LEADING ARTICLE

Sports Med. 1997 Nov; 24 (5): 289-299
0112-1642/97/0011-0298/$05.50/0

Flexibility and Its Effects on Sports Injury and Performance

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Summary

Flexibility measures can be static [end of ROM (range of motion)], dynamic-passive (stiffness/compliance) or dynamic-active (muscle contracted, stiffness/compliance). Dynamic measures of flexibility are less dependent on patient discomfort and are more objective. Acute and chronic changes in flexibility are likely to occur with stretching exercises, but it is difficult to distinguish between changes in stretch tolerance as opposed to changes in muscle stiffness. How flexibility is measured impacts these findings. There is no scientifically based prescription for flexibility training and no conclusive statements can be made about the relationship of flexibility to athletic injury.

The literature reports opposing findings from different samples, frequently does not distinguish between strain, sprain and overuse injury, and rarely uses the proper denominator of exposure.There is basic scientific evidence to suggest that active warm-up may be protective against muscle strain injury but clinical research is equivocal on this point. Typically, specific flexibility patterns are associated with specific sports and even positions within sports. The relationship of flexibility to athletic performance is likely to be sport-dependent. Decreased flexibility has been associated with increased in-line running and walking economy. Increased stiffness may be associated with increased isometric and concentric force generation, and muscle energy storage may be best manifested by closely matching muscle stiffness to the frequency of movement in stretch-shorten type contractions.

Flexibility is an area of sport concerning which every athlete, sports physician, therapist, trainer and scientist has an opinion. Divergent views on the importance of flexibility in injury and athletic performance are the rule. In part, debates about flexibility result from lack of consensual definitions and measurements and lack of scientific understanding about determinants of flexibility. This paper simplifies fundamental concepts about flexibility and its measurement, highlighting issues where we still lack definitive research.

1. The Definition of Flexibility

Measures of flexibility are performed to assess the ability of skeletal muscle and tendon to lengthen. Flexibility can be both static and dynamic.[1] Static flexibility is defined as the range of motion (ROM) available to a joint or series of joints. Typically, static flexibility measures are performed when the athlete is instructed to relax. Static flexibility should not be confused with joint laxity which is a function of the joint capsule and ligaments. However,

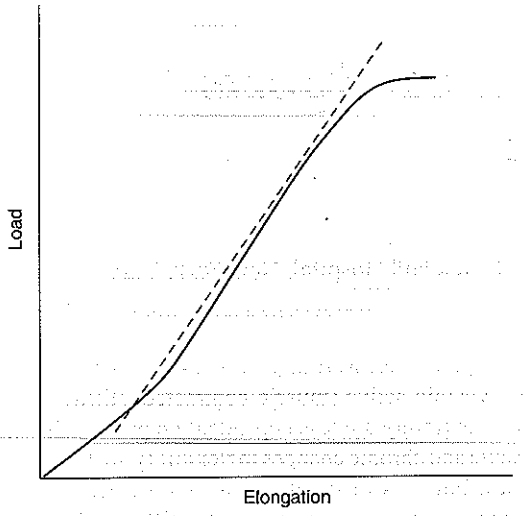

Fig. 1. A load elongation-curve, typical of the response of skeletal muscle to an applied stretch *in vivo*. The stiffness of the muscle is defined as the slope of the line of the linear portion of the curve. The stiffer the muscle, the steeper the line.

it is sometimes difficult to distinguish between a reduced ROM caused by a short muscle versus a tight joint capsule or arthritic joint.

Similarly, hyperextension requires an easily lengthened muscle and a lax capsular/ligamentous structure. Dynamic flexibility refers to the ease of movement within the obtainable ROM. The important measurement in dynamic flexibility is stiffness, a mechanical term defined as the resistance of a structure to deformation.[2] The converse of stiffness is compliance. Stiffness is measured by defining the slope of the load-elongation curve of a material (fig. 1).

2. Flexibility Measurement

Static flexibility can be measured by a number of tests. A classic test of flexibility is the toe-touch or its gravity-unassisted analogue, the sit-and-reach. These tend to be reliable measures[3,4] and are indicative of vertebral and hip flexion extensibility but may be influenced by anthropometric factors.[5] Goniometers measure ROM and also provide a continuous level variable for flexibility. Alternatively, categorical level measures (e.g. loose, normal, tight) can also be applied to the end of ROM movements such as the lotus position or Ober test.[6-8] These scores can be summed to arrive at a total body flexibility score or viewed individually for the joints tested.

Dynamic flexibility (stiffness) can be measured either actively or passively. Passive stiffness is documented by quantifying joint angle at the same time as passive torque generation. The curve generated is in essence a force *vs* deformation curve and the slope of the curve at any point in that ROM is the stiffness.[9-11] We have recently demonstrated that stiffness during the central portion of the ROM is related to terminal ROM measurement across individuals of varying flexibility ($r = -0.91$).[11] The ability to transiently deform contracted muscle describes a term we are calling active stiffness. Active stiffness is measured by the damped oscillation technique when a nearly instantaneous load is applied to a previously contracted muscle and the damped force versus time is plotted (fig. 2).

Cavagna[12] obtained a stiffness measurement comparable to the series elastic elements of an isolated muscle by applying this technique. Wilson et al.[13] have used this technique most recently and demonstrated a significant correlation with static flexibility measures ($r = -0.544$).

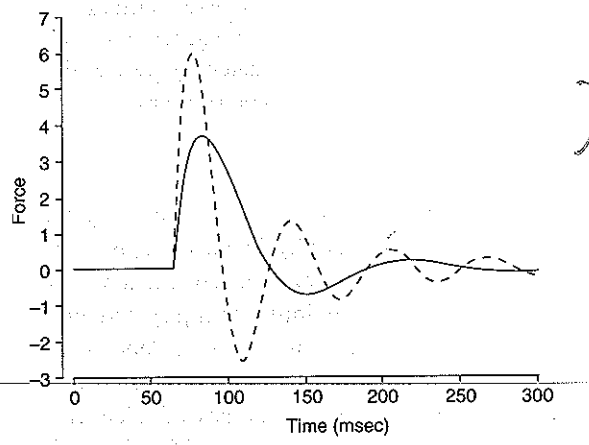

Fig. 2. A representation of the damped oscillation response of 2 systems to an instantaneous compressive force. A stiffer system (broken line) will a allow greater initial force transmission (typically measured on a force plate) and will oscillate at a higher frequency.

3. Adaptations in Flexibility

3.1 Acute Adaptations

The goal of a nearly universally practised preparticipation stretching exercise is to increase muscle and joint pliability before undergoing strenuous exercise. Acute adaptations to passive stretch can be explained by the viscoelastic response of muscle to tensile stress. When human muscle *in vivo* is held in a stretched position (static stretch) the passive tension in the muscle declines over time.[14] This is referred to as viscoelastic stress relaxation. Repeated static stretching results in decreased passive stiffness and attenuation of the stress relaxation response.[15] Baseline stiffness is restored in less than 1 hour. Exercise may have similar effects on muscle stiffness.

Safran et al.[16] has shown in an *ex vivo* animal model that repeated submaximal contractions can decrease passive stiffness and provide protection against external mechanical strain injury. It is unknown whether low intensity warm-up offers similar protection against muscle strain injury in human skeletal muscle *in vivo*.

3.2 Chronic Adaptations

Although flexibility is regarded as an integral component of fitness,[17] training adaptations are not well understood. Static flexibility measurements are commonly used to document chronic adaptations in flexibility.[18-21] A chronic increase in ROM is regarded as synonymous with decreased tissue stiffness.[22] However, only a few studies have examined changes in passive stiffness following a stretching programme.

Toft et al.[23] found a 36% decrease in passive tension of the plantar flexors following a 3-week stretching programme. Conversely, Halbertsma and Goeken[24] and Magnusson et al.[25] failed to show any change in hamstring stiffness following longer training periods despite increases in ROM. Improvements in ROM were attributed to improved 'stretch tolerance'. These findings emphasise that an increase in ROM does not necessarily equate to a decrease in passive stiffness of muscle. While hamstring flexibility training may not decrease stiffness, hamstring strength training has been shown to increase stiffness.

Klinge et al.[26] demonstrated that a 43% increase in isometric strength was associated with a 25% increase in passive stiffness. The increased hamstring stiffness was not counteracted by simultaneous flexibility training although ROM changes were not reported. Increased muscle and joint stiffness is also associated with disuse atrophy. Animal studies have shown that immobilisation results in muscle atrophy and increased intramuscular connective tissue.[27]

Additionally, Gillette and Fell[28] have demonstrated increased muscle and joint stiffness in rats following 2 weeks of limb suspension. The changes in stiffness were shown to be reversible by 2 weeks of weight bearing. Similar effects have not been studied in humans following immobilisation or decreased weight bearing. Although age-related decreases in flexibility are clinically obvious, such changes have not been studied extensively. Aging effects on flexibility may be manifest at a relatively early age. Decreased static flexibility has been demonstrated in soccer players aged in their thirties compared with younger players.[29] Alternatively, in aging active tennis players, shoulder flexibility was shown to be maintained.[30] Flexibility training of older adults has been shown to increase static flexibility.[31] We are unaware of any studies examining changes in dynamic flexibility with aging.

4. Flexibility and Injury

Epidemiology of sports injury is a topic of vast interest, but causal relationships are extremely difficult to discern from the available literature. The field is complicated by the unquestionable role that chance plays in acute injury. Nevertheless, many experts in sports medicine believe that flexibility plays a role in injuries, be they strains, sprains or overuse injuries. Finally, the relationship of dynamic flexibility to injury has never been investigated.

Table I. Studies of flexibility, stretching and injury

Reference	Sample	n	Injury type	Relationship	Problems
Nicholas[6]	Pro US football players	139	Knee ligament	72% of players rated as loose injured ligaments	Exposure?
Liemohn[39]	College track and field athletes	27M	Hamstring strain	More injury in athletes with 4° less hip flexion	No statistics performed, exposure?
Kirby et al.[40]	Young gymnasts	60F	All types	Greater toe-touching ability had more low back pain	Retrospective, exposure?
Ekstrand & Gillquist[41]	Senior soccer players	180M	All types	No relationship	Retrospective, exposure?
Ekstrand et al.[36]	Senior soccer players	180M	All types, but divided into types for analysis	Intervention had fewer injuries ($p < 0.001$)	Multiple interventions not just stretching
Ekstrand & Gillquist[38]	Senior soccer players	180M	All types, but divided into types for analysis	Tight had more groin strain and tendinitis ($p < 0.05$), no relation to hamstring strains	Temporally same as above study, same group as intervention study?
Clement et al.[42]	Runners	109 M&F	Achilles tendinitis	'Insufficient' strength and flexibility in triceps surae	Examined only cases, retrospective
Jacobs & Berson[43]	Runners	451 M&F	All types	'Stretchers' injured more ($p < 0.025$)	Retrospective, exposure?
Reid et al.[44]	Senior ballerinas	30	Lateral hip and knee 'pain and snapping'	More symptoms had reduced hip adduction ROM ($p < 0.05$)	Retrospective, exposure? Other flexibility negative
Giladi et al.[45]	Infantry recruits	295M	Stress fractures	More fractures in recruits with ≥65° hip extension rotation ($p < 0.01$)	Retroversion *vs* flexibility or laxity
Weber & Baumann[46]	First division soccer players	95M	Knee 'complaints'	Higher percentage with complaints had contracture, NS	Retrospective, exposure?
Knapik et al.[47]	College athletes	138F	All types	Flexibility imbalance in hip, right *vs* left; more injury	Relation to all types of injury, exposure?
Jones et al.[48]	Basic army trainees	303M	Lower extremity	Both high and low flexibility associated with injury	Relation to all types of injury
Hennessy & Watson [49]	Rugby players, Gaelic and hurling athletes	34M	Hamstring strain	No relationship to flexibility	Retrospective, exposure?
van Mechelen et al.[37]	Runners	326M	Running injuries	No difference between stretching group and no stretching group	Relation to all types of injuries
Maffulli et al.[50]	Child athletes	453	All types	Flexibility unrelated to injury	All types of injury, exposure? Mixed sports, low rates
Krivickas and Feinberg[51]	College athletes	201 M&F	All types	Tighter injured more in males only	All types, mixed sports, exposure?
Wiesler et al.[52]	Dancers	170 M&F	Lower extremity	Ankle ROM unrelated to injury	All types of injury, exposure?

Abbreviations and symbol: F = females; M = males; n = number of study participants; ROM = range of motion; ? = uncertain or not measured.

4.1 Epidemiological Studies

Perhaps the most ubiquitous notion is that tight muscles are more likely to be strained,[32,33] but most studies frequently fall short of addressing real exposure and are often retrospective. One study has stated that stretching prevents injury[34] while a prior review stated that there was no clear relationship between flexibility and hamstring injury.[35] Also, the demands of different sports vary considerably, and it is possible that flexibility patterns which represent risk factors for one sport may not do so for another.

Prospective studies that have demonstrated significant changes in flexibility concurrent with significant reductions in injury do not seem to exist. Such relationships can only be proven by large scale interventional studies enrolling thousands of

participants, thus providing adequate statistical power to observe low rates of injury and adjust for exposure. A summary of cohort studies that have examined the relationship of flexibility and injury is provided in table I. Two studies included in table I are in fact interventional, experimental studies[36,37] examining injuries in soccer players and runners, respectively, and arriving at opposite conclusions.

The second report by Ekstrand and Gillquist[38] which was done over the same time period as the interventional study, found that tightness was associated with more groin strains and tendinitis ($p < 0.05$) but was unrelated to hamstring strains. Most studies were not designed to measure exposure in the denominator.

Studies in army recruits suffer less from this problem, assuming that everyone has to do the same drills. In many studies, the participants are grouped into injured or noninjured categories. Such grouping may obscure real effects which may promote one type of injury (e.g. sprains) while preventing another (e.g. strains). Retrospective studies are always tainted by the strong possibility of selection bias.

In summary, we see no strong evidence proving that flexibility or stretching is associated with rates of strains, sprains or overuse injuries that can be applied across all sports or levels of competition. Sports injury is a multifactorial problem resulting from as yet undefined interactions between physiological, psychological, environmental and random factors. Without adjusting for these unknown interactions in large studies, we may never know the true relationship between flexibility and injury.

4.2 Basic Science of Flexibility and Injury

This section will deal exclusively with strain injury to muscle-tendon units. Controlled muscle strain injuries have been studied extensively in animal models.[53-62] Most of this work has focused on the mechanical failure properties of skeletal muscle[53,55,56,58,60,61] which is clinically analogous to a grade 3 muscle strain (complete disruption of the muscle tendon unit). However, most muscle strain injuries incurred during athletics are grade 1 and 2 injuries (partial tears). Nondisruptive controlled strain injuries have been studied on a more limited basis in the animal model.[54,57,59,62]

4.2.1 Failure Properties of Skeletal Muscle

Factors such as level of muscle activation,[53,58] active warm-up,[60] passive warm-up,[61] muscle temperature,[58] stretch rate,[56,58] muscle fatigue,[56] fibre type,[55] endurance training[55] and age[55] have been examined (table II). Although the epidemiological research remains controversial, there continues to be an assumed relationship between muscle tightness and risk for strain injury.[63,64] The clinical assumption is that a more compliant muscle (lower stiffness) can be stretched further (higher ultimate strain) and is therefore less susceptible to strain injury. There is some evidence for this in the animal model, in terms of active warm-up.[60]

Table II. Factors affecting mechanical properties of skeletal muscle

Factor	Force to failure	Length to failure	Energy absorbed	Reference
Muscle contraction	↑	No change	↑	53, 58
Active warm-up	↑	↑	Not measured	60
Passive warm-up	No change	↑	No change	61
Cold muscle	↑	No change (slight decrease)	↑	58
Stretch rate	No change (slight increase)	No change	No change	56, 58
Fatigue	↓	No change	↓	56
Fibre type	Slow > fast	No difference	Not measured	55
Endurance training	↑	↓	Not measured	55
Age	↑ (small)	↓	Not measured	55

Symbols: ↑ = increase; ↓ = decrease.

Safran et al.[60] demonstrated that preconditioning the muscle with submaximal contractions (active warm-up) decreases passive stiffness and increases the force and length at which the muscle fails. In contrast, a fatigued muscle fails at a lower force.[56] These findings provide a scientific basis for low intensity warm-up exercises and support the opinion that fatigued muscles are more susceptible to strain injury. While a direct comparison was not made, Kovanen and Suominen[55] showed that muscles with a high proportion of fast twitch fibres have lower stiffness and lower ultimate tensile strength, yet fail at a similar strain to predominantly slow twitch muscles. This supports the clinical finding that bi-articular muscles, which are predominantly fast twitch, are more prone to strain injuries.[65] Similarly, a decrease in failure strain with aging[55] suggests that older athletes may be at increased risk for muscle strain injury.

Interestingly, endurance training increased the stiffness and the ultimate tensile strength but decreased the ultimate strain of slow twitch muscles. Interpretation of the effects of muscle activation[53,58] and muscle temperature[58] is somewhat confusing. The ability of electrically stimulated muscle to absorb more energy prior to failure was interpreted as a protective effect.[53] A more recent investigation from the same laboratory demonstrated that warm muscle (40°C) absorbed less energy than cold muscle (25°C) prior to failure.[58] The authors conclude that 'warming muscles can aid in injury prevention and improvement in athletic performance'. In published discussion of the article, Andrish[58] points to the apparent inconsistency of interpretation of the relevance of the data from these 2 studies and we agree with his conclusion.

4.2.2 Nondisruptive Muscle Strain Injury

Nondisruptive muscle strain injury (grade 1 and 2 strains) is a more common clinical entity than complete disruption (grade 3 strain). Mechanical and contractile properties of muscle following nondisruptive strain injury have been studied in the animal model.[54,57,59,62] It is apparent that impaired contractile function precedes disruption of the mechanical properties.[54,57,59,62] Passive strain to 30% of failure load[59] and active strain to 80% of failure load[54] have been shown to reduce maximal isometric contractile function by 20 and 45% respectively. However, despite profound contractile impairment, mechanical properties (failure strain, failure load and energy absorbed) were unaffected. This suggests that the connective tissue component in skeletal muscle acts more in parallel with, than in series with, the contractile component. Only when active muscle was strained to 90% of failure load were mechanical properties compromised.[54]

Nikolaou et al.[57] demonstrated that contractile function was restored 7 days following controlled strain injury in rabbits despite significant intramuscular scar formation. It has been suggested that following functional recovery the contractile properties may be more susceptible to re-injury if muscle fibre alignment is disrupted by scar tissue.[57,66,67] This may, in part, explain the high rate of recurrence of muscle strains.[68]

4.2.3 Flexibility in Treatment of Muscle Strains

Restoration of strength and flexibility are thought to be important in rehabilitating the athlete following muscle strain injury.[33,69] Inadequate rehabilitation has been cited as a primary factor in the recurrence of hamstring strains.[69] Fibrotic tissue and intramuscular calcifications identified by radiographic imaging have also been implicated in the recurrence of muscle strains.[66,67] While strength measurements may provide some indication of functional recovery, static flexibility measures do not provide any indication of the mechanical properties of the tissue.

The abnormal tissue repair identified by Garrett et al.[66] and Speer et al.[67] may affect viscoelastic properties. Dynamic stiffness measures may provide an indication of altered mechanical properties in previously strained muscle. Flexibility exercises are an integral part of the treatment of muscle strain injuries.[33] ROM may be limited by pain in the acute phase. Early passive stretching may be beneficial in preventing fibre adhesions and restoring collagen alignment.[64] It is not known if tissue

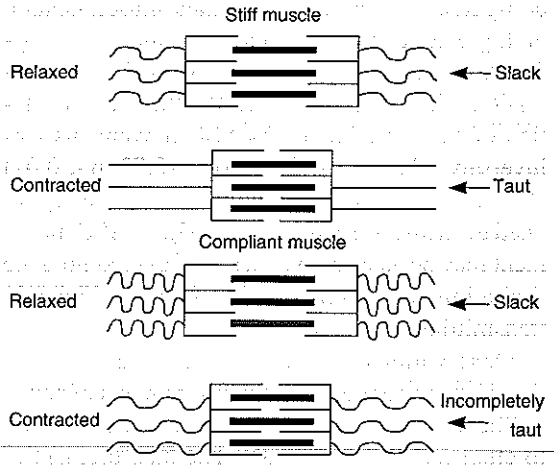

Fig. 3. A theoretical model of sarcomere shortening in a stiff muscle versus a compliant muscle. When the sarcomere is relaxed the series elastic component is on slack (wavy lines). Contraction causes sarcomere shortening and elongation of the series elastic component. The series elastic component must be taut before external force transmission is detected. For the same degree of sarcomere shortening the series elastic component will be taut in the stiff muscle while there will be remaining slack in the compliant muscle. In the compliant muscle greater sarcomere shortening must occur before the series elastic component is taut. This results in delayed force transmission.

stiffness is altered following muscle strain injury or if stretching exercises can impact tissue stiffness.

5. Flexibility and Performance

5.1 Flexibility Profiles in Sport

Even a novice sports fan can appreciate that significant differences exist between athletes of different sports with respect to attainable ROM. Female gymnasts manifest such dramatic ROM in many movements that a non-gymnast would almost certainly be injured attaining the same joint angles. Flexibility patterns are likely to be both inherent and trained, but the relative contribution of these factors is difficult to assess and may never be known with athletes beginning training at younger ages.

By profiling sports, we can look closely at factors which are homogeneous within competitors of that sport, and these observations do not distinguish between the sport causing the attribute or successful participation in the sport being the result of the attribute. Within the population of professional American football players, lineman differ from other positions in having less flexible upper extremities.[7] Goalkeepers in soccer have increased flexibility compared to all other positions[70] who as a whole were tighter than the non-soccer population, although this is not a universal observation.[71]

Increased flexibility in the ankles and shoulders has been noted in swimmers[72] compared with other collegiate athletes, and Olympic swimmers had even greater ankle flexibility than college swimmers. Professional baseball pitchers manifested increased external rotation and decreased internal rotation of the throwing shoulder both compared with their own non-dominant arm and the dominant arm of a control population.[73] In a cross-sectional study of soccer players of differing ages (range 15 years), older players had less flexibility in lumbar flexion and hip rotation than younger players.[29]

5.2 Flexibility and Utilisation of Elastic Energy

The importance of elastic potential energy in muscle during exercise is well recognised. Cavagna[12] estimated that 50 to 70% of the external work performed in level running comes from stored mechanical energy in the elastic structures of muscle. In a study of rapid small amplitude jumping, elastic energy stored in contracted calf muscles upon landing from a jump was estimated to contribute 60% of the positive work for the next jump.[74] The ability to store and subsequently utilise elastic energy is a function of the compliance or stiffness of the muscles and tendons.

Shorten[75] has stated that the amount of energy stored by stretching is equal to the product of elastic stiffness and the square of the stretch distance. The use of elastic potential energy has been studied more recently with respect to stretch-shortening cycle (SSC) movements. SSC describes the use of an eccentric muscle contraction to enhance a subsequent explosive concentric contraction.[75,76] For example, a vertical jump is clearly enhanced by

lowering the body immediately prior to the jump (counter movement jump).[77-79] This action involves eccentric loading of the knee extensors and plantar flexors immediately prior to explosive concentric contractions of these muscle groups.

SSC movements are common to most dynamic sports such as a jump ball in basketball, or spike and block jumping in volleyball. Several authors have suggested that greater force production with SSC movement is a function of improved utilisation of stored elastic energy.[75-78,80,81] The role of muscle stiffness in SSC force production has been examined.[80,81] Wilson et al.[80] demonstrated that augmentation of force production, and speed of force production, with SSC compared with purely concentric contractions, was inversely related to active stiffness. Similarly, flexibility training has been shown to decrease active stiffness and improve SSC performance.[81] In accordance with Shorten's theory,[75] these effects were specifically attributed to increased utilisation of elastic strain energy in the more compliant muscle-tendon unit.

Wilson et al.[80] have suggested that the benefit of SSC movement is related to matching the natural frequency of resonant compliance to the movement frequency. Thus, with bench press movement performed at relatively slow velocity, the elastic rebound from eccentric loading may be better matched to the actual speed of movement in the more compliant muscles.[80] Based on this theory, the optimal stiffness for SSC movement may depend on the amplitude and natural frequency of a specific movement or series of movements. The benefits of a compliant system for SSC performance are in contrast to the role of muscle stiffness in isolated isometric and concentric contractions. Active stiffness has been shown to be positively related to isometric force production ($r = 0.63$, $p < 0.05$), rate of isometric force production ($r = 0.78$, $p < 0.01$) and rate of concentric force production ($r = 0.65$, $p < 0.05$).[82] These relationships are explained by a more efficient transmission of contractile force in the stiffer muscle-tendon unit.

Before contractile force is transmitted to the joint, the slack in the series elastic component must be tightened. In a more compliant muscle-tendon unit, greater contractile shortening must occur before tension development and external force generation will be delayed (fig. 3). While augmentation of force production by SSC movements was inversely related to stiffness ($r = -0.72$, $p < 0.01$) absolute SSC force production was positively related to stiffness ($r = 0.71$, $p < 0.05$).[80] SSC movement may be an effective means of overcoming the limitations of a compliant muscle in efficiently transmitting contractile forces.

Observations on stiffness and muscle function[12,74,80,81] are based on measurements of active stiffness. Perturbations of active muscle are known to elicit reflex responses.[83] The measurement of active stiffness involves perturbation of active muscle and therefore should elicit a reflex response. It is unclear what role reflex contraction plays on the active stiffness measurement. Reflex contraction elicited by tests of active stiffness possibly obscured the constant electromyogram activity of the partially contracted muscles. The potential for reflex augmentation of contractile responses with SSC movements seems obvious.

Recently, Bobbert et al.[77] were unable to find direct evidence for this. Clinically, assessment of flexibility is generally based on passive measurements of static flexibility. Musculoskeletal 'tightness', based on static flexibility measurements, has been shown to be correlated to concentric strength measurements in professional American footballers ($r = 0.345$, $p = 0.02$),[7] supporting the idea that a stiffer muscle provides a more efficient transmission of contractile force production. However, the relationship of passive stiffness to muscle function has not been specifically examined.

5.3 Flexibility in Relation to Sports Performance

As noted above (section 5.2), the role of stiffness and flexibility may be highly dependent on the type of muscle contractions primarily involved in movement. Since profiles of athletes appear to indicate specific flexibility patterns associated both between and within sports, evidence exists that

flexibility must be related to sports performance. Objective, valid measures of performance that stand up to scientific scrutiny are difficult to come by for most team sports. Typically, we are limited to making measures of intermediate performance factors, such as speed, strength and economy in the belief that these are related to sports performance.

Since sports performance, like injury, is multifactorial, it is probably best to limit investigations to the relationships between flexibility and other measurable performance factors. Acute stretching exercises which were enough to produce significant increases in 3 out of 4 ROM exercises in 4 participants were found to have no effect on the oxygen cost or speed of a 100 yard (91.4m) dash.[84]

In examining the relationship of flexibility to walking and running, we chose to use economy (ml O_2/kg/m) as our dependent variable.[8] We were surprised to find that once speeds exceeding normal walking pace (4.8 km/h) were attained, individuals who were 'tightest' in a series of 11 static flexibility measures were also the most economical ($r = 0.433$, $p < 0.00005$). Tight individuals were up to 12% more economical than the most flexible ones. The reasons for this observation, while being purely speculative, are that increased stiffness means less active contraction of auxiliary skeletal muscles (e.g. postural muscles) or perhaps more effective elastic recoil from the previous stride. The former concept gains some credibility from studies of reduced gravity walking and running which demonstrate profoundly greater effects on running than walking.[85] The latter hypothesis gains some credibility from work on 'Groucho running'. Running with the knees in an exaggerated flexed position decreases the vertical stiffness of the body and increases the cost of running.[86]

Most recently, in a homogeneous sample of sub-elite runners, it was shown that less flexible runners were also more economical ($r = 0.53$ to 0.65).[87] What is striking about both studies of running economy and flexibility is the magnitude of the correlations. Few, if any, other predictors of running economy are as highly correlated.

6. Conclusions

Traditional measures of flexibility have been based on attainable end of ROM measurements. Measures of passive and active (with respect to degree of muscle contraction) dynamic stiffness are also possible, and some have correlated moderately to traditional flexibility measures. Basic scientific studies have verified the relationship of musculotendinous stiffness to mechanisms of muscle injury, but clinical studies have yielded conflicting findings about these relationships. No clear relationship can be described between flexibility and injury that is applicable to all sports and levels of play. While increased flexibility is important for performance in some sports that rely on extremes of motion for movement, decreased flexibility may actually increase economy of movement in sports which use only the mid portion of ROM. Future studies must distinguish between measures of flexibility and stiffness, with careful definitions of injury and exposure, and validated indices of performance.

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