The three forms of stretching prior to submaximal running did not alter VO_2, lactate, or stride-length in females.

Hold time of between 31 seconds and less than 60 seconds.

- Static stretching (45-second hold) did not impair the plantar-flexors' ability to generate force or affect gastrocnemius' tendon stiffness in either men or women (i.e., their responses were similar: Cannavan, Coleman, & Blazevich, 2009).

No stated duration of static hold.

- Static stretching before a competition simulation negatively affected rhythmic gymnasts' leaping performances (Di Cagno *et al.*, 2008).
- Pius *et al.* (2009) reported that static and dynamic stretching had similar effects on varsity female soccer players' performance of place-kicks.
- The quadriceps and hamstring muscles were subjected to no-stretching, static stretching, and dynamic stretching protocols in elite female athletes (Sekir *et al.*, 2010). Concentric and eccentric quadriceps and hamstring muscle strength at two test speeds displayed a significant decrease following static stretching but a significant increase after dynamic stretching. Normalized EMG amplitude parameters exhibited significant decreases following static stretching and significant increases following dynamic stretching during quadriceps and hamstring muscle concentric and eccentric actions. Dynamic stretching appeared to have beneficial effects whereas static stretching did not in the elite female athletes.
- Cramer *et al.* (2004) examined the effects of static stretching on concentric, isokinetic leg extension peak torque at 60 and 240 degrees/s in stretched and unstretched limbs in women. Peak torque decreased following the static stretching in both limbs and at both velocities. Static stretching impaired maximal force production.
- In elite female soccer players, pre-performance static stretching inhibited acceleration and sprint performance when compared to a no-stretching condition (Sayers *et al.*, 2007).

Static stretching was not associated with any benefit for a variety of dependent variables in females. In studies where male and female groups were compared, almost all show no gender difference in reactions to static stretching.

Static Stretching and Strength and Force Development

Strength is normally reported as a measure of force resulting from a linear movement (e.g., the amount of weight hoisted performing a bench-press). Force development pertains to the forces created as torque when curvilinear movements about a joint are observed.

Hold-time of less than 31 seconds.

- Static stretching (30-second hold) caused a significant decrease in the number of repetitions in a hamstring strength-endurance test (Kokkonen, Nelson, & Arnall, 2001). That implies that athletes should not overdo static stretching before any performance that requires a moderate to high level of intensity and/or duration (e.g., strength-endurance or muscular endurance factors).
- The acute effects of static (30-second hold) and dynamic (ballistic) stretching and no-stretching on peak torque, electromyography, and mechanomyography of the biceps femoris muscle during isometric maximal voluntary contractions of the leg flexors were studied in males. Static stretching reduced hamstring strength at the two shortest muscle lengths, but strength was unaltered by dynamic stretching and no-stretching (Herda *et al.*, 2007). Static stretching caused an increase in normalized mechanomyography amplitudes at 101°, while dynamic stretching increased mechanomyography amplitudes at all joint angles.

- Nelson, Winchester, and Kokkonen (2006) examined the relationship between the volume of static stretching (30-second hold) and knee-flexion strength inhibition. The position of hold was at the maximum tolerable level of discomfort. Hamstring stretches were increased from zero to six all on different days. Static stretching significantly reduced 1 RM after one 30-second stretch (-5.4%), and continued to decrease up to and including six 30-second stretches (-12.4%). A single 30-second stretch held at the limit of tolerance is sufficient to cause an inhibition in strength production.

Hold time of between 31 seconds and less than 60 seconds.

- Miyahara *et al.* (2007) compared the effect of dynamic/ballistic stretching and static stretching (45-second hold) on maximum voluntary knee flexions in young men. ROM increased in both stretching conditions when compared to controls. Maximum voluntary contraction was decreased by both stretching conditions when compared to the unchanged non-stretching condition. Static stretching reduced maximum voluntary contractions (strength) significantly more than dynamic/ballistic stretching.

Hold time of 60 seconds or greater.

- Neese and Malachy (2006) had subjects perform static stretching (60-second hold) on the hamstrings before eccentric exercise on one leg but not on the other over four days. Strength loss was greater at short versus long hamstring-muscle lengths. However, that pattern differed between the control and stretched leg. At the longest muscle length, strength was significantly depressed in the control leg on the three days following eccentric exercise but remained above baseline in the stretched leg on all three days. Pain peaked two days following eccentric exercise with no difference between the stretched and control legs. Static stretching before eccentric exercise appears to prevent subsequent strength loss at long hamstring-muscle lengths but not at short muscle lengths.

No stated duration of static hold.

- Heavy static stretching should not precede maximal strength efforts. Kokkonen and Nelson (1996) found that leg-strength 10 minutes after 20 minutes of static stretching or 20 minutes of ballistic stretching was degraded.
- The effects of no-stretching and a slow static-stretching protocol on maximal isometric force, time to maximal isometric force, rate of force development, and EMG amplitude of the main agonist muscles in a bench-press exercise were assessed. Maximum isometric force significantly decreased (~6%) from the pre- to post-stretching in the static-stretching group. The decrease dissipated after 30 minutes (Pezarat-Correia *et al.*, 2009).
- Nelson, Kokkonen, and Arnall (2005) measured muscle strength-endurance performance after static stretching and the repeatability of any observed phenomena. Knee-flexion muscle strength-endurance exercise was measured by exercise performed at 60 and 40% of body weight following either a no-stretching or static stretching protocol. Second, using a test-retest protocol, a knee-flexion muscle strength-endurance exercise was performed at 50% body weight on four different days, with two tests following a no-stretching regimen and two tests following static

stretching. Muscle strength-endurance was reduced significantly in both studies suggesting that static stretching should be avoided prior to tasks requiring maximal muscle strength-endurance.

- Power *et al.* (2004) examined whether a static stretching routine decreased isometric force, muscle activation, and jumping power while improving ROM and compared the duration of the dependent variable changes with the duration of the change in ROM. There were significant decreases in maximal voluntary force and muscle inactivation in the quadriceps after static stretching,. Force remained significantly decreased for 120 minutes paralleling significant percentage increases in the sit-and-reach test range of motion at 120 minutes. There were no significant changes in jumping performance or plantar flexion measures after static stretching.
- The quadriceps and hamstring muscles were subjected to no-stretching, static stretching, and dynamic stretching protocols in elite female athletes (Sekir *et al.*, 2010). Concentric and eccentric quadriceps and hamstring muscle strength at two test speeds displayed a significant decrease following static stretching but a significant increase after dynamic stretching.
- The effects of static stretching on concentric, isokinetic leg-extension peak torque at 60 and 240 degrees/s in stretched and unstretched limbs were examined in women. Peak torque decreased following the static stretching in both limbs and at both velocities. Static stretching impaired maximal force production (Cramer *et al.*, 2004).
- The effects of two minutes of static stretching, two minutes of PNF stretching, and no-stretching were compared using quadriceps and hamstring muscle strength and knee-joint ROM. Short-duration static stretching had a detrimental effect on muscle strength, particularly in relation to PNF stretching. Short-duration PNF stretching had no detrimental effect on strength (Davis & McConnell, 2007).
- Force loss after prolonged (20 minutes) static and passive stretching of the quadriceps was evaluated. Half the study's subjects also performed a no-stretching control condition. Following static stretching, maximal voluntary contraction force decreased by 12%, while muscle activation increased by 2.8% and inactivation increased by 20.2%. Too much stretching decreases force production (Behm, Button, & Butt, 2001).
- Dent *et al.* (2009) determined the acute and prolonged effects of static stretching (no specific features included) and dynamic warm-up on muscular power and strength. Active and inactive subjects performed a 10- and 30-yard dash, vertical jump, and 1 RM squat at intervals of 5, 30, and 60 minutes following 15 minutes of either static stretching or dynamic warm-up. Treatments were completed within one week of baseline testing. All performance variables were negatively affected over one hour following both static stretching and dynamic warm-up. Activity level influenced the performance variables with active subjects experiencing less performance decrement over time in 10- and 30-yard dash times and vertical jump following static stretching in particular. It was recommended that static stretching prior to muscular power activities be used cautiously as that variable did not return to baseline within one hour.
- Mixed-gender adults performed maximal isokinetic (30 and 270 degrees/s) forearm flexion strength-tests on two occasions while EMG and MMG measures were registered. Ss were randomly assigned to stretching and non-stretching protocols. Stretching significantly reduced torque. MMG amplitudes were greater for stretching

than non-stretching while EMG amplitudes were similar. Evetovich *et al.* (2003) concluded:

> *These results indicated that a greater ability to produce torque without prior* [static] *stretching is related to the musculotendinous stiffness of the muscle rather than the number of motor units activated. This suggests that performing activities that reduce muscle stiffness (such as stretching or warming-up) may be detrimental to performance* (p. 370).

Static stretching appears to have a consistent major negative effect on strength and force production. Most studies showed a detrimental effect while no-effect was rarely reported.

Static Stretching and Warm-ups

Warm-ups are a series of pre-performance activities that are usually designed to raise the central core temperature of the body and to prepare the joints to move through ROMs that will occur in a contest. The psychological content of a warm-up is particularly important (Rushall, 2003).

Hold-time of less than 31 seconds.

- Donkin *et al.* (2012) found that static stretching (23-second hold) in a warm-up role had no effect on cycling endurance performance.
- Ramierz, Williford and Olson (2007) found that static stretching as part of a warm-up before performance on the Wingate cycle test significantly decreased peak and mean power output. A conventional non-stretching warm-up was superior to one that contained static stretching.
- Wittman, Babault, and Koussai (2005) had a group perform a training routine of static stretching immediately after 10 minutes of a jogging warm-up and another group performed the same stretching routine after a 20-minute rest period. Static stretching consisted of four bilateral 30-second passive stretches of the quadriceps femoris, hamstring, adductor, and calf muscles, twice per week for five weeks. Hamstring flexibility improved significantly and was similar for both groups. The effects of a static stretching routine did not appear to be affected by a prior warm-up.

No stated duration of static hold.

- An active dynamic warm-up with golf clubs and a 20-minute total body passive static stretching routine plus an identical active dynamic warm-up were compared as warm-up procedures. The static stretching warm-up detrimentally changed many features of a driver-swing and it was opined that such an activity should not be used as a warm-up prior to complex highly-skilled activities (Gergley & Austin, 2009).
- Wright *et al.* (2006) determined the effect of three different activities (static stretching, dynamic stretching, and a 10-minute jogging warm-up) designed to prepare hip and leg musculature for an active ROM and strength-power performance in a vertical jump. The three treatments increased the ROM. Warm-up and dynamic stretching performed before a trial increased vertical jumping performance while static stretching was detrimental to performance.
- Five warm-up conditions were compared: i) control, ii) 4-min run, iii) static stretch, iv) run and static stretch, and v) run, static stretch, and practice jumps. After two minutes of rest, a concentric jump and drop-jump were performed. Running and

practice jumps had a positive effect on subsequent explosive force production whereas stretching had a negative effect (Young & Behm, 2003).

Static stretching does not add anything positive or of benefit to a general activity warm-up. Rather, the effects appear to be mostly negative. Static stretching should not be included in the warm-up for most exercises/activities.

Meta-analyses of Static Stretching Research

When attempting to draw together the general implications of diverse works in a specific field of scientific study, the traditional method has involved an extensive literature review, noting consistencies or inconsistencies in the implications of acceptable research, and depicting them as the true status of the field of investigation. That has occurred in several subsections of this paper, the most recent being the descriptions of works involving static stretching. However, another more objective form of review is to conduct a meta-analysis of published works. That method involves scouring data bases for studies on a particular topic, evaluating their scientific standard, gathering only those studies which have the same or similar independent and dependent variables, and using the data of acceptable studies to estimate statistical properties of generalizations drawn from an analysis. There have been at least two meta-analyses involving static stretching. What is of interest is to see if there is any commonality between the findings of those studies.

Kay and Blazevich (2012) examined the effect of static stretching on maximal muscular performance. The search for possible publications revealed 4559 locations with 106 works meeting the inclusion criteria for the meta-analysis. It was found that stretching durations of <30 seconds, 30-45 seconds, and ≤60 seconds imparted no detrimental effects on the measures of performance. Stretching durations longer than 60 seconds were likely to produce performance decrements. The shorter duration position holds (<30 seconds) are likely to be the least negatively effective if effective at all. Longer duration static stretching (≥60 seconds) is likely to be detrimental to muscular performance and should be avoided for clinically healthy populations. The reality of this conclusion is that static stretching of any duration is not performance enhancing but more likely to be detrimental to performance and performance factors. This raises the question: *If a procedure does not improve performance and in many situations causes performance to be affected negatively, why even do it? What benefit does it yield?* When compared to the intuitive analyses that preceded this subsection, it seems that the author-reviewed articles on static stretching in this paper yielded a much greater proportion of negatively affecting procedures than the meta-analysis.

Markovic, Simic, and Mikulic (2009) performed a meta-analysis to estimate the effects of static stretching on explosive muscular performance (e.g., jumping and sprinting). After locating 24 studies, it was found that no significant relationships were found between the total stretch duration and stretch-induced changes in jumping or sprinting performance. Static stretching in warm-up routines decreased jumping and sprinting performance, but the magnitude of effects is likely to be of small practical importance.

The above two meta-analyses give no positive implication of static stretching for explosive or maximal muscular performance. The weak attribute of static stretching is that in some cases it does no harm. There seems to be no scientific observation that justifies its use in healthy sporting people. It may have some application in injury or physical rehabilitation programs.

In studies reviewed above that involve the hamstrings, the ROM of those muscles is increased through static stretching. However, despite achieving greater transitory flexibility, the effects upon performance, performance factors, strength, and force production are either neutral but mostly undesirable. The genders appear to respond similarly to static stretching. In 1998 the American College of Sports Medicine recommended static stretching and PNF as two forms of flexibility-training in exercise programs. To these authors it seems such a recommendation needs to be revised because of the lack of benefits of static stretching when compared to those of PNF that have been shown by many studies since the turn of the century. In the few studies where the two protocols have been compared, both have been similar or PNF superior. Even when dynamic stretching has been compared to static stretching, dynamic stretching has been shown to generate more positive results/benefits than static stretching.

Stretching in General

Stretching and Recovery

Stretching has been used as an important ingredient for post-activity recovery. Exactly how it might assist in recovery rarely has been described. However, recent evidence has shown benefits from stretching as a recovery activity are questionable. Herbert and Gabriel (2002) concluded:

> *The results of five studies . . . imply that stretching reduces soreness in the 72 hours after exercising by, on average, less than 2 mm on a 100 mm scale. Most athletes will consider effects of this magnitude too small to make stretching to prevent later muscle soreness worthwhile* (p. 470).

Inappropriate stretching has been shown to actually increase muscle soreness rather than reduce it. Static stretching induced significantly more delayed onset muscle soreness (*DOMS*) than did ballistic stretching (Smith *et al.*, 1993). Stretching did not accelerate recovery from ankle surgery when the recovery involved exercise (Moseley *et al.*, 2005).

Until definitive research demonstrates a positive relationship between improved recovery and stretching routines, one should assume that stretching does not affect recovery in any beneficial manner. Other forms of activity, such as continuous moderate overall movements that are aerobic in nature, provide a better avenue for recovery. However, if stretching is to be performed, it should follow the 3S-PNF protocol or dynamic stretching rather than static stretching (Funk *et al.*, 2003).

Increased Movement Range

The basic tenet of increasing flexibility needs to be reconsidered. What is the value of being able to move a joint through a greater ROM than that which is endowed naturally or has been required for an activity? Well-funded teams generally employ specialists who emphasize stretching routines for most of the body. Professional teams make stretching part of the pre-game spectacle. What value does performing excessive assisted-stretches have for sports that require fast and agile movements?

It has already been discussed that single bouts of excessive or abusive stretching reduce strength, explosiveness, and movement velocity. Caution should be given to the effects caused by doing too much stretching, too often, for too long of a time.

When muscles are stretched beyond natural voluntary ranges of motion, the muscles and tendons are stretched unnaturally. Excessive stretching damages tissues and promotes inflammation (Yang, Im, & Wang, 2005). Continual stretching can lead to habitually "*lengthened*" muscles. That condition leads to performance altering states.

- The ROM of the joint about which the lengthened muscles gird is increased. That results in the range of effective contraction of the muscles being altered. Maximum muscle performance will have to occur in a different ROM to the original natural range. If a lengthened muscle is required still to perform in the original natural range, then performance in that range could be reduced because of weakness produced by the extra stretch from flexibility/stretching work. Thus, a conscientious program that lengthens a muscle for lengthening sake, rather than for improving skill-function, is not only misguided but also is likely to be detrimental to performance. Maximally lengthened muscles about a joint are associated often with a loosening of the joint. Increased laxity can expose a joint to increased injury through collisions or simply through maximum efforts. Intra-joint movements can also stimulate aggravations of other structural tissues as well as bony structures. Activities that are designed to *"stretch"* [lengthen] the hamstrings could contribute to hyper-extended knees. It is not difficult to imagine how this could contribute to knee or hamstring injuries during a game.
- It is reasonably accurate to consider muscles and connective tissues as having capacities similar to those of elastic bands. A fresh natural elastic band has stretch and contraction capabilities for which it was designed. However, if an elastic band is stretched and held in that position for considerable time, it loses some of its original contractile power and properties. A continually-stretched set of muscles about a joint will likely go through a similar degradation in function. It is quite possible that the loss of running velocity in gifted athletes could be attributed as much to a loss of elastic contractile properties in muscles and connective tissues from over-zealous stretching and participation as is attributed more usually to technique changes, *"attitude problems"*, etc. This important factor should not be overlooked by an athlete or coach.
- It was argued in Part I of this presentation that movements are coded as neuromuscular patterns in the brain. That coding covers all features of a movement including the muscles used, their functions and coordinations, the ROM over which they act, the energy supplied to support the movement characteristics, etc. When a skill is learned, it usually is fixed as a narrow family of movement patterns in the brain that accommodate states of fatigue, warm-up variations, and periods of efficient function. If the ROM of a joint is increased through flexibility-training, that new ROM will not be used until the existing movement pattern is altered to accommodate it. Just changing one or more ROMs will not result in improved performances or changed actions. The skill has to be relearned or modified to accommodate the ROM changes. When a new ROM is incorporated to form an altered movement pattern, the esthetics and/or movement properties can change from what existed prior to the flexibility-training. For example, dancers, gymnasts, figure skaters, etc. present more spectacularly when ROMs are extreme. When a movement distance is extended, there is greater opportunity to accelerate limbs and create more force. However, it should be realized that it is only when a concerted technique alteration is effectively

undertaken that greater flexibility can be incorporated into a previously established technique to indicate movement improvement or increase in effectiveness.

Injury Prevention

Injury prevention is used frequently to justify deliberate stretching routines that cover particularly vulnerable joints (e.g., ankles, knees, hips, and shoulders) often as a part of training, warm-ups, and performed at appropriate opportunities during a competition. High frequency flexibility exercises reduce injuries (Hartig & Henderson, 1999). Contrarily, Ingraham (2003) Ingraham (2003) asserted:

> *The use of stretching to prevent injury, off-set muscle soreness, and improve performance has been widely accepted and promoted in sports. However, little or no scientific evidence supports the practice, and recent research suggests that stretching, which increases flexibility beyond that needed for sport-specific movements, may cause injury.*

The review implied increasing range of motion beyond usual function through stretching is not beneficial and can actually cause injury and likely decreases performance.

Thacker *et al.* (2004) conducted a meta-analysis of the effectiveness of stretching as a tool for preventing sports injuries. A large number of located studies were excluded from the analysis because of poor methods and procedures. It was concluded that stretching was not significantly associated with a reduction in total injuries and similar findings were seen in subgroup analyses. There is insufficient evidence to endorse or discontinue routine stretching before or after exercise to prevent injury among competitive or recreational athletes. At best, the proposition that stretching prevents or reduces the likelihood of injuries is equivocal. The inconsistency of research findings in this topic supports the contention that methodological procedures in this area are poor and mostly misleading.

Herbert and Gabriel (2002) concluded the following:

> "*On average, about 100 people stretched for 12 weeks to prevent one injury and (if the hazard reduction was constant) the average subject would need to stretch for 23 years to prevent one injury*" (p. 470).

Witvrouw *et al.* (2004) provided a group opinion on the value of stretching for injury prevention.

> "*It is generally accepted that increasing the flexibility of a muscle-tendon unit promotes better performances and decreases the number of injuries. Stretching exercises are regularly included in warm-up and cooling-down exercises; however, contradictory findings have been reported in the literature. Several authors have suggested that stretching has a beneficial effect on injury prevention. In contrast, clinical evidence suggesting that stretching before exercise does not prevent injuries has also been reported. Apparently, no scientifically based prescription for stretching exercises exists and no conclusive statements can be made about the relationship of stretching and athletic injuries. Stretching recommendations are clouded by misconceptions and conflicting research reports. We believe that part of these contradictions can be explained by considering the type of sports activity in which an individual is participating. Sports involving bouncing and jumping activities with a high intensity of stretch-shortening cycles (SSCs) [e.g. soccer and football] require a muscle-tendon unit that is compliant enough to store and release the high amount of elastic energy that benefits*

> *performance in such sports. If the participants of these sports have an insufficient compliant muscle-tendon unit, the demands in energy absorption and release may rapidly exceed the capacity of the muscle-tendon unit. This may lead to an increased risk for injury of this structure. Consequently, the rationale for injury prevention in these sports is to increase the compliance of the muscle-tendon unit. Recent studies have shown that stretching programs can significantly influence the viscosity of the tendon and make it significantly more compliant, and when a sport demands SSCs of high intensity, stretching may be important for injury prevention. This conjecture is in agreement with the available scientific clinical evidence from these types of sports activities. In contrast, when the type of sports activity contains low-intensity, or limited SSCs (e.g. jogging, cycling, and swimming) there is no need for a very compliant muscle-tendon unit since most of its power generation is a consequence of active (contractile) muscle work that needs to be directly transferred (by the tendon) to the articular system to generate motion. Therefore, stretching (and thus making the tendon more compliant) may not be advantageous. This conjecture is supported by the literature, where strong evidence exists that stretching has no beneficial effect on injury prevention in these sports. If this point of view is used when examining research findings concerning stretching and injuries, the reasons for the contrasting findings in the literature are in many instances resolved".*

The above authors suggest that for sports that employ mainly very rapid stretch-shortening cycles, that is they have maximum velocity efforts and/or maximum range positions (i.e., the sports that are addressed in this consideration of the hamstring muscles and musculature in general, gymnastics, dance) stretching is important as one means of better preparing soft tissues for high-levels of or extreme stress. On the other hand, in sports that do not function very much at maximum intensity/velocity (e.g., swimming, rowing, kayaking, marathon running) there is *"no need for a very compliant muscle-tendon unit since most of its power generation is a consequence of active (contractile) muscle work that needs to be directly transferred (by the tendon) to the articular system to generate motion. Therefore, stretching (in order to make the tendon more compliant) may not be advantageous. There is strong evidence that stretching has no beneficial effect on injury prevention in these sports"* (Jenkins, 2005b, p. 305).

Although many benefits are claimed from stretching as a ritualistic sports-training and performance-preparation activity, the research support for such an inclusion is equivocal and in some cases contrary to relatively consistent research findings. McHugh and Cosgrave (2010) concluded that stretching for injury prevention did not affect the incidence of overuse injuries. A tepid hypothesis that pre-participation stretching reduces the incidence of muscle strains was opined but the need for further supportive research was recognized.

Auxiliary Flexibility-training

Any inclusion of a flexibility-training protocol in the conditioning of athletes should be based on the following criteria:

a) That it has been shown to have a beneficial effect on ROM.
b) That it maintains normal strength in the MFT units exercised.
c) That it helps to maintain tissue elasticity through its effect on the soft tissues in the MFT's.

d) It has no detrimental effect on skill performance.
e) It has been thoroughly researched, with an established and effective protocol.

At this point in time, there is only one method that meets those criteria, and that is the 3S-PNF (reversal of antagonists) protocol as described above. If that method is to be employed, it is imperative that those in charge of the conditioning program follow the established protocol and not deviate from it. There are spurious adaptations of PNF that have been used with ineffective and/or detrimental results some of which have been described above. Jenkins (2005b, p. 305) also recommended active PNF as being the best stretching protocol. Among its values not shared by the other two forms of stretching are: i) it leads to greater improvement in flexibility over a period of time; ii) it produces greater muscle activity (as measured by electromyography); and iii) it has an analgesic effect of *"stretch tolerance"*, that is, subjects feel less pain for the same force applied to the muscle. The result of the latter two features is that PNF increases ROM even though true stiffness does not change. It is that retention of original stiffness that leads PNF to be beneficial for its general purposes.

3S-PNF is the procedure for flexibility-training recommended by these authors. If initial warm-ups for training sessions and contests and recovery from exercise is believed to be a valid use of stretching, 3S-PNF is also the recommended method. That should not be a surprise to any reader. While the subjectivity of such a recommendation is indisputable, the enduring successes of the 3S form of PNF in the Dalhousie University Sport Science Laboratory over more than 40 years are significant verifications of the recommendation. In 1998, the American College of Sports Medicine advocated PNF as one of two forms of stretching to be added to its exercise recommendations.

PART III

IMPLICATIONS FOR RESISTANCE-TRAINING, FLEXIBILITY-TRAINING, AND STRETCHING

Resistance-training

Resistance/strength-training does not produce the outcomes that are claimed by self-interested practitioners. Below are conclusions and hypotheses that are drawn from the discussion in Part I of this paper.

1. If concerted excessive strength-training occurs across all muscles/joints of the body, unusual injuries in muscles/joints not frequently involved in a sport could increase. The corollary of that implication is that by undertaking strenuous auxiliary/strength-training over the total body, the number of potential injury sites increases when compared to those that might occur without involving a *"dedicated"* total resistance-training experience.
2. If concerted excessive strength-training occurs in only the major muscles/joints involved in a sport, the possibility of injuries is likely to be highest in those *"trained"* body areas.

   Those two hypotheses are testable and are viable research topics for graduate-level investigations. On the practical side, coaches and training staffs can log the type and site of injuries that occur in a competitive season [when exceptional effort levels are likely to be more frequent than outside of competitions] and i) look for *outlier/irrelevant* injuries partly caused by irrelevant auxiliary training, and ii) look for *sport-specific* injuries that could be caused by sport participation itself or demanding sport-specific auxiliary training.
3. The involvement in auxiliary strength-training can be excessive. Unless sufficient rest and recovery are provided after a stimulating strength-training session, the maximal benefits of the experience will not be enjoyed by an athlete (Rushall & Pyke, 1991). There are a number of considerations about the frequency and overload of a strength-training experience that can be reviewed in the *Strength-training* issues of the *Coaching Science Abstracts* (http://coachsci.sdsu.edu/index.htm).

   - It is better to give too much rest/recovery between training sessions than too little. As a general rule-of-thumb, 48-72 hours is a recovery period for strength-training that will satisfy the needs of most serious athletes of both genders. Daily strength-training excursions which seem to be increasing in vogue these days are most likely to cause more harm than good. Stress-related injuries (e.g., stress-fractures, joint-structure problems) occur from overuse. The ill-founded belief that if hard strength-training is experienced more than three times per week, more benefits will occur, is used to reinforce an argument for daily or five-times per week sessions. Such a regime is exceptionally dangerous for females because they do not respond to strength-training as well as men.[25]

- When the number of repetitions per strength exercise is divided into sets separated by short rest intervals, the amount of work performed could be excessive. The original *"three sets per exercise"* edict that has governed exercise sessions for many years was based on a contentious research article published by Berger (1962). At this time, there is strong advocacy that it is the state of exhaustion in an exercise that causes the maximal stimulating effect. With that in mind, there is a steadily increasing number of researches that show one set to exhaustion is all that needs to be experienced to gain the maximum strength stimulation. When three sets are followed, and in particular where the number of repetitions within a set is stipulated (e.g., 3 x 8 reps) there is no guarantee that performing that set will yield a maximum stimulus. If the three sets are accommodated by an athlete then the training stress usually is sub-maximal.

This presentation has introduced valid concepts that are new to or not used by the vast majority of coaches or assistant/auxiliary-coaching personnel. No longer should the specific needs of performance elements be considered as the summation of discrete training emphases (e.g., strength, speed, ball-control, concentration, range of movement, etc.). The skills and performance categories of each sport should be considered as discrete indivisible behaviors on an individual-athlete basis. The first and major decision for any performance quality needed by an athlete should be considered in terms of what is represented in the brain. The specificity of neuromuscular patterning no longer is hypothetical. Through the marvel of fMRi it is possible to see how a skill, movement, game-element, etc. is coded in the brain. As was illustrated in Figure 4 in Part I of this paper, a minor change in a movement demand can cause a completely discrete and different code of neural patterning. To think that strengthening an athlete in a particular anatomical area will *"solve a problem"* is nonsensical in terms of what is now known about human movement. Skills and movement patterns in serious training athletes are best altered by employing a total-activity correction strategy that encompasses sufficient repetitions that result in the altered skill's conditioned strength being sufficiently strong to replace the older behavior. This requirement is simply a plea for coaches, assistant-coaches, auxiliary-training personnel, and athletes to respect the dominant presence of the *Principle [Law] of [Training] Specificity*. In practical terms, there is no violating that Principle/Law in human behavior. It has the same ever-present quality in human behavior as Newton's Three Laws of Motion.

Training strength and power is subject to the same parameters as training for any other physical performance-based activity. Rushall and Pyke (1991) listed four principles of training that need to be correctly accommodated to benefit performance improvements in serious athletes.

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[25] One of these authors was involved as a guest-coach in a women's collegiate swimming team. In that season, the girls were participating in daily strength-training, some sessions occurring before a swimming practice and others occurring after. Since pool-training was scheduled twice a day, recovery from swimming stimulation most likely was hindered by the intrusion of fatigue from irrelevant auxiliary training. One time when coaching breaststroke technique, a swimmer confided that her legs were too sore to feel any changes in her kicking action. Further, she said she was so sore everyday that *"going to the toilet"* was particularly difficult and inconvenient.

1. The *Principle of Overload* governs how hard an athlete works at a practice. The amount of stimulus overload that can be beneficial to an individual athlete is limited. It is possible to exceed the adaptive capacity by setting stimuli (workloads) that are excessive. Experiments have shown that training for an excessive duration in a segment does not contribute to any further increase in the development of a particular fitness component. The initial load produces the potential for training effects while excessive amounts are of no value (Astrand & Rodahl, 1986). It is a coach's responsibility to protect athletes from being excessively overloaded with single or accumulated training stimuli. The allocation of training overloads should conform to the Roux Principle: *small stimuli are useless, moderate stimuli are useful, and excessive stimuli are harmful* (Stegeman, 1981, p. 266). Good performances cannot be produced under excessive fatigue conditions.
2. An athlete's improvement is dependent upon the provision of adequate recovery so that training effects can be maximized. The *Principle of Recovery* implies that for maximum performance benefits to occur and before a training stimulus is reintroduced, complete recovery from the previous stimulation must occur. To train without adequate recovery from previous fatiguing work does not produce any benefit to athletes for they merely learn to cope with fatigue rather than improving in specific aspects of performance. The major portions of training effects and learning experiences from practices are only developed during rest/recovery opportunities. Between-athletes differences moderate recovery rates and so programming of training stimuli and sessions will depend upon every athlete's capacities.
3. The *Principle of Specificity* indicates that the maximum benefits of a training stimulus can only be obtained when it replicates the movements and energy systems involved in the activities of a sport. Task repetitions should be psychologically, biomechanically, and physiologically similar to the sport performance criteria. Much has been written above about this principle. Essentially, it means that training that does not simulate game-circumstances will not have the potential for maximal training effects. When activities are irrelevant to what occurs in a game (i.e., most, if not all, auxiliary training activities) no game-performance benefits will result. Strength-training is irrelevant training for the sports considered in this discussion.
4. The *Principle of Individuality* dictates that the decisions concerning the nature of training should be made with each individual athlete in mind (Rushall, 1979). A coach must always consider that all athletes should be treated independently (Bompa, 1986; p. 17). Incorrect forms of training prescription result from all athletes in a team training with the same schedule and load. The optimum training loads vary between athletes. The capacity to respond to training is related to the initial level of fitness and the physiological characteristics of the individual in all athletes.

The respectful programming of those four principles to a large extent will govern coaching effectiveness. In team situations, it is convenient and expedient to program activities and experiences for all players at the same time. That makes for easy organization. Unfortunately, easy organization usually causes a decrease in the effectiveness of sport-training for producing performance improvements.

The most important training principle is the *Principle of Specificity*. Ignoring or violating that principle will result in wasted/irrelevant practice experiences. One should not expect visible improvements in performances unless the *Principle of Specificity* is faithfully programmed.

Flexibility-training and Stretching

Dogma and Myths

Flexibility-training and stretching are topics and activities that exist in most serious-athletes' training programs. Many of the reasons for their inclusion are dogmatic or mythical. A common myth is: *"all sportspersons should be as flexible as possible."* Although it has been shown that some forms of stretching are useless or dangerous as far as adding anything positive to a training or competitive experience, it is proposed that it is worthwhile to consider some of the dogmatic proposals.

The elasticity of muscles needs to be preserved for high speed/explosive performances, Jones (2002) attributed running performance to metabolism in the muscles and stiffer musculo-tendinous structures that facilitate a greater elastic energy return during the shortening phase of the stretch-shortening cycle. A certain level of muscle stiffness preserves the storage and return properties of elastic energy that can be used to energize an activity. The contribution of elastic energy to overall muscle performance is as much as 25-40% (Cavagna & Margaria, 1966; Cavagna, Saibene, & Margaria, 1964). Nelson *et al.* (2005) found that traditional stretching before sprinting, slowed 20-meter sprint times. A review of data-based investigations led to the conclusion that traditional static stretching did not improve performance capability (Ingraham, 2003).

Wilkinson and Williams (2003) provided a well presented review article that looked at research covering stretching and its effect on running economy. A number of statements concerning beliefs and theories regarding flexibility were made.

- *There is little evidence to support the claim that non-pathological* [naturally endowed] *muscle tightness reduces running economy* (p. 5).
- *There is a growing body of evidence to suggest . . . that a lack of notable flexibility in certain areas of the body may be linked with increased running economy. And it is interesting to note that studies of competitive distance runners have shown them to be less flexible than non-runners* (p. 5). [Jenkins (2005b, p. 305) stated: *The stiffer the muscle tendon unit, the faster force is transferred to the bones, and the resulting movement of the joint is quicker.*]
- Decreased flexibility in the trunk and hip prevents trunk rotation and hip turn-out while running, both restrictions improving running economy.
- Decreased flexibility in the ankle (tightness in the calf and *soleus* muscles), and the lower back/hamstrings were associated with better running economy.

One explanation why non-exceptional flexibility actually increases running performance is that it reduces energy expenditure by enhancing elastic energy storage and return in the *Achilles* tendon and calf muscles.

- *It is reasonable to suggest that inflexibility around the ankle joint would result in a greater relative stretch of the tight muscles and tendons, storing more elastic energy for subsequent recoil and reducing the active work of the muscles* (p. 6).

- *Musculoskeletal tightness can also explain the beneficial effects of limited hip/trunk flexibility . . . Limited external hip rotation could enhance running economy by stabilizing the pelvic region at the time of foot impact. Since running occurs primarily in a forward direction, rotational motion is potentially energy-wasting as it does not contribute to forward movement* (p. 6).
- *There is a cut-off point where inflexibility ceases to be tightness within a normal range of motion and becomes excessive to the point of increasing injury risk. Clinically, excessive muscle tightness is believed to be an important cause of such injuries as muscle strains and inflammation of tendons* (p. 6).

The implication from this work was: ". . . *while general stretching, designed to maintain existing levels of flexibility and muscle function, should remain an important aspect of every runner's warm-up and cool-down routines, improving flexibility beyond levels normal* [natural] *for runners is likely to impair rather than improve performance*" (p. 6).

The above references strongly support the recommendation that long-distance sub-maximal runs or stationary biking of any type should not be part of the training program for any intermittent-sprint sport athletes. Unlike long distance runners or cyclists, team-sport members have a myriad of explosive/maximal ballistic and agility movements that require the capacity of the soft tissues to move through the activities which take them through excursions and contractions that require optimal stiffness to generate maximum elasticity. The athletes considered in this paper need soft tissues that can adapt to different demands of movement intensity to perform well and avoid injury.

In the section on abusive stretching presented above, possible injuries to the hip and pelvic region were hypothesized. In Australian Rules Football, the increasing incidence of *osteitis pubis* and hamstring strains have been reported as two of the three most common injuries in the sport (Verral, Esterman, & Hewett, 2014). *Osteitis pubis* is an inflammation of the pubic symphysis and surrounding muscle insertions (Goitz, 2015). In some individuals, excessive kicking, particularly with punting, emphasizing a very high follow-through with the kicking leg, is likely to predispose an athlete to *osteitis pubis*. It is possible that excessive or dangerous stretching exercises as well as abusive protocols and auxiliary strength-training could have increased the occurrence of the two injuries. It behooves every coach and sporting organization to ensure that the total of all auxiliary training activities is not excessive in any way.

The above two examples from different activities are provided to promote the proposition for flexibility and stretching work in sports: *Only achieve to a level that will benefit sporting performance which often means a non-maximal range of movement in the targeted joints.*

In an attempt to clarify this confusing topic, the following are recommended principles for use when considering doing sane stretching of the hamstrings and coordinated muscles in high-intensity locomotor movements.

- Do not perform any stretching activities that stress the joint tissues or structures.
- Do no exercises that bounce or force a joint beyond a natural range of movement (the *"voluntary stretching limit"*).
- Only use a partner for stretching activities if the partner is knowledgeable about and adheres to the correct execution of 3S-PNF stretching.

- Moderate-speed stretching should follow a physical warm-up but precede any skilled and intensity-specific activities. [3S-PNF stretching has been shown consistently to be the only protocol that produces beneficial effects. Coaches should be wary of individuals promoting any other form of stretching.]
- No stretched position should be held other than in the correct 3S-PNF procedure.
- Once specific game-preparations begin after a warm-up, no further formal and deliberate stretching should be performed. The stretching of soft tissues should be achieved through cautious athlete-directed activities that are performed to meet the particular needs of the moment.
- If any stretching produces pain or *DOMS* that keeps returning after each stretching session, cease that form of stretching.
- A well-planned warm-up involving some performance-intensity executions of sport-relevant skills has more potential for positively influencing a performance than any stretching protocol.
- When dynamic stretching is compared to static stretching it is both more beneficial and effective for ensuing performances and performance factors.

Just what is the dividing line between sane and abusive stretching has not been defined. One could speculate that it occurs when a sane procedure is altered by the introduction of one or more dangerous practices. As was developed throughout this topic, sane stretching procedures that involve static holding propose the length of the hold should be ~6 seconds (as in 3S-PNF). In most recent studies that do not support flexibility benefits for athletic endeavors, the introduction of holds of ~30 seconds are likely to be excessive and could be one cause of negative results. Because of this lack of clarity, the best direction that can be offered is to follow the original procedures of 3S-PNF for formal stretching as well as letting athletes stretch themselves using controlled (safe) dynamic stretching in which they have confidence and are comfortable.

Conclusions about Stretching

The case has been made for there being three distinct forms of flexibility/stretching work. All have unique muscle-involvement qualities, procedures for implementation, and use-outcomes. To talk of *"stretching"* in general, that is the three forms are combined as if they had very much in common, is now nonsensical. To speak of *"stretching"* is but a dogmatic general expression of a lack of understanding of what has been attempted to be shown in this paper. 3S-PNF is so different to dynamic and static stretching that one should expect different results from its use to that which occurs with the other forms. Well-controlled and defined research results should produce different findings to those of dynamic and static stretching investigations. As well, dynamic stretching is also very different to static stretching and 3S-PNF. It too should be considered a distinct exercise that has little in common with the other two forms. Unfortunately, PNF research is much less voluminous than that which exists for dynamic and static stretching. Thus, knowledge of its use and results is less expansive than that of the others. Despite having made the point of treating the three forms of stretching as distinctly different exercises, the three forms have one feature that is common; they all increase the ROM of the muscles/joints stretched. As well, they all could be used in injury or surgical rehabilitation recognizing the differences between them.

3S-PNF and dynamic stretching are different and have useful effects in different settings. For sports, static stretching would seem to have the least, if not no utility for athletes. The consistent finding that static stretching weakens the generation of force and appearance of strength in the exercised muscles clashes with most sport training endeavors that aim for continual performance improvement. An activity that causes performance potential to regress seems inappropriate for exercise activities. Between 3S-PNF and dynamic stretching, it should be possible to achieve what might be hoped for from static stretching. Essentially, it is recommended that 3S-PNF be the primary stretching form for fostering flexibility. When it is not possible to have a partner or an appropriate aid that substitutes for a PNF-partner's role, controlled dynamic-stretching should be used.

Practical Implications for Flexibility/stretching Work

a) Athlete-controlled dynamic stretching is likely to be the most frequently used form of stretching work. In the execution of exercises, the athlete should never exceed an 80-90% level of discomfort. Dynamic exercises should only occur in free-standing mode; not against an object, with equipment, or with the help of a *"facilitating"* partner.

b) No force-increasing partner activities should ever be performed. Added power has the potential to force a joint beyond natural voluntary limitations into an unnatural position that damages the structural tissues with agitations and/or tears that range from micro- to macro-severity. Excessive forced-stretching is likely to damage the soft and structural tissues of the hamstrings toward the origins of the muscles [as seen by the unconscious placement of the right hand of the athlete in Figure 4]. The only partner activity that can be tolerated is 3S-PNF stretching where the partner's role is one of producing movement obstruction, rather than adding any movement force.

c) No stretching exercise should be held for any longer than ~6 seconds. Longer holds reduce the elastic contractile properties of the muscles and their supportive structures in an exercise. As well, if a muscle's soft and/or structural tissues are already damaged, an excessive hold will exacerbate the injury.

d) There should be no dedicated hamstring-stretching. The function of the hamstrings occurs in a relatively restricted range performing a variety of roles/functions. At no time, are the hamstrings unnaturally stretched in the normal activities of field games. If an athlete were to be subjected to an excessive range of movement through collisions or other athletes piling-on to affect a player-stop or tackle, it is likely that other muscles would be damaged before the hamstrings.

e) Hamstring injuries are most likely to occur during a maximal exertion attempting a fast action. Such injuries can be reduced in their likelihood of occurrence by retaining a warmed-state in the muscles in games and at practices and having frequently attempted excessive movement speeds at practices.

f) The trained state of the hamstrings reaches a ceiling-level (the state of maximal adaptation) usually after a period of time that is much shorter than a whole competitive season. Consequently, pre-season and early-season practices should involve *change-training* which should then morph into *maintenance-training* for the rest of the season once peak fitness is attained (Rushall & Pyke, 1991).

g) No matter what the trained state of the hamstrings is in an athlete, change-training should cease about one month before play-offs and maintenance-training instituted so that the injury potential of an athlete produced by inappropriate conditioning will be minimized.

The principal message from this presentation is that hamstring injuries will occur as much from excessive and/or over-zealous isolated muscle strengthening and flexibility work as would occur from too little training stimulation. The benefits of auxiliary training for an athlete's health, fitness, and injury-prevention are greatly overstated. The *Principle of Specificity,* as it applies to practicing and conditioning is supported by respectable research which implies that the value of auxiliary training is largely exaggerated and steeped in dogma. Excessive auxiliary training for strength and flexibility will inflate the potential for injuries rather than performance enhancement. That is particularly so for the muscles of the hamstring group.

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