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Acute Effects of Passive Muscle Stretching on the Stretch-Shortening Phenomenon.

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ACUTE EFFECTS OF PASSIVE MUSCLE STRETCHING
ON THE STRETCH-SHORTENING PHENOMENON

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

The Department of Kinesiology

by

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Abstract

Two experiments examined the acute effects of passive muscle stretching on the performance of a skill (vertical jump) which takes advantage of the stretch-shortening phenomenon. Because recent work suggests that passive stretching might impede the mechanisms (elastic and myoelectrical potentiation) thought to be responsible for this phenomenon, it was hypothesized that stretching would decrease the jump height of jumps executed with a preparatory countermovement (CMJ), but not the jump height of those initiated from a static, squatting position (SJ). In the first experiment, subjects performed CMJ and SJ jumps under two different conditions: after passively stretching the knee and hip extensors, and after 10 minutes of quiet sitting. As predicted, stretching induced a significant decrease (p<.05) in jump height for the CMJ; however, a similar decrease (p<.05) also occurred for the SJ. These results suggest that the influence of acute stretching on performance is not limited to skills which incorporate a stretch-shortening cycle, and that stretching does not necessarily impede the factors purported to be responsible for the stretch-shortening phenomenon. Experiment 2 sought to explicate the reasons why an acute bout of passive stretching can negatively impact jumping performance. Specifically, the aim was to determine if stretching could modify musculotendinous stiffness and/or electrical activity of the plantar flexors during both stretch-shortening movements and movements involving purely concentric contractions. Again, jumps performed with a countermovement were compared to static jumps; however, in order to isolate the plantar flexors, motion was restricted to the ankle joint only. CMJ jump height was compromised after stretching but SJ performance remained unchanged. The decrease in CMJ performance might be partially accounted for by a reduction in elastic potentiation, because a decrease in musculotendinous stiffness was also observed post-stretching. No change in electrical activity occurred between the pre- and post-stretch conditions for the CMJ, suggesting that a decrease in
myoelectrical potentiation did not contribute to the performance decrement. Other potential mechanisms which might have played a role in reducing performance are discussed in addition to possible reasons why the stretching treatment influenced SJ performance differently in the two experiments.
Introduction

The effectiveness and efficiency of human movement may be enhanced if the muscles primarily responsible for the movement are actively stretched immediately prior to contracting concentrically (Alexander, 1988; Bobbert, 1990; Cavagna, Saibene, & Margaria, 1964; Cavagna, Komerek, & Mazzoleni, 1971; Shorten, 1987). This effect is known as the stretch-shortening phenomenon and has been shown to occur in skills such as running, jumping, and throwing. The phenomenon can be explained by considering the mechanical properties of muscle and tendon. Both muscle fiber and tendinous tissue have the ability to store elastic strain energy after being stretched by an external force (Alexander & Bennet-Clark, 1977; Huxley & Simmons, 1971). When the external force is removed, the stored energy is released as the structures recoil back towards their original length. This energy can then be used to supplement that provided by the contractile machinery, thereby enhancing positive work output (Heglund & Cavagna, 1987; De Haan, van Ingen Schenau, Ettema, Huijing, & Lodder, 1989).

The storage and recovery of elastic energy is relatively inexpensive in terms of metabolic cost, therefore the efficiency of positive work production can increase beyond that expected from the transformation of chemical energy into mechanical work. In running, for example, a number of studies (e.g., Asmussen & Bonde-Petersen, 1974; Bosco et al. 1987; Cavagna & Kaneko, 1977; Ito, Komi, Bosco, & Karlson, 1983; Shorten, 1985) have shown the efficiency of positive work output to be between 45 and 55%, whereas the maximum efficiency of concentric metabolic work is commonly acknowledged to be only 25% (Hof, 1990).

In events dependent on power, such as sprinting and jumping, a stretch-shorten movement can also elicit an increase in power output. In sprinting, a sudden increase in power has been observed when an individual approaches maximum speed (Cavagna, Komerek, & Mazzoleni, 1971). This power increase happens to coincide with an
increase in the negative work done in each step, which suggests that a greater stretch and recoil of the elastic elements is partly responsible for the power increase (elastic potentiation). In jumping, power output is substantially increased when a jump is performed with an active pre-stretch rather than jumping from a static position (Bobbert, 1990). Increases in power output have produced greater jump heights; jumps with a countermovement are generally 15 - 20% higher than static jumps (Asmussen & Bonde-Petersen, 1974; Komi & Bosco, 1978).

The degree to which performance can be enhanced depends not only on the quantity of elastic energy that can be stored in the muscle and tendinous tissues, but on the amount of energy that can be recovered for use in the positive work phase. In order to maximize the recovery of stored elastic energy, the coupling time (the length of time between the eccentric and concentric phase) must be minimized (Abbot & Aubert, 1952; Aruin et al., 1979; Bosco, Komi & Ito, 1981; Bosco & Rusco, 1983; Cavagna & Citterio, 1974). Huxley and Simmons (1971) have demonstrated that elastic energy is stored in the cross-bridges when they are actively stretched during an eccentric contraction. If the coupling time is too long, elastic energy may be lost as heat due to the natural detachment of the cross-bridges. Some strain energy is retained in the tendon, but even this is gradually dissipated if the stretch is held too long (Shorten, 1987). Because stored elastic energy is rarely fully recovered during the concentric phase, it is especially important to maximize the storage of elastic energy during an eccentric contraction.

The amount of elastic energy that can be stored in the musculotendinous unit is a function of the unit's stiffness and the extension produced by an imposed force (Shorten, 1987). According to Hooke's law, the amount of energy which is stored in an ideal spring can be represented by the following equation:

\[ E = \frac{1}{2} k x^2 \quad (1) \]
where $E$ = stored elastic energy; $k$ = stiffness of the material; and $x$ is the extension of the material produced by an external force. Although the musculotendinous unit is not an ideal spring in that its stiffness is variable and non-linear (van Ingen Schenau, 1984), the above equation can still be used to illustrate that elastic energy storage can be increased by increasing both the amount of structural deformation and the stiffness of the structure being stretched.

The degree of deformation can be increased by enhancing the stretching force. This may be achieved by increasing the velocity of the pre-stretch. Isolated muscle studies have indicated that an eccentric action potentiates the force that can be generated by each cross-bridge (Cavagna & Citterio, 1974; Cavagna et al., 1985; Edman et al., 1978), and that the amount of potentiation increases with stretching velocity (Edman et al., 1978). Furthermore, lengthening of active muscles has been shown to evoke a stretch reflex (Bosco & Komi, 1979) controlled by muscle spindles. The stretch reflex increases the neurological input to the muscle under stretch, which can increase the force of contraction at the end of the eccentric phase. This mechanism is referred to as myoelectrical potentiation (Bosco, Tarkka, & Komi, 1982) and also increases with the velocity of prestretch (Hamill & Knutzen, 1995). Any increase in myoelectric potentiation, or the force that can be generated by each cross-bridge, results in a greater stretch of the elastic elements and, consequently, a greater amount of elastic energy is stored.

The stiffness of the musculotendinous unit is more difficult to manipulate within an individual. Nevertheless, it is possible that acute stretching exercises, designed to increase joint range of motion, might reduce the stiffness of the musculotendinous unit (Magnusson et al., 1996; Rosenbaum & Hennig, 1995; Taylor et al., 1990). Using a KinCom dynamometer to measure the passive torque provided by the hamstrings during knee extension, Magnusson et al. (1996) found that the stiffness (defined as the change
in torque divided by change in position) of the hamstring muscle group declined over five consecutive static stretches. Similar results have also been demonstrated in vitro by subjecting rabbit extensor digitorum longus and tibialis anterior muscle-tendon units to tensile loads (Taylor et al., 1990). Both these studies however, measured the resistance to stretch under passive conditions (passive stiffness), and not when the muscle was activated. For passive stretching to influence the storage of elastic energy, the stretching treatment must alter the stiffness of the musculotendinous unit under active conditions (active stiffness). Although no study has not yet investigated the effect of passive muscle stretching on active musculotendinous stiffness, work by Rosenbaum and Hennig (1995) suggests that a decrease in stiffness should occur. After investigating the acute effects of stretching the triceps surae on Achilles tendon reflex activity, these investigators found that the passive peak force caused by a tendon tap was significantly reduced following the stretching treatment. The tendon tap was performed with a reflex hammer which was allowed to drop from a pre-determined height so that it delivered a constant impulse on impact with the tendon. The reduction in passive peak force after stretching was interpreted as evidence that the tendon had become more compliant. As muscle transfers contractile force to the skeletal system through tendons, it is reasonable to assume that a more compliant tendon will give rise to a more compliant musculotendinous unit under active conditions. According to Equation 1, it is possible that such a change in the stiffness properties of the unit will reduce the ability of the unit to store elastic energy, and therefore attenuate elastic potentiation. Consequently, the effect of a stretch-shortening movement may be compromised if the movement is performed immediately after a bout of acute stretching.

Rosenbaum and Hennig (1995) also reported that the reflexive peak force and reflexive electromyographic activity of both the gastrocnemius and soleus muscles were diminished when elicited post-stretching. This finding indicates that acute stretching
could possibly reduce the amount of myoelectric potentiation caused by the stretch reflex during stretch-shortening movements. In turn, a decrease in myoelectric potentiation would degrade the effect of a stretch-shorten cycle. Thus, pre-exercise stretching might negatively impact the performance of stretch-shortening skills by impeding two separate mechanisms: elastic and myoelectric potentiation.

Because passive stretching is commonly employed as part of an athlete’s pre-event warm-up procedure, the current pre-event activities of many athletes, therefore, come into question. Even if the stretching portion of a warm-up is completed several minutes before an event, the possible detrimental aspects of stretching might still be present during performance because it has been shown that the effects of stretching on range of motion can last for up to 90 minutes (Moller et al., 1985). A main purpose of this dissertation, therefore, is to establish the effect of acute stretching on the performance of a skill which takes advantage of the stretch-shortening phenomenon. Another concern is to assess the influence of acute stretching on the neuromechanical properties of the musculotendinous unit under active conditions. By monitoring the active stiffness and electrical activity of the unit before and after administering a bout of passive stretching, an attempt is made to identify potential mechanisms which might be responsible for any change in performance as a result of the stretching procedure.

In the first experiment, the consequence of passively stretching the knee and hip extensors on multijoint, vertical jump performance is determined. In particular, jumps performed with (countermovement jump) and without (static jump) a prior eccentric contraction are compared. If both elastic and myoelectric potentiation are diminished by acute stretching, performance in the countermovement jump should decrease, but static jump performance should be unaffected. In the second experiment, the possibility that acute stretching changes the elastic properties and myoelectrical activity of the musculotendinous unit is explored. Again, countermovement jumps are compared to
static jumps; however, instead of multijoint jumping, single-joint jumps are performed using the plantar flexors only. The single-joint technique is employed to simplify the experiment and to control the issue of coordination. A further advantage of confining muscle involvement to the plantar flexors is that a non-invasive technique exists to ascertain the active stiffness of this muscle group (Cavagna, 1970). It is possible, therefore, to determine if acute stretching changes the elastic properties of the musculotendinous unit.

Electromyography (EMG) recordings of the gastrocnemius and soleus muscles are also collected in Experiment 2. From these data, the effect acute stretching has on myoelectric potentiation is determined.

In brief, the dissertation aims to determine whether an acute bout of stretching degrades the performance of a stretch-shortening skill by altering the neuromechanical properties of the musculotendinous unit.
Experiment 1: The Acute Effects of Passive Stretching on Vertical Jump Performance

The degree to which various skills take advantage of the stretch-shortening phenomenon depends upon the movement mechanics of the skill. If the movement first imposes an active stretch on the muscles primarily responsible for creating a desired action, then a favorable situation for the storage and release of elastic energy arises. For example, in jumping movements, upward propulsion is generally preceded with a preparatory countermovement. This acts to forcibly stretch the extensor muscles of the knee joint before they contract concentrically to execute the jump. If the concentric phase immediately follows this eccentric action, elastic and myoelectric potentiation serve to enhance jumping performance (Bosco et al., 1982). It is possible, however, that acute stretching might negatively impact both these mechanisms. Several studies suggest that the musculotendinous unit becomes more compliant as a result of acute static stretching (Magnusson et al., 1996; Rosenbaum & Hennig, 1995; Taylor et al., 1990). Because the amount of elastic energy that can be stored in a structure is proportional to the stiffness of that structure (van Ingen Schenau, 1984), a decrease in musculotendinous stiffness (increase in compliance) could reduce the ability of the unit to store elastic energy. Furthermore, acute static stretching has been shown to diminish the strength of the stretch reflex elicited by a tendon tap (Rosenbaum & Hennig, 1995). Static stretching, therefore, might also reduce myoelectric potentiation by weakening the stretch reflex that occurs as a result of a quick, eccentric contraction. Consequently, jumping performance might be compromised if a bout of stretching exercises are performed immediately prior to engaging in jumping activity.

This experiment investigated the effect of passive stretching on multijoint, vertical jump performance. In particular, jumps performed with a countermovement were compared to jumps performed from a static position. It was hypothesized that, if
acute stretching negatively impacts the mechanisms responsible for the stretch-shortening phenomenon, countermovement jump performance should be compromised but static jump performance should be unaffected.

Method

Subjects

Ten male subjects (age 20.6 ± 2.2 years; height 1.73 ± 0.03 m; mass 69.9 ± 9.8 kg; mean ± SD) enrolled in undergraduate classes in the Department of Kinesiology at Louisiana State University were recruited for participation in this study. Although each subject was physically active and free of injury, none were engaged in any kind of regular physical training program at the time of the study. All subjects provided informed consent prior to taking part in the experiment and the study was approved by the appropriate institutional control committee. The subjects were not informed about the hypotheses of the study.

Task and apparatus

Each subject performed the following types of jump: 1) a static jump which involved no active pre-stretch of the knee and hip extensors. This was initiated from a semi-squatting position and no preparatory countermovement was allowed. 2) a countermovement jump which involved an active pre-stretch of the hip and knee extensors. From an erect position, a downward countermovement was first performed before the whole-body-center-of-gravity was propelled vertically upwards. All the jumps were performed on a force platform (AMTI, Newton, MA) and force data were collected and analyzed with accompanying AMTI software.

Procedures

The subjects made five visits to the laboratory on separate days.

Day 1. The first visit was used as an accommodation session to familiarize the subjects with the testing procedures and to allow the subjects adequate practice to
competently perform both types of jump with maximal effort. In addition, the subjects practiced a technique to control their postural position at the beginning of the positive work phase of each jump.

An attempt was made to control the starting posture for upward propulsion in both the countermovement jump and the static jump so that a fair comparison of jumping performance could be made between jump type and between pre- and post-stretch conditions. This was accomplished with the aid of a goniometer and two stringlines that were strung horizontally at a particular height for each subject. To determine this height, the subject was first asked to assume a comfortable, semi-squatting position on the force platform as if a static jump was going to be performed. Knee joint angle was then measured with a goniometer by the investigator. The subject was then asked to adjust his knee joint angle until an angle of 90 degrees was obtained. The vertical distance from the subject's eyes to floor was then measured and recorded. The process was repeated several times until a consistent height measurement was achieved. Two stringlines, approximately five meters apart, were then strung horizontally at this height between posts positioned in front of the force platform. The stringline closest to the force platform was set a distance of five meters from the platform's front edge. When performing a jump, the subject first positioned himself on the force platform so that his line of sight was perpendicular to the stringlines. The subject then lowered his whole-body-center-of-gravity, by flexing at the knees, until he saw the far stringline disappear behind the near one. At this instant, the subject's eye height had to be the same as that previously recorded with the subject in a semi-squatting position at a 90 degree knee joint angle. If the subject's trunk angle remained consistent, a knee joint angle of 90 degrees would also have been repeated. Subjects were asked to keep their spine straight to help maintain a constant trunk angle.
To perform the static jumps, the subject slowly lowered his body until both stringlines coincided with his line of sight, held this position for approximately three seconds, and then jumped vertically upwards. To perform countermovement jumps, the subject quickly lowered his body until the stringlines were in alignment, and then proceeded to jump vertically upwards without hesitating. Each subject was instructed to minimize the coupling time between the eccentric and concentric phases. In both types of jump, subjects were asked to place their hands on their hips because it has been shown that the contribution of the arms to vertical jump performance can be 10% or more (Luhtanen & Komi, 1978). Although the countermovement jump was much more difficult to perform, all the subjects were able to master the technique during the accommodation session.

To confirm the method of controlling knee joint angle was successful, a pilot study was conducted in which four subjects were videotaped performing both types of jump after 30 minutes of practice. A motion analysis system (Peak Performance Technologies Inc., Denver, CO) was then used to measure knee joint angle at the commencement of the positive work phase. All the subjects were able to consistently perform both the countermovement jump and static jump from knee joint angles which were within a relatively narrow range (90 ± 3 degrees).

Days 2-5. Data were collected on days 2-5. Subjects performed each type of jump after 10 minutes of quiet sitting or immediately after passively stretching the knee and hip extensors. On two of the days, the no-stretch (NS) condition was imposed, while on the other two days, static stretching (SS) was done. The NS and SS days were determined at random with the static jump and countermovement jump order counterbalanced. This allowed each type of jump to be performed first for both the NS and SS conditions. The static and countermovement jumps were performed three times each with approximately 30 seconds in between each repetition. A period of ten minutes
was imposed between the set (three repetitions) of static jumps and the set of
countermovement jumps. To ensure that a stretch-shortening cycle did not occur in the
static jump, the vertical ground reaction force/time curve was examined after each
repetition. If the force dropped below body weight at the start of the jump, then the
particular trial was discarded and the jump repeated. The subjects were instructed to
jump as high as possible in all trials, and were not informed of how high they jumped.

Stretching protocol. Stretching activity consisted of three different static
stretching exercises designed to passively stretch the hip and knee extensors. The first
exercise required the subject to lay supine on an examination table with one leg hanging
freely over the side and the other supported by the table. The experimenter then
simultaneously flexed the knee joint and extended the hip joint of the free leg until he
was verbally informed by the subject that the pain threshold had been reached. This
position was held for 10 s after which extra force was applied if the subject informed the
experimenter that he could be stretched further. After another 10 s, a third stretching
increment was imposed if it could be tolerated by the subject. If the subject could not be
stretched further after the first or second stretching increment, the position was held until
30 s from the beginning of the exercise had elapsed. The back, buttocks, and the
supported leg were kept firm against the table throughout the exercise. Once the leg had
been stretched for 30 s, the same procedure was repeated for the opposite leg. This
exercise stretched the quadriceps group of muscles, in particular the rectus femoris.

A similar protocol was implemented for the other two exercises. In the second
exercise, the subject lay prone on the table and a padded wooden block, approximately
20 cm in height, was placed underneath the distal end of one thigh, thereby extending
the hip joint. The experimenter then flexed the knee joint of this leg by pushing the heel
of the foot towards the subject’s buttocks. This exercise also stretched the quadriceps
muscle group.
The third and final exercise was performed with the subject supine. With one leg of the subject firmly pressed against the examining table, the experimenter flexed the other leg at the knee and hip joint and pushed the subject’s knee towards his chest. In addition to stretching the knee extensors (quadriceps), this exercise also stretched the extensors of the hip (upper hamstrings and gluteus maximus).

**Data collection and reduction**

For each trial, the output from the force platform was collected and stored in digital form using the AMTI software program (Newton, MA). Data were sampled at 500 Hz for a period of three seconds. The software was used to calculate the following variables from the force/time data: vertical displacement of the whole-body center-of-gravity from the point of take-off (jump height); maximum vertical ground reaction force; and maximum vertical power of the center of gravity. Take-off was defined as the instance when the vertical ground reaction force became zero. The velocity at take-off, determined from a double integration of the force/time curve, was used to calculate jump height. The results were not calculated until completion of data collection.

**Analysis of results**

Initially, the statistical model used to analyze the jumping data was a 2 (Jumping Type) x 2 (Treatment) x 2 (Jump Order) repeated measures ANOVA. However, the Jump Order factor was subsequently removed from the analysis because neither the Jump Order main effects nor any of the interactions related to Jump Order were significant. Hence, all reported parameters are the mean of six measurements (3 trials x 2 days) which were analysed by a 2 (Jumping Type) x 2 (Treatment) repeated measures ANOVA. Fisher’s protected LSD post hoc test was employed to investigate any differences between the pre- and post-stretch conditions indicated by significant main effects or interactions. For all analyses, statistical significance was accepted at an alpha level of 0.05.
Results

Jump height

A significant main effect for Jump Type $F(1, 9) = 28.37, p < 0.001$ was obtained. Post hoc analysis (Fischer’s protected LSD) revealed that static jump height was significantly less than countermovement jump height in both the no-stretch (NS) condition ($14.6 \pm 10.4\%$) and the static stretch (SS) condition ($14.5 \pm 10.8\%$) (see Figure 1). A main effect for Treatment $F(1, 9) = 11.66, p < 0.01$ was also obtained; the stretching treatment caused a significant decrease in jump height for both types of jump. Post hoc analysis showed that static jump height in the SS condition was significantly less ($4.4 \pm 4.1\%$) than in the NS condition. Likewise, the stretching treatment caused a significant decrease ($4.3 \pm 4.1\%$) in countermovement jump height. The Jump Type by Treatment interaction $F(1, 9) = 0.18, p > 0.05$, however, was not significant.

Peak vertical power

A significant main effect was obtained for Jump Type $F(1, 9) = 40.73, p < 0.001$ (see Figure 2). The static jump displayed significantly less peak power than the countermovement jump in both the NS condition ($5.1 \pm 3.1\%$) and the SS condition ($6.0 \pm 3.7\%$). A significant main effect also occurred for Treatment $F(1, 9) = 10.1, p < 0.05$. Peak power in both the static jump and countermovement jump significantly declined ($3.2 \pm 2.9\%$ and $2.17 \pm 2.83\%$ respectively) after stretching. The Jump Type by Treatment interaction $F(1, 9) = 0.88, p > 0.05$ was not significant.

Peak vertical force

The main effect for Jump Type was not significant $F(1, 9) = 2.4, p > 0.05$, conditions (see Figure 3). A main effect was obtained, however, for Treatment $F(1, 9) = 12.09, p < 0.01$. Peak force in both the static jump and countermovement jump
Figure 1. Jump height as a function of jump type and treatment
Figure 2. Peak power as a function of jump type and treatment
Figure 3. Peak force as a function of jump type and treatment
decreased (1.65 ± 1.53% and 2.18 ± 2.62% respectively) significantly after stretching. The interaction Jump Type by Treatment $F(1, 9) = 2.4, p > 0.05$, was not significant.

**Discussion**

The primary question addressed in this study was: Does acute muscle stretching degrade the performance of a skill which takes advantage of the stretch-shortening phenomenon? The findings of several recent investigations (Magnusson et al., 1996; Rosenbaum & Hennig, 1995; Taylor et al., 1990) suggest that acute stretching might inhibit the mechanisms which are thought to be responsible for the stretch-shortening phenomenon; that is, the use of elastic energy and myoelectric potentiation. It was therefore speculated that static stretching exercises, performed immediately prior to executing a vertical jump with a countermovement, would hinder jumping performance. Results showed that jump height, peak vertical ground reaction force, and peak power were reduced significantly after a bout of static stretching for jumps performed with a countermovement. However, similar decrements in performance following stretching exercises were also obtained when jumps were performed without a countermovement (static jumps). In both conditions, static jump height was approximately 14% lower than countermovement jump height. Consequently, the stretch-shortening effect was unaffected by stretching. Thus, although it appears that an acute bout of passive stretching negatively impacts vertical jump performance, it is not possible to conclude that the treatment necessarily impedes the mechanisms which account for the stretch-shortening phenomenon. Nevertheless, the results of this study cannot dismiss the possibility that passive stretching, if performed just prior to executing a movement involving a stretch-shorten cycle, diminishes the amount of stored elastic energy and myoelectric potentiation.
Although one might first assume that some other mechanism was responsible for decreasing performance in both types of jump, it is feasible that the countermovement jump was affected because of the reasons hypothesized (i.e., a decrease in elastic and myoelectric potentiation), and that a separate mechanism caused the decline in static jump performance. Because of the unexpected finding that a similar decrement in static jump performance occurred, other areas of the literature were searched with the intent of assessing whether or not the impact of stretching on the stretch-shortening mechanisms could have been masked by factors the original design did not account for. Evidence that a decrease in musculotendinous stiffness might also hinder static jumping, but for reasons other than impacting the amount of elastic energy that can be stored in the series elastic component, was found. After demonstrating a significant positive relationship between concentric performance in the bench press and active musculotendinous stiffness of the involved musculature, Wilson, Murphy, and Pryor (1994) suggested that a stiff musculotendinous unit might allow the force generated by the contractile component to be transmitted to the skeletal system much more effectively than a compliant unit. The decrease in peak force and peak power in the static jump, therefore, might have been due to a reduced rate of force transmission to the skeletal system through more compliant tendons. Wilson et al. (1994) further suggested that in concentric movements, a stiffer system would allow for an improved force production by the contractile component due to improved length and velocity conditions. Specifically, these researchers stated that at a given state of contraction, a stiffer musculotendinous unit should give rise to a greater length and a decreased shortening velocity of the contractile component, thereby placing the contractile component at a more optimal point on both the force/velocity and force/length curve in terms of force production. This is because there is not as much “slack” in a stiffer system that has to be taken up during the initial part of the contraction. In the present study, therefore, the
stretching treatment might have altered static jump performance by indirectly restricting
the contractile component from operating on the most favorable parts of both the
force/length and force/velocity curves. However, although this speculation is initially
appealing, it becomes less compelling when considered in further detail. The notion that
a greater contractile component length is more optimal really depends on where the
contractile component is on the force/length curve at the start of the concentric phase,
and over what range of the curve it operates during a particular movement. In the static
jump for example, suppose the prime movers are placed on the descending limb of the
force/length curve as the squat position is assumed, then a greater contractile component
length due to a stiffer tendon would not be advantageous. Nevertheless, there are no
data available to disprove the hypothesis that a stiffer unit allows the contractile
component of muscle to operate at a more optimal length and velocity in concentric
contractions. One must recognize, therefore, that the static jump might have been
hindered by such mechanisms if the stretching protocol was successful in reducing the
active musculotendinous stiffness of the knee and hip extensors.

Interestingly, the above speculations regarding the influence of
musculotendinous stiffness on the force/length and force/velocity relationships only
apply to movements produced purely with concentric actions. In other words, the same
effect would not be found if the muscle was actively lengthened prior to the concentric
phase as in a stretch-shorten cycle. This is because the eccentric action serves to take up
the slack in the series elastic component before the muscle has a chance to shorten. A
decrease in stiffness, therefore, would not affect countermovement jump performance
through the same mechanisms as those which might influence static jump performance.
Rather, countermovement jump performance might be hindered by a decreased ability of
the musculotendinous unit to store elastic energy should the unit become more
compliant.
Because of practical limitations, however, it was not possible to measure active stiffness, so it is not known if any change in active stiffness occurred as a result of the stretching treatment. If active stiffness was not reduced by the treatment, some other mechanism(s) would have to account for the decrease in both the countermovement jump and static jump height, and it would be probable that the same mechanism similarly influenced both types of jump.

Potentially, the acute response of muscle and/or joint proprioreceptors (e.g., Golgi tendon organs and low threshold pain receptors) to sustained stretch might be responsible for decreasing performance in both the countermovement and static jumps. Golgi tendon organs respond to stretch or tension by initiating a reflex inhibition (autogenic inhibition) of both the muscle being stretched and its synergists (Alter, 1988; Moore, 1984). Similarly, the stimulation of pain receptors located in the muscles, tendons, and joint capsules can also inhibit the neural pathways responsible for muscle activation (Moore, 1984). Because the subjects experienced repeated bouts of sustained stretching at their pain threshold, the stretching bout could have produced a level of inhibition which diminished the number of available motor units, thereby limiting force and power production in both types of jump. The likelihood of motor unit inhibition being the predominant mechanism, however, is questionable. Using the Hoffman (H) reflex to measure the excitability of the motor neuron pool associated with the triceps surae, Guissard, Duchateau, and Hainaut (1988) obtained evidence to suggest that autogenic inhibition is limited to the duration of the stretching maneuver. In contrast, Thigpen et al. (1985) showed the H reflex to remain depressed after the triceps surae was released from a sustained stretch, but the time elapsed before the post-stretch measurements were taken was not reported. It is difficult, therefore, to suggest with any degree of certainty that autogenic inhibition is a mechanism through which
stretching can negatively impact jumping performance. Clearly, further research is required to establish the likelihood of autogenic inhibition being an important factor.

Although the mechanisms responsible for the performance decrements cannot be established from the present data, the findings from this experiment, nonetheless, have important practical ramifications. The applied nature of this research has shown that acute stretching can negatively impact the performance of a ballistic skill such as the vertical jump. Moreover, and contrary to original expectations, it appears that this finding is not limited to movements which involve a stretch-shortening cycle. The performance of a wide range of skills, therefore, might be affected if an acute bout of stretching is undertaken immediately prior to engaging in activity. Thus, it is recommended that the prime-mover muscles to be used in a particular skill should not be passively stretched just prior any event where success is related to maximum power output.

This recommendation opposes the general perception that passive stretching before vigorous exercise is a prudent practice. Because stretching has been promoted as an important measure to prevent injuries (Bryant, 1984; Corbin & Noble, 1980; Shellock & Prentice, 1985), many athletes regularly include a thorough stretching program as part of their training and pre-event warm-up protocol. However, convincing experimental evidence to support the widely conjectured assertion that stretching has a prophylactic effect is lacking. Consequently, future work might be directed at evaluating the possibility that a trade-off exists between the benefits of stretching (i.e., injury prevention) and the cost (i.e., performance decrement). It is suggested that such a trade-off will vary according to the skill type or competitive event.
Experiment 2: The Acute Effects of Passive Stretching on the Neuromechanical Properties of the Musculotendinous Unit

In Experiment 1, it was hypothesized that an acute bout of passive stretching would decrease the performance of jumps executed with a countermovement, whereas the performance of jumps with no prior eccentric action would not change. The rationale for this hypothesis was based on previous research (Magnusson et al., 1996; Rosenbaum & Hennig, 1995; Taylor et al., 1990) which indicates that passive stretching could possibly inhibit the mechanisms thought to be responsible for the stretch-shortening phenomenon; that is, the use of elastic energy and myoelectric potentiation (Bosco et al., 1982). However, performance in both types of jump was similarly diminished. Consequently, it was difficult to narrow the focus in terms of which mechanism or mechanisms were responsible for the findings, especially as no measures of active stiffness or myoelectrical activity were recorded. It was the purpose of Experiment 2, therefore, to further investigate why an acute bout of passive stretching impedes performance in both static and countermovement jumping. An attempt was made to identify potential mechanisms by investigating the acute effects of passive stretching on the neuromechanical properties of the musculotendinous unit. Specifically, the study aimed to determine if passive muscle stretching could modify active musculotendinous stiffness and/or electrical activity of a single muscle group during ballistic movements about a single joint.

As in Experiment 1, countermovement jumps were compared to static jumps; however, in order to simplify the experiment, control the issue of coordination, and to focus exclusively on a specific muscle group, jumps were performed using the plantar flexors only. Restricting movement to the ankle joint allowed one of the most effective muscle groups in terms of elastic energy storage to be isolated — the triceps surae (Alexander, 1988).
Because tendons have a greater ability to store elastic energy than do muscle fibers (Alexander & Bennet-Clark, 1977), muscles with long tendons and short fibers are better able to provide elastic energy when subjected to a stretch-shorten cycle. Having a long tendon — the Achilles tendon — and short, pennated fibers, the triceps surae muscle complex has a small fiber/tendon length ratio and, therefore, falls into such a category. Hence, it was theorized that by isolating the triceps surae, the best possible test for the effect of passive stretching on the storage and use of elastic energy would be provided.

A further advantage of confining muscle involvement to the plantar flexors is that a non-invasive technique exists to ascertain the active stiffness of this muscle group (Cavagna, 1970). It was possible, therefore, to determine the effect of acute stretching on the elastic properties of the musculotendinous unit under active conditions. A reduction in active stiffness might account for performance decreases in both static and countermovement jumping, although it is likely that the underlying mechanisms would be different for each jump type. In the countermovement jump, a reduced stiffness might compromise the storage and use of elastic energy, whereas in the static jump, a more compliant unit may decrease the effectiveness of force transmission from the contractile component to the skeletal system.

In addition to active stiffness measurements, EMG recordings of the gastrocnemius and soleus muscles were collected. Such data allowed us to examine the notion that a decrease in myoelectric activity, possibly initiated by Golgi tendon organ reflex inhibition, might contribute to a diminished performance. Electrical activity of the muscles was determined by integrating the EMG recordings over the course of the movement. A decrease in integrated EMG (IEMG) values in the jumps following stretching would indicate a decline in muscle activation as a result of the stretching procedure.
EMG data were also used to assess the effect of acute stretching on myoelectric potentiation. Myoelectric potentiation refers to the increase in neural input to a muscle as a result of the muscle undergoing a quick, eccentric contraction. This action supposedly increases neural activation by evoking the stretch reflex controlled by muscle spindles (Bosco & Komi, 1979). Myoelectric potentiation was represented by the difference between the IEMG values for static jump and the IEMG values for the positive work phase of the countermovement jump (Bosco et al., 1982). A decrease in myoelectric potentiation would suggest that acute stretching reduces the effect of the stretch reflex which, according to Bosco et al. (1982), is partly responsible for the performance enhancement when jumps are performed with a countermovement as opposed to jumping from a static position.

Method

Subjects

Ten males (age 22.5 ± 1.84 years; height 1.79 ± 0.08 m; mass 80.7 ± 13.2 kg; mean ± SD) enrolled in undergraduate classes in the Department of Kinesiology at Louisiana State University volunteered as subjects and provided informed consent in accordance with local guidelines for the use of humans as research subjects. The subjects had not experienced any injury to the triceps surae muscle group in recent years and were able to perform single-joint jumping and passive stretching exercises without feeling any traumatic discomfort. To further ensure that each subject could perform to their full potential and achieve maximal performance, they refrained from any intense exercise involving the plantar flexors for three days prior to data collection. The subjects were not informed about the hypotheses of the study at any time.

Procedures

Each subject attended four sessions on separate days. Two sessions were used to accommodate the subject with the testing procedures. Informed consent was obtained
prior to the first practice session. During the other two sessions, data were collected and consisted of measuring the following variables: active stiffness of the triceps surae muscle-tendon complex; passive joint range of motion of the ankle joints; static and countermovement jump height; peak power and vertical ground reaction force during each jump; and the electrical activity of the triceps surae muscle group during each jump. All variables were measured before (BS) and after (AS) a bout of static stretching and were not looked at until data collection was complete.

Measurement of active stiffness. A modified version of a non-invasive technique, developed by Cavagna (1970), was employed to measure the active stiffness of the triceps surae musculotendinous unit. In the original method, Cavagna had subjects land from a small vertical jump (approximately 5 cm) on a force platform so that they fell on the balls of their feet with the triceps surae in sustained contraction. Their knees were kept straight during the landing period. Cavagna demonstrated that the sudden deceleration downwards leads to oscillations of the vertical force and that these oscillations are typical of damped harmonic motion. The stiffness, k, of the elastic structures can be calculated from the frequency, $f$, of the oscillations and from the damping coefficient, $b$.

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{M} - \left(\frac{b}{2M}\right)^2} \quad (1)$$

where $M = \text{body mass}$.

The damping coefficient can be obtained from the exponential decrease of amplitude, $x$, of the successive oscillations.

$$x = \text{const.} \cdot e^{-bt} \quad (2)$$

If the double derivative with respect to time, $t$, is taken and the resulting equation is expressed in logarithmic form, equation (2) becomes:

$$\log x = \text{const'} - \left(\frac{b \log e}{2M}\right) \cdot t \quad (3)$$
where $\ddot{x}$ are the peak values of the acceleration. Because $\log \ddot{x}$ is a linear function of $t$, the damping coefficient, $b$, can easily be calculated from the slope of the line. Once $b$ is determined, the stiffness, $k$, can be obtained from equation (1).

The Cavagna technique was performed on five subjects during pilot testing. However, even after extensive practice, stiffness measurements were not readily reproducible. Within ten trials, intra-individual coefficients of variation were, on average, approximately 10%. After landing from the small vertical jump, the subjects found it difficult to maintain equilibrium; therefore, the high variability in the stiffness results was probably due to the technique being performed incorrectly. It is particularly important to maintain equilibrium upon landing in order to prevent the intervention of antagonistic muscles whose activity may hinder the oscillatory motion which follows the downward deceleration. Because of the difficulty in performing the technique used by Cavagna, a modified version was employed. The skill was simplified so that it could be performed in a more consistent and correct manner. Instead of first performing a small vertical jump, subjects were instructed to raise their center-of-gravity by maximally plantar flexing with straight knees so that they were in toe-standing position on the edge of the force platform. At a ready signal, the subjects then “dropped” from this position by relaxing the plantar flexors until their feet become level with the platform. At this point, they terminated the movement by eccentrically contracting the plantar flexors. To facilitate their balance, the subjects were allowed to lightly hold onto a support rail throughout the execution of the technique. As in the original method, the sudden deceleration downwards led to vertical force oscillations that were typical of damped harmonic motion, and the stiffness of the plantar flexors was calculated from the frequency of these oscillations. Each subject performed this technique ten times and the stiffness value was calculated for each trial. These values were then averaged to obtain the stiffness measure. The reliability of this technique was assessed by calculating the
coefficient of variation for each subject over the ten trials. A coefficient of variation below 5% was considered acceptable.

To accommodate the subjects to the technique and to help achieve a low coefficient of variation, a separate practice session was held the day before stiffness data were collected. Five blocks of ten trials were performed. To further assess the reliability of the technique, the active stiffness measurements obtained at the end of the accommodation session (the last block of ten) were compared to the pre-stretch values obtained on the test day by computing an intraclass correlation. All trials, both on the accommodation and test day, were performed barefoot to eliminate any effects of footwear compliance.

Measurement of joint range of motion. Range of motion at the ankle joint was measured by a simple, plastic hand held device called an angle finder (Dasco Pro Inc., Rockford, IL). The device consists of a 360 degree protractor which is connected to two straight edges set at 90 degrees to each other. A pointer, attached to the center of the protractor, consistently orientates itself along the line of gravity and, therefore, establishes a true vertical alignment. If either of the straight edges are placed on an inclined surface, the angle of the inclined surface from the vertical can easily be determined by observing the position of the pointer on the protractor.

The straight edges of the angle finder were short enough to allow it to be placed consistently in the same place on the Achilles tendon. After the experimenter placed the angle finder on the tendon, the subjects were instructed to undergo maximum dorsiflexion at the ankle joint whilst keeping the whole foot on the ground and allowing no flexion at the knee joint. They achieved this by progressively moving the other leg forwards whilst holding on to the backs of two chairs for support. When the subject could not rotate the tibia any further without the heel of the foot raising from the floor or without flexion occurring at the knee joint, a reading was taken by the experimenter.
The value of this reading represented the angle the Achilles tendon formed with the vertical. Three readings were taken for each ankle. The average of these six readings was taken as the range of motion measurement. To assess the reliability of this technique, an intraclass correlation between measurements taken on each test day before the stretching exercises were implemented was calculated.

**Measurement of jump height, peak force, and peak power.** As in Experiment 1, jumps were performed on a force platform. Jump height, in addition to peak force and peak power, was therefore measured using the same procedures that were employed with multijoint jumping. Five trials were performed for each type of jump and the measures for each trial were averaged. The difference between the average static and countermovement jump heights was then used to assess the strength of the stretch-shortening effect. To perform the countermovement jump, the subjects initially stood in a plantar flexed or toe-standing position on the force platform. They then quickly lowered their whole-body-center-of-gravity (COG) before contracting the triceps surae concentrically to propel the COG vertically upwards. Thus, in this condition, the calf muscles and tendons were actively stretched (eccentric contraction) immediately prior to the positive work phase. Subjects were instructed to minimize the time between the eccentric and concentric phases of the jump (coupling time). In the static jump, the subjects propelled their COG upwards from a static position with their feet level with the force platform. Consequently, no pre-stretch took place and the jump was performed purely with a concentric contraction. As in Experiment 1, subjects were also instructed to perform every trial with maximum effort and were kept blind in regard to the hypotheses of the study.

In both types of jump, the subjects stood on the edge of the force platform so that only the balls of their feet were in contact. In the countermovement jump, this enabled the subjects to lower themselves to the level of the platform without their heels
impacting with the platform itself. In the static jump, standing on the edge was useful to place the Achilles tendon under tension before jumping. It was important to initiate the static jump under these circumstances so that lower jump performances, in relation to the countermovement jump, could not be partially attributed to the requirement of taking up tendon slack before a propulsive force could be generated.

To ensure that the propulsive or positive work phase of each jump was initiated from the same starting position, a weak elasticated band was strung between two wooden posts and positioned so that it was level with, and parallel to, the edge of the force platform. In the static jump condition, the subject would stand on the edge of the platform and set his heels so that they were just in contact with the band. A jump was then performed from this position. In the countermovement jump, the subject dropped from the initial toe-standing position and timed the eccentric contraction so that the COG vertical velocity was zero at the moment of heel/band contact. If the heels did not contact the band, or deformed the band below the level of the force platform, the jump was repeated.

The subjects were also instructed to keep their knees locked throughout the movement to prevent the quadriceps contributing to the performance of the jump. An electrogoniometer was placed over the right knee joint in order to monitor this requirement. If the knee joint flexed more than five degrees during the jump, the trial was repeated. The raw signal from the electrogoniometer was amplified (EMG-67 processor, Therapeutics Unlimited, Iowa City, IA), and analyzed by an EMG software package (Easyest LX, Keithly Instruments, Inc., Taunton, MA). The software was programmed to give an instant plot of the knee joint angle against time at the end of each jump. This plot allowed the experimenter to assess the magnitude of knee joint flexion immediately after each trial.
As with the stiffness procedures, a separate practice session was undertaken the day before in order to accommodate the subject to each jumping technique and the testing protocol. Five blocks consisting of five trials were performed for both the countermovement jump and static jump. Adequate rest periods were imposed between blocks to ensure that fatigue did not interfere with jumping performance.

The subjects practiced both types of jump under the same conditions they were to experience on the day data were collected; that is, electrogoniometers were placed over the knee and ankle joints and EMG electrodes were attached over the gastrocnemius and soleus muscles. Subjects received verbal feedback on how well they prevented their knee joints from flexing and on their ability to commence the positive work phase of each jump with their heels level with the force platform.

Measurement of muscle electrical activity. EMG activity in the soleus and gastrocnemius muscles was recorded with surface electrodes (bipolar, silver/silver chloride). The raw signal was amplified (EMG-67 processor, Therapeutics Unlimited, Iowa City, IA), full-wave rectified, and integrated (IEMG) to obtain a measure of the total electrical input to the muscles during the movement. Data acquisition and analysis was achieved through the application of an EMG software program (Easyest LX, Keithly Instruments, Inc., Taunton, MA). In the countermovement jump, the eccentric and concentric phases of the movement were integrated separately. This allowed myoelectric potentiation to be assessed; it was defined as the difference between the IEMG from the concentric phase of the countermovement jump and the IEMG from the static jump. In order to distinguish between the eccentric and concentric phases in the countermovement jump, an electrogoniometer was placed over the ankle joint to monitor the joint angle. Plantar flexion (an increasing joint angle) represented the concentric phase and dorsiflexion (a decreasing joint angle) the eccentric phase. Both the EMG and electrogoniometer signals were sampled at 1000 Hz for a duration of 1.5 seconds.
However, all IEMG values were expressed for a period of 1 second in order to normalize the data for duration of activation. Measurements were performed on the right leg only.

**Experimental protocol.** Subjects visited the laboratory on four separate days. Two days were allocated for accommodation sessions and two days for data collection (testing days). Stiffness and jumping data were collected on separate days and the respective accommodation session for each testing day was conducted the day before the tests were performed. Ideally, stiffness and jumping data should have been collected in the same testing session. However, it was felt that more reliable data could be obtained by collecting the two sets of data on separate days. During pilot testing, all the data were collected in one day which created a long testing session (approximately 2 1/2 hours), and this proved to be quite demanding for the subjects. Moreover, the subjects found it difficult to switch between the skill requirements for single-joint jumping and the skill requirements to perform the modified Cavagna technique without some negative transfer occurring. It was decided, therefore, to have the subjects perform each technique on a separate day and to implement a respective accommodation session the day before in order to maximize their potential to perform each technique correctly.

The order in which the test sessions were performed was counterbalanced. On both testing days, the general procedure was as follows:

1. Active stiffness or jumping performance was measured
2. Subjects rested for five minutes
3. Ankle joint range of motion for both ankles was measured
4. Subjects passively stretched the triceps surae muscle group of both legs
5. Ankle joint range of motion for both ankles was re-measured
6. Active stiffness or jumping performance was re-measured
On the stiffness day, the subjects required little preparation before executing 10 trials of the modified Cavagna technique. They simply removed their shoes and socks in order to perform barefoot, and changed into a pair of shorts. On the jumping day, in addition to wearing the correct attire, subjects had to be fitted with the appropriate equipment before any data was collected. An electrogoniometer was placed over the lateral aspect of the right knee joint and over the medial side of the right ankle joint. After appropriate skin preparation, surface EMG electrodes were also positioned over the medial gastrocnemius and lateral soleus muscle bellies, and a ground electrode was placed over the head of the left fibula. The electrodes and goniometers were then left in place for the duration of the experimental session. Once subject preparation was complete, the subject positioned himself on the force platform and the investigator connected the electrodes and electrogoniometers to the amplifier, making sure that there was an appropriate amount of slack in the leads. Five countermovement jumps and five static jumps were then performed with the jumping order counterbalanced.

On both testing days, after completing the pre-stretch trials, the subjects rested for five minutes to eliminate the possibility of fatigue affecting later trials. At the end of this five minute period, the range of motion at both ankle joints was measured. Subjects then stretched the triceps surae muscle group of both legs.

Two standard static, passive stretching exercises were applied three times each for a period of 30 seconds. In the first exercise, the subject placed one foot on an inclined board and allowed it to bear the majority of body weight. The subject then leaned forward whilst holding onto the backs of two chairs until maximum dorsiflexion was achieved and noticeable tension was felt in the calf. At this point, the stretch was held static for 30 seconds. At all times, the knee joint of the leg being stretched was kept locked and the sole of the foot kept flush with the surface of the board. The same procedure was then repeated on the opposite leg.
The second exercise followed a similar protocol but, instead of keeping the knee straight, it was flexed in order to relax the tension in the gastrocnemius muscle, thus placing more stretch on the soleus. After completing both exercises, ankle joint range of motion was re-measured. Subjects then repeated the modified Cavagna technique or the countermovement and static jumps (depending on the test day) so that post-stretch data could be obtained.

**Analysis of results**

The statistical model used to analyze the jumping data was a 2 (Jumping type) x 2 (time) repeated measures ANOVA. Fisher's protected LSD post hoc test was employed to investigate any differences indicated by significant main effects or interactions. Joint range of motion data was also analyzed with a 2 (Day) x 2 (Time) repeated measures ANOVA. Because joint range of motion was measured on both the jumping and stiffness testing days, the model allowed a comparison between days (Day factor) as well as between the before-stretch and after-stretch conditions (Time factor).

Stiffness data were analyzed with a one-tailed dependent t-test to determine the significance of differences between the pre- and post-stretch conditions. The test was one-tailed because the direction of change was predicted; active stiffness was expected to decrease as a result of the stretching procedure. For all analyses, statistical significance was accepted at an alpha level of 0.05.

The reliability of the techniques used to measure joint range of motion and stiffness was assessed by computing appropriate intraclass correlations. For range of motion, the correlation between measurements taken on each test day before the stretching exercises were implemented was calculated. For the modified Cavagna technique, the active stiffness measurements obtained at the end of the accommodation session (last block of 10 trials) were compared with the pre-stretch values on the test day. Furthermore, an inter-trial coefficient of variation ($CV = \sigma / \mu \times 100$) for both
stiffness test day trial blocks (one block of 10 trials before stretching and one block of 10 trials after stretching) was calculated.

Results

Jump height

Significant main effects were obtained for both Jump Type $F(1, 9) = 180.45$, $p < 0.0005$ and Time $F(1, 9) = 7.43$, $p < 0.05$ (see Figure 4). The interaction, Jump Type by Time, was also significant $F(1, 9) = 8.53$, $p < 0.05$. Fischer’s protected LSD post hoc test revealed that countermovement jump height was significantly lower (7.4 ± 6.1%) after stretching (AS) than before stretching (BS), but static jump height showed no significant change as a result of the stretching treatment. However, static jump height was significantly less than countermovement jump height both before stretching and after stretching (60 ± 6.7% BS; 56 ± 6.3% AS).

Peak vertical power

A significant main effect was obtained for Jump Type $F(1, 9) = 197.82$, $p < 0.0005$, but there was no significant main effect for Time $F(1, 9) = 4.96$, $p = 0.053$ (see Figure 5). However, there was a significant Jump Type by Time interaction $F(1, 9) = 6.99$, $p < 0.05$. Post hoc analysis showed that peak power in the countermovement jump was significantly less (4.1 ± 4.2%) after stretching but peak power in the static jump remained unchanged.

Peak vertical force

A significant main effect was obtained for Jump Type $F(1, 9) = 208.72$, $p < 0.0005$, but there was no significant main effect for Time $F(1, 9) = 1.83$, $p > 0.05$ (see Figure 6). The interaction, Jump Type by Time, was also non-significant $F(1, 9) = 4.61$, $p = 0.06$, although there was a trend towards significance.
Figure 4. Single-joint jump height as a function of jump type and time
Figure 5. Single-joint jump peak power as a function of jump type and time.
Figure 6. Single-joint jump peak force as a function of jump type and time
IEMG

Because the IEMG activity for the soleus and gastrocnemius muscles demonstrated similar patterns of activation, the IEMG for both muscles were combined. For countermovement jump EMG data, only the IEMG for the concentric phase was submitted for analysis; this enabled a direct comparison to be made between the countermovement and the static jump in order to assess myoelectric potentiation. There were no significant main effects for Jump Type $F(1, 9) = 0.08, p > 0.05$, or Time $F(1, 9) = 4.0, p > 0.05$ (see Figure 7). However, there was a significant Jump Type by Time interaction $F(1, 9) = 6.6, p < 0.05$. Post hoc tests disclosed that there was a significant decrease in the IEMG for static jump ($9.1 \pm 6.5\%$), but IEMG for the countermovement jump remained unchanged as a result of the stretching treatment. Comparing between jumps, there was no significant difference in IEMG activity between the static and countermovement jump before stretching. After stretching, however, static jump IEMG was significantly less ($5.6 \pm 9.2\%$) than countermovement jump IEMG.

Active stiffness

Active stiffness of the triceps surae muscle-tendon complex significantly decreased $t(9) = 2.159, p < 0.05$ from $30.53 \pm 4.59$ kN/m before stretching to $29.69 \pm 4.63$ kN/m after stretching. The correlation between measurements taken at the end of the accommodation period and those on the test day was 0.99. On the test day, the inter-trial coefficients of variation for pre- and post-stretch trial blocks were less than 5% for all subjects; a mean value of $3.5 \pm 1.0\%$ was obtained.

Range of motion

A significant main effect was obtained for Time $F(1, 9) = 105.52, p < 0.0005$, but there was no significant main effect for Day $F(1, 9) = 3.31, p > 0.05$ (see Figure 8).
Figure 7. Single-joint jump IEMG as a function of jump type and time.
The interaction Day by Time was also non-significant $F(1, 9) = 0.58, \ p > 0.05$. On the jumping day, ankle joint range of motion (JROM) significantly increased by $2.37 \pm 0.59$°. On the stiffness day, a significant increase of $2.14 \pm 1.03$° occurred. The correlation between pre-stretch measurements on the jumping and stiffness days was 0.99.

Figure 8. Ankle joint range of motion as a function of testing day and time
Discussion

The chief aim of this study was to determine if acute muscle stretching modifies active musculotendinous stiffness and/or electrical activity of muscle during maximal effort ballistic movements performed with and without a preparatory countermovement. It was supposed that the findings might expound upon the mechanisms responsible for the noted decrement in post-stretch performance of both static and countermovement multijoint jumps performed in Experiment 1. The ballistic movements performed in the present study were single-joint jumps with movement restricted to the ankle joint. Such a constraint facilitated the measurement of active stiffness by allowing the triceps surae muscle group to be isolated. Active stiffness of the triceps surae and Achilles tendon complex was measured with a technique developed by Cavagna (1970). After a few modifications to Cavagna's original method, reliable stiffness measurements were obtained. The modifications were made because the original technique proved to be too difficult for the subjects to execute properly and consistently from trial to trial. Pilot testing revealed that, even after considerable practice, the coefficient of variation over ten trials was generally greater than 10%. With the modifications, inter-trial coefficients of variation for both pre- and post-stretch trial blocks on the test day were less than 5% for all subjects. Furthermore, the correlation between measurements taken at the end of the accommodation session and the pre-stretch measurements on the test day was 0.99. These results indicate that the modified Cavagna technique was a reliable method for the purpose of measuring active stiffness.

The results of the stiffness tests suggest that acute muscle stretching can reduce the active stiffness of the musculotendinous unit. Consequently, stretching might negatively impact the amount of elastic energy that can be stored in the musculotendinous unit and affect the performance of skills which undergo a stretch-shorten cycle. It was interesting to note that a significant Jump Type by Treatment
interaction occurred for jump height; the countermovement jump height decreased significantly but the static jump height did not. Thus, the strength of the stretch-shortening effect was lower after the stretching protocol was administered. It is tempting to suggest therefore, that these results partially support the original hypothesis posed in Experiment 1. It was theorized that acute stretching might compromise countermovement jump performance, but not static jump performance, as a result of impeding the mechanisms responsible for the stretch-shortening phenomenon. The statistically significant reduction in active musculotendinous stiffness indicates that a decreased amount of elastic potentiation in the countermovement jump might have occurred. However, the functional significance of the change in active stiffness must be questioned as the decrease was relatively small (only 0.84 kN/m or 2.8%). According to Hooke’s law, \( E = \frac{1}{2} k x^2 \), a 2.8% decrease in stiffness \((k)\) would result in a concomitant 2.8% decrease in the amount of stored elastic energy \((E)\), assuming the extension \((x)\) remained unchanged. Because countermovement jump height (and therefore the kinetic energy at take-off) was reduced by 7.4% after stretching, it seems unlikely that a decrease in elastic potentiation (caused by a reduction in the amount of stored elastic energy) was the main restrictor of jumping performance. One must remember, though, that the stiffness measurements were recorded on a separate day to the jumping data. Consequently, it is possible that the stretching protocol caused a greater decrease in musculotendinous stiffness on the jumping day. The likelihood of such a possibility is low, however, as a similar response to stretching with regard to an increase in ankle joint range of motion (JROM) was obtained on both jumping and stiffness days. Furthermore, no significant differences were observed between days for ankle JROM before stretching. Thus, we feel that it is fair to assume that the stretching exercises had a similar effect on active musculotendinous stiffness on both testing days.
In addition to investigating the effect of stretching on elastic potentiation, this study also sought to determine the effect of stretching on myoelectrical potentiation, a second mechanism purported to be responsible for the stretch-shortening effect. Bosco et al. (1982) demonstrated that in a similar single-joint jumping skill, jumps performed with a countermovement elicited a greater IEMG during the positive work phase than jumps performed without a countermovement. They attributed this to the stretch reflex mechanism, concluding that jumps performed with a countermovement activate muscle spindles which, via a reflex loop, increase neurological input to the muscles undergoing eccentric contraction. Because Rosenbaum and Hennig (1995) have shown EMG activity of the of the mechanically elicited triceps surae reflex to be depressed after acute stretching, it was speculated that stretching would also decrease the amount of myoelectric potentiation. However, no evidence was found for myoelectric potentiation prior to the stretching exercises being administered. Since no differences existed between the IEMG of the static jump and the IEMG of the positive work phase of the countermovement jump, the data from this experiment do not support the notion that the stretch reflex is partly responsible for the enhancement in jump height when a jump is performed with a countermovement rather than jumping from a static position. The present findings, therefore, do not corroborate the work of Bosco et al. (1982), who concluded that elastic potentiation accounts for approximately 70% of the stretch-shortening effect, and that myoelectric potentiation accounts for the remaining 30%. In view of the fact that no other study has substantiated the existence of myoelectric potentiation, it is recommended that future research be conducted to determine if myoelectrical potentiation is indeed a mechanism which can partially account for the well established performance-enhancing effect of a stretch-shorten cycle.

Indirectly, some studies have provided evidence against the existence of myoelectrical potentiation. Several authors claim that during the eccentric phase of a
stretch-shorten cycle, a typical response of the contractile component is to shorten despite the overall lengthening of the musculotendinous unit (Belli & Bosco, 1992; Griffiths, 1991; Hof, 1983). After investigating the gastrocnemius musculotendinous unit in the freely walking cat, Griffiths (1991) observed that the muscle fibers shortened by 1.0 ± 0.3 mm during the stance phase of the step cycle while the entire unit was undergoing extension. Similarly, after studying human subjects perform rhythmic hopping movements involving the triceps surae exclusively, Belli and Bosco (1992) concluded that the contractile component mainly performs concentric work while the series elastic component lengthens. Mechanical behavior was assessed by inputting experimentally derived data into a computer simulation of the movement; the model then enabled the interaction between the contractile component and the series elastic component to be studied. Using comparable techniques, Hof (1983) indicated that a similar mechanical behavior of the musculotendinous unit exists during human walking. All these researchers attributed such behavior to a compliant Achilles tendon. If active lengthening does arise primarily from tendon extension rather than an increase in fiber length, then doubt must be cast on the contribution of myoelectric potentiation to performance in skills which utilize a stretch-shorten cycle. For the stretch reflex to take place, a sudden stretch of the muscle fibers is necessary. Therefore, if the tendon lengthens without an accompanying muscle fiber stretch, myoelectric potentiation should not be possible. Unlike the investigation of Bosco et al. (1982), the IEMG data in the present study directly support this notion.

Interestingly, though, the IEMG data from the post-stretch jumps give the impression that myoelectric potentiation did occur following the stretching treatment. IEMG recorded in the concentric portion of the countermovement jump was significantly greater than that recorded in the static jump. However, to consider this myoelectric
potentiation would be incorrect as the difference was due to a depression of electrical activity in the static jump, rather than an increase in the countermovement jump.

A decrease in electrical activity might arise from the acute response of Golgi tendon organs to sustained stretch. Golgi tendon organs respond to stretch or tension by producing a reflex inhibition (autogenic inhibition) of both the muscle being stretched and its synergists (Moore, 1984). It was theorized that acute stretching might produce a level of inhibition to diminish the number of available motor units, thereby limiting force production and, in turn, jump height in both the static and countermovement jump. However, a decrease in IEMG after stretching was only found in the static jump. Such a finding is paradoxical because static jump height did not change, whereas countermovement jump height decreased significantly. Clearly, the amount of IEMG suppression in the static jump, although statistically significant, was not sufficient to impact the height of the jump. Post-stretch values for peak vertical force and power were also similar to pre-stretch values irrespective of the decrease in electrical activity. Consequently, these results do not indicate that stretching can affect the performance of jumps executed with or without a preparatory countermovement through the mechanism of autogenic inhibition.

The findings from this experiment, therefore, cannot fully explain the mechanisms responsible for sub-maximal performances of jumps performed after a bout of passive muscle stretching. A decrease in elastic potentiation appears to be a contributing factor, but cannot account for performance inhibition alone. Autogenic inhibition and a reduction in myoelectric potentiation do not seem to play any role. Because the present study tested for no other mechanisms, additional work must be conducted to determine the major underlying mechanism or mechanisms which can explain why passive muscle stretching hinders the performance of a skill such as the vertical jump.
General Discussion

The experiments conducted as part of this dissertation sought to determine if a warm-up bout of passive muscle stretching was detrimental to skills which take advantage of the stretch-shortening phenomenon such as the vertical jump. Furthermore, an attempt was made to establish the mechanisms which could explain the results. Experiment 1 was an applied study which revealed that in multijoint jumping, stretching the prime-mover muscles just prior to performance can decrease the jump height not only of jumps executed with the usual preparatory countermovement, but also those initiated from a static, squatting position. These results suggest that the influence of acute stretching on performance is not limited to skills which incorporate a stretch-shorten cycle, and that stretching does not necessarily impede the mechanisms thought to be responsible for the stretch-shortening phenomenon. Subsequent work by Kokkonen, Nelson, and Cornwell (unpublished research) strengthen this supposition. These investigators found that an exclusively concentric, one repetition maximum (1 RM) contraction for both the knee extensors and knee flexors was significantly decreased by 4-8% if the 1 RM was performed following 20 minutes of static stretching exercises.

The intention of Experiment 2 was to explicate the reasons why an acute bout of passive stretching can cause performance decrements in a ballistic skill such as jumping. Active stiffness and electrical activity measures were recorded whilst subjects performed single-joint static and countermovement jumps using the triceps surae group of muscles only. By isolating a specific muscle group and assessing the effect of stretching on the neuromechanical properties of musculotendinous unit, an attempt was made to reveal the underlying mechanisms responsible for the findings in the first experiment. A main prediction was that the stretching treatment would substantially decrease the active stiffness of the musculotendinous unit, in this case the triceps surae muscle group and
the associated Achilles tendon. Although there was a significant decrease in active stiffness, the impact of this change must be questioned because the stiffness decline could account for only a approximately one-third of the decrease in countermovement jump performance, and obviously had no effect on static jump performance as static jump height remained unchanged. It is concluded that the stretching protocol did not decrease the active stiffness of the musculotendinous unit by a sufficient amount to indicate that stiffness related mechanisms were the main cause of performance decrements in jumps performed after a bout of passive muscle stretching.

Other speculative mechanisms investigated by Experiment 2 appeared to have no impact. Myoelectric potentiation — the increase in concentric electrical activity as a result of a prior, active pre-stretch or eccentric action initiating the stretch reflex — was not found to occur in any condition (either before or after stretching). Thus, the hypothesis that stretching might impact the countermovement jump rather than the static jump because of a reduction in the amount of myoelectric potentiation was not validated. Furthermore, the results bring into question the work of Bosco, Tarkka, and Komi (1982) who are the only investigators to claim the authenticity of myoelectric potentiation. These authors had five subjects perform single-joint jumps using the plantar flexors exclusively, and showed that the concentric phase of the countermovement jump elicited a greater IEMG than the static jump. Bosco, Viitasalo, Komi, and Luhtanen (1982), however, failed to demonstrate a similar potentiation in multijoint jumps. It is recommended that further research be conducted to determine the validity of myoelectric potentiation in skills such as the vertical jump.

Electromyographic data from the second experiment also indicated that autogenic inhibition was not responsible for the effect of stretching on performance. A full account of why passive stretching can negatively impact performance therefore remains elusive and awaits further research.
A possible direction for future research would be to investigate the effect of acute stretching on the information associated with proprioceptive feedback. Such feedback not only involves the muscle spindles and Golgi tendon organs, but other sensory organs such as joint receptors (e.g. pacinian corpuscles and ruffini endings) which are found in joint capsules and stabilizing ligaments. Collectively, these organs act as proprioceptors which provide the neuromuscular system with afferent feedback to help in the selection of an appropriate group and sequence of muscular activity for a given task (Enoka, 1994). Several studies have shown that a loss of proprioception produces deficits in neuromuscular coordination of both single joint (Rothwell et al., 1982) and multijoint movements (Ghez and Sainburg, 1995; Sainburg et al., 1995; Sainburg, Poizner, and Ghez, 1993). It is conceivable that passive muscle stretching causes enough distortion in these receptor organs to alter their pattern of activation for a particular movement which, in turn, disrupts motor unit sequencing so that the optimal coordination pattern, and therefore maximal performance, cannot be achieved.

Anecdotal evidence to suggest that physical manipulation of proprioceptive organs might alter muscular performance is provided by the clinical experience of altering muscle spindle function. It has been observed that after performing muscle spindle compression techniques on athletes, muscles produce a weaker response during subsequent muscle tests (Paul Chek, personal communication ¹). Although this kind of evidence is not compelling by any means, it bolsters somewhat the speculation that stretching might influence muscular performance by altering proprioceptive information.

One might further speculate that such a mechanism impacts skills which require a high degree of coordination more than skills which are less complex with regard to motor unit recruitment patterns. In the present study, presumably the countermovement

¹. Paul Chek is a clinical neuromuscular physiology consultant (see web page www.paulchekseminars.com).
jump employed a more complex pattern of motor unit recruitment than the static jump, because the movement reversal has to be precisely timed to take advantage of the stretch-shortening phenomenon. One would expect, therefore, that if passive stretching does perturb proprioceptive information, countermovement jump performance would be impacted much more than the static jump. In fact, in Experiment 2, static jump height was unaffected by the stretching treatment, whereas countermovement jump height was significantly decreased. It is possible that in single-joint static jumps, the complexity of motor unit recruitment is not high enough to be influenced by an alteration in proprioceptive afferent discharge. In multijoint jumps, however, because of the numerous muscles involved and the responsibilities of two-joint muscles, static jumps become highly complex in terms of motor unit recruitment. Additionally, because the motion of a particular limb segment produces forces at other segments in the kinetic chain, neural control signals must also take into account the interactions that occur between segments (Sainburg et al., 1993). One would expect, therefore, that if stretching does produce deficits in neuromuscular coordination by altering proprioceptive information, the multijoint static jump would also show a performance decrement when performed after stretching; this, in fact, was the case in Experiment 1.

In multijoint arm movements that required abrupt reversals in direction, Ghez and Sainburg (1994) have shown that normal subjects adapt their patterns of muscle activation to the occurrence of interaction torques, and that this control is substantially diminished in deafferented patients who lack proprioceptive feedback. Consequently, to investigate the effect of stretching on neural control of the vertical jump, future work might seek to determine if the relationship between interactive joint torques and muscle activation patterns is altered after the prime-mover muscles are passively stretched.

Another possible explanation for the diminished performance in post-stretch jumps results is that passive stretching might simply alter the sarcomere lengths of the
muscle fibers and cause the muscle to operate over a less optimal range of the force/length curve in terms of force production. For example, at muscle lengths greater than resting length, maximum force output decreases because not as many crossbridges can become strongly bound to actin due to less overlap between the actin and myosin filaments. It is possible, therefore, that if the prime-mover muscles are stretched immediately prior to performing a jump, the muscles spend a longer time on the “descending limb” of the force/length curve during the movement, thereby limiting power output and, ultimately, jump height. However, such a mechanism should similarly affect both purely concentric movements and movements which incorporate a stretch-shorten cycle. Although both multijoint static and countermovement jumps had a similar decrease in performance, only the countermovement jump was negatively impacted when motion was restricted to the ankle joint. Nevertheless, the fact that the single-joint static jump was unaffected by the stretching treatment should not be enough to discount the possibility that stretching impacts muscular performance by altering sarcomere length. Because a relatively small muscle group was exclusively responsible for accelerating the whole-body-center-of-gravity vertically upwards without the potentiating effect of a countermovement, the average static jump height was already very low (only 1.53 cm) prior to stretching. Consequently, any decrease in jump height from this initially small value might have been too small for the equipment to detect. It is recommended, therefore, that future research also investigate the effect of passive stretching on the force/length relationship of muscular contraction.

The reason why pre-exercise stretching can cause performance deficits, however, might not be limited to one specific mechanism. It is possible that stretching causes several alterations to the neuromuscular system and it is the cumulative effect of such changes that ultimately impact performance. The components which contribute to the overall outcome might be a decrease in elastic potentiation, an altered pattern of...
proprinoceptive feedback, and a modified force/length relationship. Obviously, though, further research is required to confirm this speculation and to provide an unclouded explanation for the results of the present studies.

Besides the quest to uncover the underlying mechanisms responsible for our findings, research should also be conducted to answer some practical questions. First, how long does the effect of a stretch last? The initial post-stretch jump in both experiments was performed within a few minutes of completing the last stretching exercise. In practice, some athletes complete the stretching part of a warm-up 20-30 minutes before competition. Although it has been shown that the stretching influence on range of motion lasts for up to 90 minutes (Moller et al., 1985), future studies should determine if there is a lasting effect of stretching on performance.

Another practical question to arise from the present research is whether or not athletes should be concerned about a trade-off between the possible benefits of acute stretching (i.e., injury prevention) and the cost (i.e., performance decrement). It is widely asserted that if stretching exercises are performed just prior to physical activity, the risk of musculoskeletal injury is lessened (e.g., Bryant, 1984; Shellock & Prentice, 1985). However, the basis for this conjecture has been formed from either anecdotal evidence or from the findings of retrospective studies which have investigated the relationship between injury occurrence and inherent flexibility (Safran, Seaber, & Garret, 1989; Shellock & Prentice, 1985). In fact, the only prospective study to test the hypothesis that pre-exercise stretching lowers the incidence of musculoskeletal injury found no differences in the number of injuries between an experimental (n =735) and control group (n=803) of Australian army recruits after a 12 week training program (Pope et al., 1996). Presently, therefore, there is no convincing experimental evidence to support the claims that stretching has a prophylactic effect. It is recommended that future research further investigate the potential of stretching to prevent injury, in addition...
to its impact on performance, for a variety of different skills. A wide selection of skills should be assessed on an individual basis because it is probable that the benefit/cost trade-off will vary according to the type of skill or competitive event.

Although future work might conclude that some skills will benefit from acute stretching, this dissertation has shown that including a rigorous bout of passive muscle stretching in a pre-event warm-up is not always a judicious practice. This is contrary to the popular belief that stretching almost invariably facilitates performance. The present findings suggest that stretching should not be undertaken just prior to executing ballistic skills which do not push the range of motion limits, and where success is related to maximum power output.

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References


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Appendix A

Extended Review of Literature
The Role of Muscle and Tendon Elasticity in Human Movement

Human movement depends not only on the ability of skeletal muscles to contract, but also on the ability of muscles to return to their original length after being stretched by an external force. The property that allows a structure to return to its original shape or size when a force is removed is called elasticity. If an elastic structure is stretched, it stores energy which can be partially recovered when the stretching force is removed and the structure recoils from its stretched position (not all the energy can be recovered as some is lost as heat). Springs are obvious structures that behave in this way; however, muscles can also respond elastically, especially when a movement subjects the prime-movers to an eccentric contraction immediately prior to contracting concentrically. In other words, the muscles primarily responsible for the movement are actively stretched by passive (e.g., reactive, gravitational, frictional, and inertial) forces before they shorten to produce the desired action. This type of movement strategy is known as the stretch-shorten cycle (SSC) and it has been shown to enhance performance in everyday skills such as running and jumping (e.g., Alexander, 1988; Bobbert, 1990; Cavagna, Saibene, & Margaria, 1964; Cavagna, Komerek, & Mazzoleni, 1971) — a phenomenon known as the stretch-shortening phenomenon. As in the elastic deformation of a spring, the SSC allows a muscle to store and release elastic energy which can then be utilized to potentiate the amount of work done in a particular movement or skill. It is the purpose of this paper to review the role that elastic energy plays in human movement and to answer the following questions: 1) how important is muscle and tendon elasticity to the performance of certain skills? and 2) what factors can influence the degree to which elastic energy contributes to the performance of a skill?

Initially, the basic mechanisms thought to be responsible for the elasticity of muscle tissue and the stretch-shortening phenomenon are debated in an attempt to
establish an appropriate foundation for the discussion of issues later presented. In the process of establishing the basic mechanisms, studies involving animal muscle preparations are discussed. Most of the basic knowledge pertaining to the effect of the SSC has been obtained by studying isolated whole muscle (e.g. Abbot & Aubert, 1952, Cavagna & Citterio, 1974; Heglund & Cavagna, 1987) and single fiber (e.g. Edman, Elzing & Noble, 1978; Sugi, 1972) preparations from several animal species. The interaction between muscle force, muscle length, velocity of lengthening or shortening, tendon biomechanics, and neural activation is quite complicated when studied in vivo. The mechanisms underlying the movement mechanics of muscle are, therefore, easier to understand when the movement is controlled as can be done in the study of animal muscle preparations. In addition to providing valuable basic information, these investigations are also used to support theories explaining effects found in-vivo using human subjects.

Running and jumping skills have been the main focus for applied research involving humans. Section 3 establishes the effect of the SSC on movement efficiency and performance enhancement in these skills. From the research findings, the value of elastic energy in skills such as running and jumping is discussed. Following this discussion, section 4 presents factors that can influence the degree to which elastic energy can be used to enhance skill performance. For the purpose of this review, such factors are termed “modulating factors”. Research investigating modulating factors raises several questions concerning the practical ramifications of inducing various experimental treatments on the neuromuscular system. This review concludes with some observations and speculations as to how such manipulations may allow one to enhance or degrade the contribution of elastic energy to performance of a motor skill. Thus, hypotheses for future research are developed.
The Stretch-Shortening Phenomenon: Basic Mechanisms

The elastic response of muscle and tendon

Both muscle fiber and tendinous tissue have the ability to store energy after being stretched by a force. Muscles and their respective tendons are collectively referred to as musculotendinous units and have classically been described in terms of three functionally distinct elements (Hill, 1938). The Hill three-component model (Figure 9) consists of an active contractile component (CC), a series elastic component (SEC), and a parallel elastic component (PEC). The CC represents the muscle fibers and exerts a force through extensible structures which are in series with the fibers. These extensible structures — which consist of tendon and cross-bridge linkages within the sarcomeres of the muscle fibers (Huxley & Simmons, 1971) — are represented by the SEC. The SEC is responsible for the elastic characteristics of the musculotendinous unit and acts passively, extending or shortening in response to the forces exerted by the CC. The tendon accounts for a major portion of the series elasticity, but some elasticity actually resides within the contractile proteins of the muscle fibers (Alexander & Bennet-Clark, 1977; Huxley & Simmons, 1971). The cross-bridge linkages bear tension during muscular contraction and stretch under the load (Figure 10). Evidence for this was found by Huxley and Simmons (1971). The force/length diagram of the elastic component in a frog semitendinosus single muscle fiber was determined after eliminating tendon compliance. The fiber underwent rapid shortening from a state of isometric contraction at optimum fiber length ($l_0$ — the length at which the number of cross-bridges is maximum) and at a greater length (thereby reducing the number of cross-bridges). The amount of shortening required from the elastic component to reduce the force to zero was approximately the same in both conditions, even though the initial force was greater when shortening was initiated from $l_0$. This suggests that the SEC...
Contractile Component - CC

Series Elastic Component - SEC

Parallel Elastic Component

Figure 9. The Hill three-component model

Thick Filament

Thin Filament

a)

b)

c)

Figure 10. Attachment of a single myosin head to an actin filament in three situations: a) average starting position. b) at the end of a shortening stroke. c) after active lengthening.
resides in the cross-bridges rather than some other structure which would have been
stretched more by the greater force. It is thought that subfragment 1 (S1) of the myosin
head is linked to the thick filament by a spring-like element assumed to be subfragment 2
(S2) (Figure 10). Huxley and Simmons (1971) suggested that the S2 fragment extends
by at least 13nm/half sarcomere without breaking during a maximum isometric
contraction. If a stretch is applied, Rack and Westbury (1974) calculated the limit to be
in the range of 25-35nm/half sarcomere.

The PEC depicts another component of elasticity, but is not put under tension by
contractile forces. It is responsible for the tension in a relaxed muscle when the muscle
is stretched beyond its resting length. This component represents the sarcolemma and
fascia (Hill, 1938).

For an ideal material, elastic behavior may be characterized by a linear
relationship between the force applied to the structure and its resulting deformation
(Shorten, 1987). This is the basis of Hooke's law which says that the applied force F is
proportional to the deformation of the material x:

\[ F = kx \]

where k is the stiffness of the material. The inverse of stiffness is known as the
compliance of the material. When a structure is stretched or compressed by a force, the
work done by the force is stored as elastic energy (E) in the structure (Shorten, 1987)
and is expressed as:

\[ E = \frac{1}{2} kx^2 \]

However, neither muscle or tendon behaves in a perfectly elastic manner. Studies have
shown SEC compliance to decrease with increasing muscle force (Hill, 1950; Hof,
Geelen, & van den Berg, 1983; Proske & Morgan, 1987). According to van Ingen
Schenau (1984), the relationship between $F$ and $x$ can be approximated by a power curve:

$$F = k x^n$$

where $n$ is a constant $> 1$. The energy which can then be stored equals:

$$E = (1/n+1) k x^{n+1}$$

The amount of elastic energy which can be stored in the SEC is, therefore, simply a function of the SEC stiffness and the amount of deformation produced by an imposed force. Alexander and Bennet-Clark (1977) have estimated that the cross-bridges can store up to 4.7 joules (J) of energy per kilogram (kg) of muscle fiber, whereas tendon collagen can store between 2000 and 9000 J/kg of material. Consequently, the capacity of elastic energy storage will be greater in muscle groups with long tendons and short muscle fibers (Alexander & Bennet-Clark, 1977). Later in this review, it will be shown that these types of muscle groups play a prominent role in skills which incorporate a SSC. The next section, however, deals with the positive effects of muscle elasticity under controlled conditions. From in-vitro and in-situ studies on isolated muscle preparations, data are presented which indicate that the SSC can augment the force, power, and work output of the musculotendinous unit, as well as having a beneficial effect on mechanical efficiency.

**Research using animal muscle preparations**

The effect of the SSC on force and power. The amount of force produced by the CC is dependent on its length and velocity of shortening. Hill (1938) showed a hyperbolic relationship to exist between muscle force and shortening velocity by subjecting isolated frog muscles to maximal stimulations under different loads. Specifically, when the velocity of shortening increases, the amount of force the muscle can produce decreases. Force generation, however, can also be modulated by the SEC, as the elastic characteristics of the SEC can alter the velocity requirements of the CC.
This is especially evident during the SSC. Due to the recoil characteristics of the SEC after a stretching load is removed, the CC does not have to shorten as fast for a given velocity of whole muscle shortening (Lieber, 1992). In accordance with the force/velocity relationship, this allows the CC to produce more force than would be possible without the effect of SEC recoil. Consequently, more power is produced (the product of force and velocity).

For maximum contractions, the mechanical energy stored in the SEC during the eccentric phase can be utilized to produce a greater shortening velocity than that which the CC is capable of generating by itself (Hill, 1950). This was demonstrated by Cavagna and Citterio (1974), who determined the force/velocity relationship of frog sartorius, semitendinosus, and gastrocnemius muscles when shortening against a given force (isotonic quick release). Releases (allowing muscles to shorten) were performed from a state of isometric contraction and immediately after stretching the contracted muscle. In both cases, the muscle was released from the same length. With prior stretching, the muscle was able to shorten against a constant force ($P$) equal to and even greater than the maximum attainable isometric force ($P_o$). When $P$ was lowered below $P_o$, the velocity of shortening was greater after stretching, thereby shifting the force/velocity curve along the velocity axis (to the right). It appears that the recoil velocity of the SEC augments the shortening velocity produced by the CC (Shorten, 1987). As a result, more power is produced during the concentric contraction.

In the same set of experiments, Cavagna and Citterio (1974) also performed releases under zero load but controlled the speed (controlled release) so that it was constant and greater than the maximum speed of shortening of the CC. This enabled the force/length diagram due to the recoil of the SEC to be determined. The amount of shortening required of the SEC to allow the force to fall from $P_o$ to zero was 50-100% greater when the muscle was released immediately after stretching as opposed to being
released from a state of isometric contraction at the same length; correspondingly, more mechanical energy was released. At the end of the stretch, the contracted muscle attained force values 1.5-2 times greater than the isometric force.

Other studies also have demonstrated an enhancement of force production after stretching an active muscle. Similar results have been obtained in isolated whole muscle (Abbot & Aubert, 1952; Cavagna, Saibene, & Margaria, 1965) and in single muscle fibers (Edman, Elzinga & Noble, 1978; Sugi, 1972). As indicated by Cavagna, Mazzanti, Heglund and Citterio (1985), three potential mechanisms responsible for the enhancement of force as a result pre-stretching a muscle have been proposed: 1) the number of attached cross-bridges increases (Sugi & Tsuchiya, 1981); 2) a greater force is developed in each cross-bridge than that developed during an isometric contraction (Cavagna & Citterio, 1974; Edman et al., 1978; Sugi & Tsuchiya, 1981); and 3) other force bearing structures are recruited in parallel with the cross-bridges (Edman et al., 1978). After releasing pre-stretched muscle fibers of the frog against a force equal to $P_0$, Cavagna et al. (1985) suggested the second mechanism, a greater force developed by each cross-bridge, was responsible for the resulting force enhancement. This was based on the fact that isotonic shortening took place, even though the stiffness measured above $P_0$ was equal to, and sometimes smaller than, the stiffness measured under isometric conditions. If either of the other proposed mechanisms were responsible, an increase in stiffness would be expected because the stiffness of an active fiber is proportional to the number of attached cross-bridges.

The magnitude of force enhancement has been shown to be affected by both speed and length of the applied stretch (Edman et al., 1978; Rack & Westbury, 1974; Sugi, 1972). After applying a wide range of stretch velocities (0.1 to 150 cm/sec) to tetanized muscle fibers of the frog, Sugi (1972) found that muscle tension increased gradually with increasing stretch velocity. At velocities of more than 30 cm/sec though,
tension rose markedly at first, then began to decline while the stretch was still in progress. This indicates that the CC may "slip" if the rate of stretching is too high. During an active stretch, the cross bridge linkages distort from their original position, rotating backwards to a position of higher potential energy (Huxley & Simmons, 1971). If the resulting force becomes too great, the cross-bridges will be forcibly detached and may not have time to reform if the stretch velocity is more than 30 cm/sec (Sugi, 1972); thus, a decline in tension results. Similar results have also been documented by Edman et al. (1978). These findings imply that, within certain limits, human performance may be enhanced if the speed of active stretching is increased.

To determine the effect of stretch amplitude, Rack and Westbury (1974) applied alternate lengthening and shortening movements on tetanized cat soleus and gastrocnemius muscles. With constant velocity movements (velocities ranged from 5-40 mm/s) of small amplitude, tension rose quickly during the stretching phase and fell during shortening in a simple fashion. With larger amplitudes, the tension immediately increased as with the smaller movement, but later in the stretch the resistance of the muscle decreased eliciting a more gradual change in tension. The authors termed the initial high resistance "short range stiffness" and attributed it to the elastic properties of the cross-bridges between the actin and myosin filaments. It was suggested that if the amplitude of the stretch was too large, the cross-bridges would break down and the energy would be dissipated as heat. This would account for the reduction in stiffness because, with fewer cross bridges attached, the resistance to stretching decreases. The critical amplitude depended on the speed of the stretch; when the stretch was rapid, an extension between 2-3% of initial fiber length was recorded before a decline in stiffness occurred. It was calculated that this would create 25-35 nm of movement in each half-sarcomere, two to three times that which occurs during a maximal isometric contraction. With a slower stretch, the short range stiffness lasted for a shorter distance. The authors
did not provide an explanation as to why this happened. Presumably, it was due to the natural detachment of the cross bridges during the cross bridge cycle taking place before the stretch could progress too far.

Regardless of the length over which the short range stiffness persisted, as long as the stretch amplitude did not exceed this length, most of the work done on the cross-bridges re-emerged as reusable energy during the subsequent shortening. Consequently, it appears that muscle fibers exhibit properties closer to those of an ideal spring during movements of small rather than large amplitude. One would expect, therefore, small amplitude movements to be more efficient than movements of larger amplitude. Efficiency, in addition to work output, is now considered in the following section.

The effect of the SSC on work and efficiency. Due to an enhancement of force during stretching, the SEC is able to store and deliver more energy when the muscle undergoes a SSC as opposed to shortening from an isometric contraction at the same length. This allows the muscle to perform a greater amount of mechanical work as it shortens (Cavagna & Citterio, 1974; Heglund & Cavagna, 1987). Work performed by a shortening muscle (concentric contraction) is commonly termed "positive work" whereas work done as a muscle lengthens (eccentric action) is known as "negative work" (Winter, 1978). The increase in positive work following a pre-stretch is not usually accompanied by a concomitant increase in oxygen cost; therefore, the mechanical efficiency (defined as the ratio of mechanical work, or power, output to the metabolic work, or power, input) at which the work is done increases (Heglund & Cavagna, 1987; De Haan, van Ingen Schenau, Ettema, Huijing, & Lodder, 1989). This can be explained by the fact that the additional energy used to produce a greater positive work output is essentially free of metabolic cost. As previously stated, this energy is stored in the SEC of the musculotendinous unit when it is stretched by an external force. It is true
that some metabolic energy is required to maintain the muscle in an eccentric action while the muscle is being stretched; however, the storage and recovery of elastic energy more than compensates for the chemical energy spent during this time (Cavagna, 1977).

The first researchers to calculate the efficiency of dynamic muscular contraction from simultaneous oxygen consumption and mechanical work measurements on isolated muscles were Heglund and Cavagna (1987). Prior to this, most in vitro studies attempting to measure muscle efficiency employed myothermic methods (e.g. Hill, 1939; Gibbs & Gibson, 1972) rather than oxygen consumption measures. Heglund and Cavagna (1987) allowed frog sartorius, rat extensor digitorum longus (EDL), and rat soleus muscles to shorten at a constant velocity using two different procedures. In the first, lengthening under a relaxed condition to a specified length preceded isometric stimulation. The muscle was then allowed to shorten with stimulation being continued for the first part of the movement only. In the second procedure, stimulation began before stretching and also continued during the first part of the subsequent shortening. In both cases, shortening took place at the same constant velocity and began from the same length. With active stretching, the work performed during the subsequent shortening in all three muscles was substantially higher than when relaxed lengthening preceded the concentric contraction (by a factor of 1.27 for frog sartorius, 3.56 for rat EDL and 2.47 for rat soleus). However, oxygen consumption was not appreciably different between the two conditions. Calculating efficiency as the ratio between positive work and energy expenditure (energy expenditure being expressed as the caloric equivalent of the net oxygen consumed) efficiencies were therefore higher when active stretching was performed. For sartorius, efficiency increased from 25% to 35%; EDL from 19% to 50%; and soleus from 15% to 40%.

Previous work has estimated the maximal efficiency of transformation of chemical energy into mechanical work by the CC of muscle to be 29% (Whipp &
Wasserman, 1969; Cavanagh & Kram, 1985). Lower values have often been reported however (e.g., Hill, 1939; Gibbs & Gibson, 1972; Heglund & Cavagna, 1985), and commonly, 25% is taken as the "standard" (Hof, 1990). The work of Heglund and Cavagna (1987), therefore, shows that active stretching of a muscle prior to shortening can increase the efficiency of doing positive work to values well above the accepted standard for movements involving purely a concentric contraction.

A similar study to establish the effect of an active pre-stretch on positive work and efficiency was undertaken by De Haan et al. (1989). The investigators suggested the stimulation protocol used by Heglund and Cavagna (1987) — and all previous studies of mechanical or energetic effects of pre-stretching the contracting muscle — created an unrealistic balance between negative and positive work. Using the force/length tracings presented by Heglund and Cavagna (1987), De Haan and colleagues pointed out that the amount of negative work was more than four times that of the subsequent positive work output. They proposed such an imbalance was caused by stimulating the muscle too soon; that is, at or prior to the onset of the stretch phase. With the intention of simulating a more "realistic" condition, De Haan et al. (1989) imposed an activation protocol which elicited more positive than negative work, and then calculated the efficiency of rat gastrocnemius muscle in contractions with pre-stretch (PS) and without pre-stretch (PI). Stimulation took place 150 ms before concentric contraction began for both the PS and the PI conditions. The muscle was lengthened from $L_o - 3 \text{ mm}$ to $L_o + 3 \text{ mm}$ at a stretch velocity of 20 mm/sec (1.4 $L_o$/sec); therefore, the distance of active stretch was 2.4 mm. The authors reported a substantial enhancement of force and positive work in the PS contraction as compared to the PI contraction, emphasizing that this occurred despite a relatively short distance of active stretch. From these findings, they concluded that it is not necessary to apply long stretches and large amounts of negative work to obtain the enhancement effect.
However, Heglund and Cavagna (1987) also imposed active stretches of similar lengths (2.0 -2.5 mm); therefore, it appears that De Haan et al. (1989) were incorrect to assume that the protocol followed by Heglund and Cavagna (1987) led to a greater amount of negative work being done than positive work because the active stretch was too long. Instead, the negative balance was probably caused by a relatively small amount of shortening; the force/length tracings reveal that active shortening continued for distances of less than 1 mm. In contrast, De Haan et al. (1989) allowed the muscle to shorten over 6 mm.

In the process of calculating efficiency, De Haan et al. (1989) calculated the changes in concentrations of ATP, PC, and lactate over 10 repeated contractions, instead of using oxygen consumption measures to determine energy expenditure. Equal energy consumption was found for both types of contractions. As a result, there was a significant difference between the efficiency of the PS contraction (36.8%) and the PI contraction (26.3%), although this gain in efficiency was not as large as those reported by Heglund and Cavagna (1987). This may also be explained by the small shortening distances in the study of Heglund and Cavagna (1987). The relative gain in positive work, and therefore efficiency, will be higher at smaller shortening distances due to an increased relative contribution of elastic energy delivered by the SEC (De Haan et al., 1989).

For a better understanding of the physiological significance of their results, De Haan et al. (1989) attempted to quantify how much of the additional positive work output was due to the storage and return of elastic energy. Basing their calculations on SEC compliance estimates, it was proposed that elastic energy utilization represented two thirds of the additional work. The remaining one third was accounted for by an enhancement of force assumed to be caused by some non-elastic potentiation effect of the cross-bridges induced by the active stretch (Cavagna et al., 1985); however, the
mechanism responsible for potentiating the contractile machinery has yet to be identified. Because the authors did not directly measure SEC compliance, they cautioned that these portions were sensitive to the estimation of compliance.

In follow-up experiments, the force-compliance characteristics of the SEC in rat gastrocnemius muscle were determined using quick releases from isometric tetanic contractions at different musculotendinous unit lengths (Ettema, Huijing, van Ingen Schenau, & De Haan, 1990). From these characteristics, the work performed by the CC and SEC could be readily distinguished. Calculations supported the previous estimates of De Haan et al. (1989) in that most of the additional positive work as a result of the PS contraction was due to the release of stored elastic energy by the SEC, the average contribution from elastic energy being 80%. Future research is required to confirm that the remaining portion of additional work is provided by some non-elastic potentiation of cross-bridge force production. In addition, the mechanism responsible for this form of potentiation needs to be established.

The Cavagna effect. Active stretching has also been shown to modify the elastic properties of the musculotendinous unit (Cavagna, Citterio, & Jacini, 1981). Using frog sartorius muscle, Cavagna et al. (1981) induced high speed shortening from a state of isometric contraction and after stretching the muscle at different speeds and amplitudes. As expected, stretching caused more energy to be released than when shortened from an isometric contraction. It was observed, however, that an additional amount of elastic energy was also released for the same fall in force (from $P_0$ to zero); this was termed an "iso-force" gain in energy. Because the fall in force was the same, it was postulated that this was entirely due to the modification of the elastic properties of the muscle caused by the active stretch. In other words, active stretching of a muscle prior to shortening leads to a greater compliance during the recoil of the SEC. This modification was shown to increase with the speed of stretching; a maximum was
attained at approximately 0.5 $lo/\text{sec}$. A stretch amplitude of 5-6\% of $lo$ elicited the maximum iso-force gain in energy. Cavagna et al. (1981) theorized that this behavior allows the musculotendinous unit to maintain two contrasting desirable capabilities: rapid force transmission and the storage of elastic energy. According to requirements, it can behave in two different ways — as a more rigid structure when the force is developed solely by the CC and as a more compliant structure when an external force is applied as in the SSC.

Since this discovery by Cavagna et al. (1981), the increase in compliance of the SEC due to stretching has been labeled by some researchers as the "Cavagna effect" (Hof et al., 1983; Lensel-Corbeil & Goubel, 1990). More recently, the Cavagna effect has been re-investigated by Lensel-Corbeil and Goubel (1990). They observed the Cavagna effect only when stretches are of sufficient amplitude (> 2.5\% $Lo$) and when the release was made from a length corresponding to 115\% of $Lo$. In view of these restrictions, the value of the Cavagna effect for human movement must be questioned.

Relative length changes of the muscle components. During the pre-stretching phase of a SSC, some researchers have shown that a typical response of the CC is to shorten despite the overall lengthening of the musculotendinous unit (Ettema et al., 1990; Griffiths, 1991). Using rat gastrocnemius muscle, Ettema et al. (1990) discovered that the CC lengthened only at long stretch durations, but this was after some initial shortening had taken place. Griffiths (1991) observed that, in the freely walking cat, gastrocnemius muscle fibers shortened by $1.0 \pm 0.3 \text{ mm}$ during the stance phase of the step cycle while the entire musculotendinous unit was undergoing stretch. This was due to the compliance of the Achilles tendon. Griffiths (1991) suggested that such a compliant tendon may act as a mechanical buffer for the fibers, protecting them from sudden impulses such as those occurring in running and jumping.
Furthermore, a compliant tendon may allow the CC to remain at a more optimal length in terms of the force/length relationship. Gordon, Huxley and Julian (1966) demonstrated that a whole muscle or muscle fiber develops peak force at intermediate lengths. Tension declines as the fiber is either lengthened or shortened from the optimal length. For a given increase in length of the musculotendinous unit, the CC of a muscle with a compliant SEC may not have to lengthen as much as a muscle with a stiff SEC under an active stretch. SEC compliance, therefore, can indirectly affect the force producing capabilities of a muscle by allowing the muscle to perform at a more favorable position on the force/length curve.

Summary and conclusions

Basic research using animal muscle preparations has shown the musculotendinous unit to possess non-linear elastic characteristics when stretched by an external force. The elastic structures consist of tendon and cross-bridge linkages within the muscle fibers. As a result of active stretching, elastic energy is stored within these structures and the force developed by the contractile machinery is enhanced. If a concentric contraction immediately follows an active stretch, the muscle shortens with greater power (the force/velocity curve is shifted along the velocity axis), produces more positive work, and is more efficient than when it shortens from rest or from an isometric contraction. These potentiating effects are mainly due to the release of stored elastic energy. Force enhancement is also a contributor, but to a lesser degree. For positive work, calculations show that elastic energy contributes approximately 80% and force enhancement approximately 20% to the additional work performed.

The magnitude of force enhancement and additional work performed during the shortening phase is affected by both speed and length of the applied stretch. Within limits, the amount of force and positive work output increases with an increase in stretch velocity and stretch amplitude.
The speed of stretching can also influence the degree to which active stretching can modify the elastic properties of the SEC during recoil. SEC compliance is higher during the concentric phase if a muscle shortens after an active stretch as opposed to shortening from an isometric contraction. This modification tends to increase with increasing stretch velocity, a maximum being attained at 0.5 \(lo/sec\). However, stretches of sufficient amplitude are required (> 2.5% \(lo\)). The musculotendinous unit can therefore act as a compliant structure in order to utilize elastic energy when stretched by an external force, and as a more rigid structure to provide a rapid transmission of force when the force is developed internally.

During short stretch durations, a typical response of the CC is to shorten despite the overall lengthening of the muscle-tendon complex. This is due to tendon compliance, a property which may provide protection for the muscle fibers when sudden impulses are applied. In addition, this characteristic may allow the CC to operate at a more favorable length in terms of force production.

In summary, this section has provided insight into the basic mechanisms of the stretch-shortening phenomenon under controlled conditions. Basic research using isolated whole muscle and single fiber preparations has generated convincing evidence that the SSC can potentiate a concentric contraction. The elastic properties of the musculotendinous unit seem to be mainly responsible for the enhancement effect. The following section aims to establish if similar effects occur in more complex situations such as those found in the performance of human motor skills. Specifically, the role that elastic energy plays in running and jumping will be discussed.

**The Influence of Elastic Energy in Skill Performance**

First, the types of skill which may take advantage of the stretch-shortening phenomenon are discussed. The influence of elastic energy on the performance of two common, everyday skills — running and jumping — is then explored.
jumping skills have been the main focus of in vivo experiments designed to investigate the role of elastic energy in human performance. This section establishes the effect of the SSC on these skills in terms of movement efficiency and performance enhancement. From the research findings, the value of elastic energy to skills such as running and jumping is then discussed.

Mechanics of movement

The degree to which various skills take advantage of the stretch-shortening phenomenon depends upon the movement mechanics of the skill. If the movement first imposes an active stretch on the muscles primarily responsible for creating a desired action, then a favorable situation for the storage and release of elastic energy arises. For example, in jumping movements, upward propulsion is generally preceded with a preparatory counter-movement. This acts to forcibly stretch the extensor muscles of the knee joint and the ankle plantar flexors. Likewise, in throwing, the throwing arm is first rotated backwards in the opposite direction to the throw, thereby stretching the prime-movers. During locomotion, however, active stretching of the lower limb muscles during the stance phase is an inherent consequence of the movement pattern.

In contrast to the above-mentioned activities, the major muscles used in skills such as cycling, swimming, and rowing do not normally undergo a SSC, even though the skills are repetitive in nature (Cavagna, 1977; Shorten, 1987). The muscles tend to shorten from a relaxed state; therefore, it is unlikely that the SEC contributes significantly to positive work output. In these types of skills, performance is probably more dependent on the contractile properties of muscle as opposed to skills involving a SSC such as running, walking, and jumping (Shorten, 1987).

Running and walking

Efficiency of movement. The importance of elastic energy in locomotion was first demonstrated by Cavagna, Saibene, and Margaria (1964). After measuring the
external mechanical work (sum of work done against gravity and that due to kinetic energy changes of the center of gravity) and internal mechanical work (that due to limb movements relative to the center of gravity) done in level running, the efficiency of positive work production was calculated by dividing the values for total work (external plus internal) by the net energy expenditure. The value for efficiency turned out to be 40 - 50%, well above the standard efficiency (25%) of the contractile component. It was postulated that this discrepancy was due to elastic energy being used as an additional energy source during the concentric period of the muscular contraction. The contribution from elastic energy was estimated to be approximately half of the total mechanical work performed. These findings prompted the researchers to make the analogy that human running is similar to a bouncing ball. A ball loses kinetic energy as it hits the ground but, in the resulting deformation, elastic strain energy is stored. The deformed structure then recoils to its original shape, losing strain energy but regaining some kinetic energy which propels it off the ground.

Similar results and conclusions have been presented by other researchers (Asmussen & Bonde-Petersen, 1974b; Bosco et al. 1987a; Cavagna & Kaneko, 1977; Ito, Komi, Bosco, & Karlson, 1983; Shorten, 1985). Asmussen and Bonde-Petersen (1974b) investigated the effect of various horizontal loads on the apparent efficiency (defined as $\Delta$ mechanical power/ $\Delta$ metabolic rate) of both walking and running. In the same subject, apparent efficiencies of 53.8 and 32.3% for running and walking respectively were reported. The large difference between these efficiencies is not surprising because the mechanics of running give rise to a greater potential to store and recover elastic energy during each stride than the mechanics of walking (Cavagna, 1977). Nevertheless, the value for walking suggests that, in walking, the possibility of some recovery of mechanical energy also exists.
In follow-up work, several researchers sought to determine how elastic energy return and the efficiency of walking and running was affected by the speed of locomotion (Cavagna & Kaneko, 1977; Ito et al., 1983). Cavagna and Kaneko (1977) determined that, in walking, efficiency reached a maximum (35 - 40%) at intermediate speeds whereas, in running, efficiency gradually increased (45 - 80%) with speed. A greater relative amount of elastic energy used in the concentric or propulsive phase of the step cycle at higher speeds was the reason given for the trend in running. It was theorized that, as the speed of running increases, so does the rate of active stretching which, as isolated muscle studies have shown (Cavagna et al., 1981; Cavagna, 1977), can increase the amount of elastic energy storage.

In conflict with the findings of Cavagna and Kaneko (1977), Ito et al. (1983) showed that efficiency remained relatively constant with increasing running speed. Nevertheless, a relatively high value (55%) for efficiency was obtained. Again, this was attributed to extra energy being delivered to the system by the recoil of the SEC during the concentric phase of muscular contraction. Elastic energy, therefore, was assumed to be solely responsible for the inflated efficiency results.

The authors quantified the contribution of elastic energy by calculating the difference between expected positive work output (calculated as the product of metabolic cost and the efficiency (taken as 20%) of the CC) and the measured positive work output. The absolute amount of the extra work contribution increased with running speed; the relative amount, however, remained constant.

The discrepancy between the results of Cavagna and Kaneko (1977) and Ito et al. (1983) is probably due to the differences in mechanical work calculations. In the latter study, the transfer of energy within- and between-body segments was taken into consideration whereas, in the former study, no such allowances were made. If energy transfer is not considered when calculating work output, the corresponding values for
efficiency will be artificially inflated. This effect may be more marked at higher speeds, which would explain why Cavagna & Kaneko (1977) found efficiency to increase with increasing running speed.

In a more direct attempt to determine the contribution of elastic energy storage to energy conservation in running, Shorten (1985) calculated mechanical energy transformations during a typical step cycle using two configurations for the energy model. Both utilized the segmental kinetic and potential energy approach, including within- and between-segment energy transfers; however, in one model elastic energy stored in the knee extensors was added to the model whereas, in the other model, this was not done. Elastic energy storage was estimated from the knee extension moment and an angular compliance function. The inclusion of stored energy significantly reduced the net efficiency from 43% to 34% suggesting that elastic energy contributions were significant in relation to the magnitude of changes in the whole-body energy curve (Shorten, 1985). The possibility, though, that some of the stored elastic energy was dissipated as heat was not investigated. If this had occurred, the contribution of elastic energy to mechanical work would have been less. However, the estimates for energy storage related only to the knee extensors. The plantar flexors and the arch of the foot are also sources of elastic energy storage (Alexander, 1987). For a more complete analysis, therefore, estimates of energy storage in these structures should also have been considered. This would have served to reinforce the notion that the SEC of muscle acts as an energy-conserving mechanism.

Nevertheless, all the above-mentioned studies indicate that the SEC can serve as such a mechanism in human movement, and that the use of elastic energy is not limited to isolated contractions in vitro. Efficiency values for groups of muscles in intact humans performing the multi-jointed skill of locomotion have been shown to be similar to those for isolated muscles performing a SSC under controlled movement conditions.
Because previous work strongly suggests that the use of elastic energy is primarily responsible for the high efficiencies found in isolated muscle contractions, it seems reasonable to speculate that muscle elasticity is also primarily responsible for the similar efficiency values found in running. In fact, such a speculation has been made by all the investigators who have shown high running efficiencies to exist (Asmussen & Bonde-Petersen, 1974b; Bosco et al. 1987a; Cavagna & Kaneko, 1977; Cavagna, Saibene, and Margaria, 1964; Ito et al., 1983; Shorten, 1985). Further evidence supporting the idea that elastic energy is largely responsible for reducing the metabolic energy demand in running will be presented in a later section (see Location of elastic energy storage). The next section, however, explores the possibility that muscle and tendon elasticity can also have a potentiating effect on mechanical power.

**Enhancement of power.** Most investigations studying the influence of elastic energy in running have focused on the efficiency of movement as the dependent variable. While this is an important determinant for success in aerobic activities such as long distance running, successful performance in sprinting events is more dependent on the rate of work production or mechanical power. Cavagna, Komerek, and Mazzoleni (1971) measured power during sprint running by means of a force platform. Power was calculated from the start of the run (zero velocity) to the speed attained at maximal effort (about 9.5 m/s). At speeds lower than 6 to 7 m/s, the power/velocity curve was similar to the classical curve developed for isolated muscle (Hill, 1938). In isolated muscle, maximum power is attained at approximately one-third the maximal speed of shortening. At higher velocities therefore, the maximal force and power should decrease, thereby limiting the running speed. In fact, a peak in the power/velocity curve was obtained at a velocity of 5 m/s, with a decrease in power taking place thereafter until a velocity of about 7 m/s was reached. At this point, however, the following events occurred: 1) power increased markedly, 2) the average propelling force stopped
decreasing and became constant, and 3) the negative work done at each step began to increase. On the basis of previous work (Cavagna, Dusman & Margaria, 1968; Cavagna, Komerek, Citterio, & Margaria, 1971), and because the onset of the power increase coincided with an appreciable increase in negative work, it was postulated that the high power developed at the highest speeds was made possible by the contribution of elastic energy stored in the muscles which were actively stretched during the stance phase. Furthermore, as pointed out by the authors, the recovery of this energy may require an appreciable degree of skilled movement. One subject showed considerable power up to 5 m/s, but displayed the lowest maximal power and speed, indicating that the work absorbed by his muscles at the highest speed was not taken advantage of. Evidently, a technique factor may be involved; however, confirmation of this speculation awaits future research.

**Location of elastic energy storage.** The studies discussed thus far suggest that during running, muscles and their respective tendons act in a similar fashion to springs — they are deformed by an external force, and then recoil once the force is removed, releasing energy which was stored during the deformation. The question now is: Where are these springs located? The most obvious candidates are the leg muscles that are active while the foot is on the ground — the extensor muscles of the hip, knee, and ankle. During contact, the hip extensors tend to shorten performing positive work and therefore do not meet the requirements to serve usefully as springs (Brandel, 1973; Ito et al., 1983). On the other hand, the knee extensors and plantar flexors both actively lengthen during the support phase; thus, they are both instrumental in providing a spring-like property to the lower extremity (Ito et al., 1983). However, the relative contribution of energy from each muscle group in terms of the total elastic energy being stored and released has yet to be firmly established. This is because, presently, there are no direct methods with which to accurately measure elastic energy contributions during
either walking or running. The best that can be done is to estimate such values by making various assumptions about the structural properties of the musculotendinous unit under consideration. Assumptions also have to be made when calculating the magnitude of force in the unit and the amount of deformation caused by the force. For example, Ker, Bennet, Bibby, Kester, and Alexander (1987) estimated the strain energy stored in the Achilles tendon of a 70 kg man running at 4.5 m/s from a series of indirect measurements. The magnitude, direction, and point of ground reaction force application were taken from the work of Cavanagh and Lafontune (1980). By taking moments about the ankle, the force in the Achilles tendon was calculated to be 4.7 kN. This approach must have assumed that the triceps surae muscle group was solely responsible for the forces acting across the joint. Furthermore, the moment arm of the tendon about the joint could only be estimated. The cross-sectional area and the effective length of the tendon (which was taken as the distance from origin to insertion minus the length of the muscle fibers) was estimated from amputated feet. The stiffness characteristics of the tendon were assumed to be the same as for other human tendons that are more suitable for tensile testing in dynamic testing machines. Similarly, using tensile test results from other tendons, the Achilles tendon was assumed to stretch by 18 mm at the calculated load of 4.7 kN. From the above assumptions and calculations, it was estimated that the tendon could store 35 J of energy during the support phase.

A further 2 J of energy storage was calculated for the fiber portion of the triceps surae complex. The mass of the fibers was taken as 0.8 kg and it was assumed that the muscle exerted its maximum isometric stress. Even using the data of Alexander and Bennet-Clark (1977), who calculated the energy storage capacity of cross-bridge linkages to be 4.7 J/kg muscle, a value of only 3.8 J can be obtained. From these calculations, it is apparent that, in muscles with long tendons and short fibers, elastic energy resides mainly in the tendon.
In the above scenario, Ker and his coworkers made no attempt to estimate the amount of energy stored in the quadriceps. Alexander (1988) pointed out that this muscle group may serve as a spring but, without giving any explanation as to why, dismissed the notion of it playing a significant role. Shorten (1985), however, found evidence to suggest otherwise. From the knee extension moment and an angular compliance function, the change in energy of the quadriceps SEC was estimated as the work done by the moment against the series elasticity. The net knee joint moments and forces during treadmill running were determined by analyzing the body as a 15-segment model using motion analysis techniques. Stored energy was found to increase as the extensors contracted eccentrically during the support phase, reaching a peak value of 66 J after 100 ms.

Although this value (66 J) is much higher than that calculated for the Achilles tendon (Ker et al., 1987), the ability to recover the stored energy also has to be taken into account. Dynamic testing has revealed that about 93 percent of the work done in stretching a tendon may be returned during its recoil when the stretching load is removed (Alexander, 1987). In muscle fiber though, a lower percentage of recovery probably occurs due to elastic energy storage being dependent upon the cross-bridge attachments. As soon as a cross-bridge becomes detached, the strain energy it stores is immediately dissipated as heat and cannot be used in the concentric phase (Huxley & Simmons, 1971). This may occur if an applied stretch becomes too excessive (Rack & Westbury, 1984) or the period of time between the eccentric and the following concentric contraction exceeds the duration of the attachment portion of the cross-bridge cycle (Cavagna & Citterio, 1974). Muscles which are better suited for useful recovery of stored elastic energy, therefore, should have relatively long tendons and short muscle fibers, a characteristic of pennate muscles. The triceps surae complex is a good example and, consequently, has a high potential for using the energy that it may store. The
quadriiceps however, even though they are pennate muscles, have a higher fiber/tendon length ratio and, thus, may not be as effective as the triceps surae in returning elastic energy to the musculoskeletal system during running. For this reason, Alexander (1988) suggested the triceps surae and Achilles tendon complex to be the most effective spring.

In support of Alexander's suggestion, Hof et al. (1983) presented evidence to show that the triceps surae complex can also behave like a spring during walking. They determined calf muscle moment and work in level walking by inputing experimentally derived data from human subjects into a computer simulation of the movement. The model enabled the interaction between the CC and SEC to be studied. The calf muscle contractions were shown to be always eccentric-concentric; the muscle first stretched as the muscle moment increased to a maximum (ankle dorsiflexion), then shortened (ankle plantar flexion) as the moment decreased rapidly, reaching a value of essentially zero at toe off and during the swing phase. There were often short periods during dorsiflexion, however, when the moment decreased, especially after an initial peak. It was thought that these fluctuations signified "slips" in the CC; in other words, the cross-bridges were forcibly detached. If this was the case, part of the elastic energy that may have been stored would have been lost as heat. Nevertheless, the positive work of the CC was still appreciably lower than the total positive work of the muscle. This suggests that, although not optimal, an important contribution to positive work was still supplied by the stored elastic energy in the SEC.

In addition to providing additional positive work at a negligible metabolic cost, the results of the above study also revealed other advantages of the SEC elasticity. First, the length of the CC changed over a smaller range than did the length of the musculotendinous unit, allowing the CC to remain close to the optimum point of the force/length relationship. Secondly, due to the velocity of shortening being augmented
by recoil of the SEC, the shortening speed of the CC was kept relatively low and in the most efficient range. Ankle angular velocity was as high as 6 rad/s during push off, but the CC velocity was usually between 0.4 and 1 rad/s. Finally, the SEC allowed a peak power much higher than the maximum contractile power to be developed. The physiological limit for the CC is estimated to be between 150-250 W/kg of muscle mass (Hof et al., 1983). However, a peak power of 450 W was reported at the larger step lengths. The authors explained that, without the "catapult action" of the SEC, a calf muscle mass two to three times the actual mass would be required to achieve this value.

A third structure which may usefully serve as a spring during running is the arch of the foot and its associated ligaments (Ker et al., 1987). The forces loading the foot during mid-stance tend to flatten the longitudinal arch: films of barefoot runners have shown that the ankle joint is forced about 10 mm nearer the ground than when the foot is unloaded (Alexander, 1987). This means that the ligaments supporting the arch must stretch in order for this to happen.

The elastic properties of the arch were investigated by Ker et al. (1987) in experiments with human feet that had been amputated because of disease. The same loading pattern as that during the support phase of running was imposed on the feet by a dynamic testing machine. It was found that the foot deformed and then recoiled, returning 78% of the strain energy. After cutting the plantar aponeurosis, the long and short plantar ligaments, and the spring ligaments in turn, all the major ligaments of the arch were shown to be important contributors to the spring mechanism. The amount of energy stored was dependent upon the load applied. A force of 6.4 kN at the ankle joint was required to simulate the force pattern when running at 4.5 m/s. This was not feasible because the calcaneous was crushed at its contact with the steel block of the testing machine under such loads (the skin and adipose tissue of the heel had been removed). However, the arch stored 10 J of strain energy at a load of 4 kN and it was
estimated by extrapolation that 17 J would be stored at 6.4 kN. This means that 13 J of energy may be available for use as mechanical work. Although this is not as substantial as the amount of elastic energy estimated to be available from the triceps surae and quadriceps, the contribution of energy from the arch of the foot is still important. This is evident from calculations performed by Ker et al. (1987). They estimated that the external energy lost then regained in the stance phase of a 70 kg man running at 4.5 m/s is about 100 J. Approximately half of this energy, therefore, can be stored as strain energy in the triceps surae and the arch of the foot. In the above scenario, Ker et al. (1987) calculate that 35 J is stored in the Achilles tendon, 2 J in the muscle tissue of the triceps surae, and 17 J in the structures of the arch of the foot — a total of 54 J. Also, Shorten (1985) estimated that the quadriceps may be capable of storing 66 J in subjects running at a similar speed; but, because mean subject mass was not reported, it would be incorrect to add this amount to the total calculated by Ker et al. (1987). Nonetheless, the findings of Shorten tend to suggest that the quadriceps also play a major role in the storage of energy. It is likely, therefore, that a 70 kg man running at 4.5 m/s has the potential to store much more than 54 J of energy in the structures of the leg and foot during the support phase of the step cycle. Consequently, these calculations strongly indicate that the mechanism of elastic energy storage and reuse is the primary reason why humans can locomote with a greater efficiency than the inherent efficiency of concentric muscular contraction.

Jumping

Efficiency of movement. Studies investigating the use of elastic energy in jumping have largely focused on the enhancement of power and jumping performance rather than the efficiency of the skill. This is not surprising because, in most events which involve a jumping action, there is rarely a requirement for continuous, repetitive jumping. Efficiency of the movement, therefore, is not usually a major concern.
Nevertheless, several studies (Belli & Bosco, 1992; Bosco et al., 1987a; Bosco et al., 1987b; Bosco et al., 1982; Thys, Cavagna, & Margaria, 1975) have investigated the efficiency of muscular work during jumping. Their purpose has been to determine if elastic energy is used to the same degree in jumping as it is in running.

In jumping, the opportunity exists to compare jumps with and without pre-stretching the muscles primarily responsible for propelling the body upwards. Typically, subjects have performed a series of rhythmic, vertical jumps under rebound and no-rebound conditions (Bosco et al., 1982; Bosco et al., 1987a; Belli & Bosco, 1992). In the rebound condition, concentric work takes place immediately after the stretching phase. In other words, the time in-between the eccentric and concentric phases (coupling time) is negligible. This allows a following jump to be performed from a pre-stretch condition, thereby creating a SSC. In the no-rebound condition, however, a short delay (typically 0.5 s) between the two phases is introduced to ensure the concentric phase is performed from an isometric contraction, rather than allowing any pre-stretch activity.

The efficiency of mechanical work under no-rebound conditions has been used to represent the efficiency of the CC. For the CC, efficiency values have ranged between 17 and 19%, generally lower than the efficiency of isolated muscle. Activation of additional muscles other than those creating the positive work could account for this difference (Belli & Bosco, 1992). Under rebound conditions, however, much higher values have been found (27 to 58%). This has been taken as evidence that a portion of the positive work does not derive from the conversion of biochemical energy, but is delivered, free of cost, by the SEC as it recoils during the concentric period (Belli & Bosco, 1992; Thys et al., 1975). In the no-rebound condition, there is not the possibility for this recoil to occur. The brief delay between the eccentric and concentric phase is enough time to allow any stored elastic energy to be lost as heat (Cavagna,
the work performed, therefore, is solely reliant on the energy delivered by the CC.

Although rebound jumps are performed with a higher efficiency than no-rebound jumps, the results of several studies show that rebound jump efficiencies are generally lower than the efficiency of running (Belli & Bosco, 1992; Bosco et al., 1987a; Bosco et al., 1987b). For example, Bosco et al. (1987b) found the mean efficiency of a group of athletes to be 55% during treadmill running at 3.33 m/s, 27.8% while performing repetitive vertical jumps under rebound conditions, and 17.2% for jumps with no rebound. Because the velocity of muscle shortening was shown to be similar in both running and jumping, the discrepancy between the efficiencies of running and rebound jumping could not be attributed to a different rate of cross-bridge turnover. Instead, running may utilize a greater amount of elastic energy as a percentage of the total positive work output (Bosco et al., 1987b). Evidence for this is provided by elastic energy storage estimations and positive work output calculations. Approximately 100-130 J of energy has been estimated to be stored in the elastic tissues during a single step or jump (Ito et al., 1983; Shorten, 1985; Ker et al., 1987; Thys et al., 1975). However, the positive work output during each step in running (100-150 J) has been shown to be substantially lower than that performed during a jump (530 J) (Alexander, 1988; Ito et al., 1983; Bosco et al., 1987b). Thus, a greater relative contribution of elastic energy to the positive work output might account for the higher efficiency values obtained in running.

In support of this notion, Thys et al. (1975) showed the efficiency of jumping to be similar to running when the amplitude of movement was very small — the positive work performed at each jump was only 173 J. Although only two subjects were studied, in each case the resulting efficiency was relatively high; one subject achieved an efficiency of 58% and the other 44%. These values are similar to those found in
running and are much higher than those calculated for vertical jumps in which a much greater amount of positive work was performed. Comparable findings have also been noted in isolated muscle (De Haan et al., 1989). It is reasonable to assume, therefore, that the effect of elastic energy on efficiency is greater at smaller positive work outputs.

A relationship has been shown to exist, however, between the efficiency of muscular work during large amplitude jumping and the energetics of running. Bosco et al. (1987a) represented the effect of a pre-stretch on the efficiency of jumping as the ratio of rebound jump to no-rebound jump efficiency. This ratio was shown to have a significant and negative correlation with energy expenditure during treadmill running at a speed of 3.3 m/s. One may therefore speculate that individuals who are highly economical runners have a greater ability to use energy stored in the elastic components of muscle during the period of negative work. This speculation must assume, however, that the higher efficiencies obtained when performing rebound jumps are primarily the result of elastic potentiation. Bosco et al. (1987b) suggested that this may not entirely be the case and proposed an additional mechanism. They pointed out that, in movements which involve a SSC, positive work is performed in a shorter time than in movements performed without a pre-stretch. It was assumed that this results in higher efficiencies because less energy is expended due to the muscle being active for less time. To support their comments, data were presented which showed the time of positive work production in both running and rebound jumps to be significantly less than that in no-rebound jumps. Furthermore, when they combined the results of several studies (Bosco et al., 1982; Bosco et al., 1987a; Ito et al., 1983), mechanical efficiency in both running and jumping performance demonstrated a strong relationship with the time of positive work. The credibility of their argument, however, is undermined by comparing efficiencies with the time to accomplish varying amounts of positive work rather than a given amount. A reduction in the amount of positive work may be the reason for
decreasing the time in which the work is done; therefore, an increase in efficiency may simply be due to a greater relative amount of elastic energy being used. Moreover, because the recoil of elastic elements augments the velocity of the CC (Cavagna & Citterio, 1974; Hill, 1950; Shorten, 1987), the elastic phenomenon may directly be responsible for a shorter positive work time in movements with a pre-stretch.

Further evidence supporting the role of elastic energy in jumping was provided by Belli & Bosco (1992). They had subjects perform a series of vertical plantar flexions (PF) and a series of vertical rebounds (RJ) on a force platform. The subjects' knees were locked so that the movement was performed exclusively with the triceps surae muscle group. External work performed by the center of gravity (CG) was determined from the force/time trace. A mechanical model was also used to calculate the portion of work performed by the CC and SEC in both activities. As expected, there was a significant difference between the values of external mechanical efficiency (calculated from the work performed by the center of gravity) for PF (17.5%) and RJ (29.9%). No significant differences existed, however, between the muscle efficiencies calculated from the work performed by the CC (17.4% in PF and 16.1% in RJ). Consequently, it was concluded that the differences in external mechanical efficiency reflected the storage and return of elastic energy rather than CC efficiency.

The mechanical model also revealed the actions of the CC and SEC while the foot was in contact with the force plate. During downward movement of the CG, the CC oscillated but mainly performed concentric work while the SEC lengthened. As outlined previously, this behavior has also been noted in walking (Hof et al., 1983) and is important in producing peak powers that are much higher than the maximum power of the CC. Not only may this increase efficiency by reducing the time to perform a given amount of work, an increase in power may also enhance the performance of the jump
Power output and other factors pertaining to jumping performance are now considered in the following section.

Enhancement of performance. As early as 1885, Marey and Dumeny (cited in Cavagna, 1977) noticed that when two jumps are performed in succession, the second jump is always higher than the first. These investigators suspected that some mechanical energy was stored during the landing phase of the first jump and then used to enhance the second jump height. Since then, various researchers have confirmed and quantified their observations (e.g., Asmussen & Bonde-Petersen, 1974; Bosco, Tarkka, & Komi, 1982; Cavagna, Komarek, Citterio, & Margaria, 1971). Maximal jumps with and without pre-stretch have been used to determine the effect of the SSC on parameters such as jump height, power output, work output, and ground reaction force profiles. Jumps without pre-stretch are initiated from a semi-squatting position in which no preparatory counter-movement is allowed; they are known as static jumps. For the pre-stretch condition, two types of jump have been employed — the counter-movement jump and the drop jump. In the counter-movement jump, the subject starts from an erect position then performs a downward counter-movement, ideally to the same starting knee angle as the static jump with which the jump is to be compared; at this instant, the body is propelled upwards to complete the jump. The drop jump involves the subject dropping from a variable height platform prior to jumping upwards. All jumps are normally performed with the subjects’ hands on their hips because the contribution of the arms to the vertical jump may be 10% or more (Luhtanen & Komi, 1978).

The static jump and counter-movement jump were analyzed by Cavagna et al. (1971), but they also had subjects perform two jumps in succession as suggested by Marey and Dumeny (1885). All jumps were performed on a force plate in order to record the ground reaction force, power output, vertical velocity, and vertical displacement of the body's center of gravity. Average results revealed that no
substantial differences existed between the two types of jump involving a pre-stretch (counter-movement jump and the second jump of a series of two). Significant differences did occur though between the jumps utilizing a pre-stretch and the jump with no pre-stretch (static jump). Although the height of the jump was 10% higher in the jumps with a pre-stretch, the most noticeable difference was in the time to perform positive work — average power was about 70% greater in the jumps involving a counter-movement. Cavagna et al. (1971) suggested that this was a consequence of the greater force developed; they reasoned that a greater force would have caused a larger upward acceleration and, therefore, decreased the time to reach a given speed.

However, a greater force would also have imposed a greater stretch of the elastic elements and potentiated the effect of their recoil; therefore, the SEC would have provided an additional source of power enhancement.

In similar experiments, the counter-movement jump has resulted in an increase in jump height of 5.5% (Asmussen & Bonde-Petersen, 1974a), 13.5%, 16.7%, and 21% (Komi & Bosco, 1978). The inconsistency of these results may be due to several reasons. First, in order to compare the performance of the counter-movement jump to the static jump, the upward movement should be initiated from the same starting knee angle. This is because the amplitude of muscular contraction can influence performance (Cavagna, 1977; Bosco, Komi & Ito, 1981). None of the above-mentioned studies appeared to control for this. Secondly, subject characteristics may have influenced performance. Komi and Bosco (1978) observed differences in performance enhancement between women physical education students, men physical education students, and male volleyball players. Although the absolute values for female jumping heights were less than those of their male counterparts, the relative increase in height after a pre-stretch was greater (21% compared with 15%). When considering men only, the volleyball players were more proficient at utilizing the effect of the pre-stretch to
increase jump height (16% compared with 13.5%). These results suggest that gender and skill level may influence the ability to store and reuse elastic energy. Finally, problems exist with the methods used for calculating jump height. In all the above studies, investigators calculated jump height to be 1.226 times the square of the duration the subject was airborne. For this to be true, the CG of the body must be the same at landing as at take-off. Invariably, this does not happen in practice as an individual’s posture is rarely the same at landing as at take-off. A better method is to directly determine take-off velocity by integrating the force trace. Jumping height is then, simply:

\[ \frac{V^2}{2g} \]

where \( V \) = vertical velocity at take-off, and \( g \) = gravitational constant (9.81 m/s\(^2\)). Nevertheless, regardless of the methodological inadequacies, counter-movement jumps have always elicited a greater jumping height than static jumps, and the contribution of elastic energy has generally been accepted as the mechanism responsible for this effect (Asmussen & Bonde-Petersen, 1974a; Bosco, Tarkka, & Komi, 1982; Cavagna, Komarek, Citterio, & Margaria, 1971).

The second type of pre-stretch jump, the drop jump, has been used as a means of imposing a greater stretch than that produced by the counter-movement jump (Asmussen & Bonde-Petersen, 1974a; Bobbert et al., 1986b; Komi & Bosco, 1978; Lees & Fahmi, 1994). The expectation has been that jumping from a height would stretch the elastic elements more and, therefore, a greater rebound height would result. However, the data from studies investigating the effect of drop jumps are equivocal. Although the drop jump has always resulted in a greater jumping height than the static jump, this has not been the case when comparing the drop jump with the counter-movement jump. The drop jump has been shown to enhance jumping height (Asmussen & Bonde-Petersen, 1974a; Lees & Fahmi, 1994) and produce no significant difference.
(Komi & Bosco, 1978, Bobbert et al., 1986b) in comparison to the counter-movement jump. Bobbert (1990) established, however, that the drop jump always displayed a greater power output than the counter-movement jump.

It may be possible to explain why the drop jump has not always elicited a greater jump height than the counter-movement jump by considering the technique employed in each jumping condition. After undertaking an extensive biomechanical analysis of the drop jump, Bobbert et al. (1986b) noticed that two distinct movement strategies were present — some subjects made a large amplitude movement after landing from the drop (this strategy was called a counter-movement drop jump or CDJ), whereas others chose to make a small amplitude movement (a technique referred to as bounce drop jump or BDJ). The choice of strategy seemed to be arbitrary and could not be related to any anthropometrical variables. Because the type of drop jump executed appeared to influence the degree to which the drop jump differed from the counter-movement jump, a follow-up study was carried out in which the jumping technique was controlled (Bobbert, Huijing & van Ingen Schenau, 1987). Subjects performed a counter-movement jump, a BDJ and a CDJ in random order from a drop height of 20 cm. The maximum downward displacement of the body's CG was greatest in the counter-movement jump (CMJ); it was 12 cm lower than in the CDJ and 24 cm lower than in the BDJ. This was due to greater hip and knee joint angles in the counter-movement jump at the start of the push off phase. These differences in movement amplitude were accompanied by substantial differences in the time during which the body's CG was accelerated upwards (BDJ<CDJ<CMJ). Despite this, only slight differences were noted in vertical velocity at take off and in jumping height (BDJ=CDJ<CMJ). Vertical acceleration, therefore, was greatest in the BDJ (the jump reached a similar take-off velocity as the other jumps but in less time), the result of a greater vertical resultant GRF during the push off phase. The resultant GRF is a product of muscular forces creating
moments about the joints. In the BDJ, the muscles created larger moments at the knee
and ankle joints (BDJ > CDJ > CMJ) as well as a larger power output about these joints
(BDJ > CDJ = CMJ).

Several possible mechanisms were proposed by Bobbert et al. (1987) to account
for the above findings. First, they suggested that each jumping technique may have
elicited different CC and SEC shortening velocities, even though similar shortening
velocities existed for the respective musculotendinous units during the 75 ms period
prior to take-off (no differences between respective joint angular velocities were present
during this time). The plantar-flexing moment declined more rapidly in the BDJ than in
the other two jumping conditions, therefore it is likely that the series elastic elements
shortened faster in the BDJ. Thus, the contractile elements would have shortened less
rapidly in the BDJ to maintain a similar overall musculotendinous unit shortening
velocity as the respective units in the other types of jump. According to the
force/velocity relationship, this would have allowed the CC to produce a larger force in
the BDJ and, hence, a larger power output.

Bobbert et al. (1987) also proposed that the pre-stretch may have directly
influenced the force generating properties of the CC (as opposed to indirectly
influencing force production by the action of the SEC). Isolated muscle studies have
indicated that an eccentric action or active pre-stretch potentiates the amount of force that
can be generated by each cross-bridge (Cavagna & Citterio, 1974; Cavagna et al., 1985,
Edman et al., 1978). The amount of potentiation increases with stretching velocity
(Edman et al., 1978) and decreases with the length of the time interval (coupling time)
between the eccentric and concentric phase (Cavagna & Citterio, 1974; Edman et al.,
1978). Bobbert and his colleagues pointed out that these variables differed between the
jumping conditions; the highest and lowest stretching velocities occurred in the BDJ and
counter-movement jump respectively, and coupling time was the shortest in the BDJ and
longest in the counter-movement jump. It was suggested, therefore, that the greatest amount of cross-bridge force potentiation may have occurred in the BDJ and the smallest amount in the counter-movement jump. It is difficult, however, to separate this mechanism from the mechanism of elasticity; any increase in force would result in a greater stretch of the elastic elements and, hence, would increase the amount of stored elastic energy.

The final mechanism to be considered was the possibility that higher activation levels of the knee extensors and plantar flexors occurred during drop jumping. Lengthening of active muscles has been shown to evoke a stretch reflex (Bosco & Komi, 1979; Bosco, Tarkka & Komi, 1982) controlled by muscle spindles. This reflex increases the neurological input to the muscle under stretch and therefore could increase the force of contraction at the end of the eccentric phase. This mechanism is referred to as myoelectric potentiation (Bosco et al., 1982). Such potentiation increases with the velocity of the stretch and is maximum at the end of an eccentric contraction. Activation levels then decrease; therefore, in order to elicit maximum facilitation of the concentric phase, coupling time between eccentric action and concentric contraction should be minimized (Hamill & Knutzen, 1995). Bobbert and his coworkers (1987), however, did not find any evidence to suggest that stretch reflex was a major cause of the differences observed in mechanical output, even though each type of jump displayed differences in stretching velocity and coupling time. Electromyography (EMG) levels for the knee extensors and plantar flexors were only slightly higher for the drop jumps than for the counter-movement jump, and no differences were obtained between each type of drop jump. Consequently, Bobbert et al. (1987) concluded that myoelectrical potentiation could not adequately explain the mechanical output differences between each type of jump during the propulsive phase. In light of this, one could speculate that each pre-stretching technique caused different magnitudes of propulsive mechanical output.
mainly by effecting to different degrees the interrelated mechanisms of elasticity and cross-bridge force enhancement.

An interesting addition to Bobbert et al.'s (1987) work might be to also examine a static jump. This jump does not require a pre-stretch and, consequently, should not evoke a stretch reflex. One would therefore expect to see a significant difference in myoelectric potentiation between jumps with and without a pre-stretch. Bosco, Viitasalo, Komi, and Luhtanen (1982) have attempted to establish the effect of myoelectrical potentiation in jumping although equivocal results were obtained. The fact that only three subjects were analyzed, however, made establishing the role of the stretch reflex mechanism in jumping difficult. In two subjects, no differences were noted, but one subject displayed a greater integrated EMG (IEMG) value in the counter-movement jump than in the static jump.

More conclusive results were obtained by Bosco, Tarkka and Komi (1982), although a modified jumping technique was analyzed—subjects performed jumps using plantar flexion only. To ensure that the movement was produced solely by the calf muscles, an orthopedic cast was used to immobilize both the knee and hip joints. Subjects then performed maximal vertical jumps with and without pre-stretching the plantar flexors. In the no pre-stretch condition, plantar flexion was performed from a static position with the foot flat on the ground (static jump), while the pre-stretching condition required the subject to first perform a preparatory counter-movement from a toe-standing position (counter-movement jump). Electromyography results showed that calf muscle activation during the concentric phase was significantly greater in the counter-movement jump than in the static jump. Similarly, the upward displacement of the body's CG and the average ground reaction force was of greater magnitude in the counter-movement jump. Average ground reaction force differences between the static jump and counter-movement jump were reflected in muscle activation levels. The
authors interpreted these findings as evidence that myoelectrical potentiation, initiated by
the stretch reflex, makes a significant contribution to the enhancement of performance
when an active pre-stretch is performed. They did, however, acknowledge that elastic
energy was also an important contributor to performance enhancement. Their
conclusion was based on the calculation of the IEMG/average force ratio during the both
the static jump and counter-movement jump conditions; this ratio was significantly
smaller in the counter-movement jump, indicating that a smaller amount of electrical
activity was necessary to develop the same amount of force. The relative contribution of
elastic and myoelectrical poteniations was estimated to be 72% and 28% respectively.
These calculations may be erroneous, however, because any increase in myoelectrical
potentiation results in a concomitant increase in elastic potentiation. Moreover, no
derivation details were presented, therefore Bosco et al.'s estimations must be treated
with caution.

Clearly, more work needs to be done in this area. The finding that muscle
activation can be increased by active pre-stretching in the simple, single joint movement
of plantar flexion (Bosco et al, 1982) is enough to warrant further research into the role
of the stretch reflex mechanism in more complex, multi-joint movements such as
unrestricted jumping. Not only should more subjects be employed, but the effect of
jumping technique on the level of myoelectric potentiation should be investigated.
Perhaps EMG could be used as a biofeedback technique to optimize a coordination
pattern that would elicit a maximum effect of the stretch reflex. Such a paradigm may
prove to be an elegant one because, if the procedure has a positive effect, the storage and
return of elastic energy would also be maximized as similar variables influence the
degree to which the two mechanisms are activated. If both the stretch reflex and the
storage and return of elastic energy can be enhanced, it is likely that a concomitant
enhancement of jumping performance would ensue.
The potential to further enhance jumping height by optimizing the pre-stretching technique is evident from previous studies (Asmussen & Bonde-Petersen, 1974a; Bobbert et al., 1987; Cavagna et al., 1971). Power output, rather than jump height, has proved to be the dependent variable most enhanced by an active pre-stretch. An increase in power has not led to substantial improvements in jump height because, usually, power enhancement has coincided with a decrease in movement amplitude, a result of the jumping strategy employed (Bobbert et al., 1987). Consequently, positive impulse (the integral of the ground reaction force/time trace during the concentric phase) has probably not been significantly increased by the pre-stretching techniques used. To jump higher, it is important to maximize positive impulse because it is this variable which is responsible for the change in momentum (the product of mass and velocity) of a body (Hibbeler, 1989). As an individual's body mass remains constant during a jump, it follows that positive impulse is correlated to the velocity at take-off — the variable that determines the height of the jump. Through EMG biofeedback training, it may be possible to manipulate the pre-stretching technique — and therefore the mechanisms of myoelectrical potentiation and elasticity — so that high forces are created over larger movement amplitudes. Thus, larger positive impulses would be generated which, in turn, would produce greater take-off velocities and, consequently, improvements in jump height.

There seems to be little doubt that the SSC is an effective means to enhance jumping performance. However, whether or not individuals can further enhance jumping performance by optimizing the coordination of the pre-stretching phase is a question that remains unanswered. As in the skill of sprinting, the optimal technique to elicit the maximum potentiation effect from muscle elasticity and myoelectric potentiation awaits future research.
Summary and conclusions

Tendon and muscle elasticity play an important role in many human movement skills. In skills such as running and jumping, elasticity contributes to the effectiveness and efficiency of performance through the mechanisms of force enhancement and elastic energy storage. If the mechanics of the exercise are such that a concentric contraction immediately follows an active stretching phase, an appreciable amount of elastic energy can be recovered and used for positive work. Calculations show that, in certain situations, elastic energy may be responsible for approximately half of the positive work produced. Elastic energy is essentially free of metabolic cost, therefore, efficiency of positive work production increases beyond that expected from the transformation of chemical energy into mechanical work by the contractile component of muscle.

In events dependent on power such as sprinting and jumping, a stretch-shorten movement can also elicit an increase in positive work production and power output. For example, in sprinting, a sudden increase in power can occur when an individual approaches maximum speed. This happens to coincide with an increase in the negative work done in each step, which suggests that a greater stretch and recoil of the elastic elements is partly responsible the power increase. Evidently, a skill factor may also be involved but, because the research in this area is scant, further work should be undertaken to either confirm or refute this speculation.

In jumping, power output is substantially increased when a jump is performed with a pre-stretch rather than jumping from a static position. Although muscle elasticity plays an important role in enhancing power output, other mechanisms may also be contributors to this effect. Myoelectric potentiation, via the stretch reflex, can increase the force of contraction during the concentric phase and therefore increase power. Also, an active stretch may enhance the force-generating capability of the contractile machinery directly by increasing the ability of each cross-bridge to develop force. It is difficult to
estimate the relative contribution of each mechanism, however, because any increase in either myoelectric potentiation or the force-producing ability of each cross-bridge results in a concomitant potentiation of the storage and release of elastic energy.

Although a pre-stretch enhances power output considerably, the effect on jumping height is not as pronounced. An increase in power has not led to a great improvement in jump height because, usually, power enhancement has coincided with a decrease in movement amplitude. As in sprinting, the maximum contribution of elastic energy to jumping performance may therefore be ultimately dependent on a technique factor. Future research should investigate how individuals can best take advantage of elastic energy which essentially “free” energy. Biofeedback may be one means of identifying the most favorable pattern of movement to elicit the maximum effect from the stretch-shortening phenomenon.

Modulating Factors

There are a number of factors that can modulate the degree to which elastic energy can be used to enhance skill performance. Research investigating modulating factors raises several questions concerning the practical ramifications of inducing various experimental treatments on the neuromuscular system. This section makes some observations and speculates as to how such manipulations may allow one to enhance or degrade the contribution of elastic energy to performance of a motor skill. Thus, hypotheses for future research are developed.

Coupling time

Coupling time refers to the length of time between the concentric and eccentric phase in a SSC (Bosco et al., 1981). As coupling time increases, the ability to reuse the elastic energy stored in the SEC has been shown to decrease (Abbot & Aubert, 1952; Aruin et al., 1979; Bosco & Rusco, 1983; Bosco, Komi & Ito, 1981; Cavagna & Citterio, 1974). Abbot & Aubert (1952) reported that after an isolated muscle is actively
stretched and kept active at the stretched length, the force attained at the end of stretching declines over a relatively short period of time, but settles at a value above the isometric force possible at the same length. Cavagna and Citterio (1974) hypothesized that this was due to an internal rearrangement of the muscle towards the state attained when contracting isometrically at the same length. In order to test this hypothesis, these authors released isolated muscles from their optimal length under the following three conditions: 1) from a state of isometric contraction, 2) immediately after stretching, and 3) after an interval (0.3-1.6 s) following the end of the stretch. They found that, when a lag time was allowed, the change in SEC length for a given fall in force was reduced and approached that derived from a state of isometric contraction. In other words, the amount of stored elastic energy that was released and used for the purpose of shortening declined. It has been suggested that the mechanism responsible for such a decline is the natural detachment of the cross-bridges, because elastic energy stored in the cross-bridges can only be maintained as long as the cross-bridges remain attached. As a result of cross-bridge detachment, the strain energy built up in the cross-bridge during the stretch is dissipated as heat, and is therefore unavailable to be used in a subsequent concentric contraction (Rack & Westbury, 1974; Shorten, 1987). Some strain energy is retained in the tendon however, but even this is gradually dissipated if the stretch is held too long (Shorten, 1987). In human knee extensor muscles, it has been calculated that elastic energy storage decays exponentially at a rate equivalent to a half-life of about four seconds (Aruin et al., 1979). In skills which take advantage of muscle elasticity, it may therefore be prudent to perform the concentric phase of the movement immediately following an active stretch.

The effect of coupling time has been investigated in both running (Bosco & Rusko, 1983) and jumping (Bobbert et al., 1987; Bosco et al., 1981). In jumping, Bosco et al. (1981) have shown that, when jumps are performed with a preliminary
counter-movement, coupling time is negatively correlated with enhanced performance. After testing 14 subjects, the average coupling time was calculated to be 23 ms. It has been suggested that the average duration of the cross-bridge attachment is approximately 30 ms (Curtin et al., 1974). Consequently, those subjects who performed a jump with a coupling time less than 30 ms would have benefited from elasticity residing in the muscle fibers unlike those subjects who took longer to make the transition from negative to positive work. Bosco et al. (1981) also found jumping performance to be positively correlated to the speed of pre-stretching.

In running, Bosco & Rusko (1983) attempted to manipulate coupling time by asking ten subjects to run on a treadmill at different speeds in both normal footwear and whilst wearing special soft soled shoes. The soft shoes were used to prolong the duration of the coupling time. The results indicated that, at the faster speeds, running in soft shoes required more energy than running in normal shoes, while no differences were found at the slower speeds. The authors’ reasoned that, at the higher speeds, coupling time became a limiting factor for the recoil of elastic energy, because fast twitch fibers were progressively recruited as the running speed increased. It was presupposed that the fast twitch fibers were more sensitive to the increase in coupling time induced by the soft shoes because their cross-bridge lifetime is much shorter than slow twitch fibers. Bosco & Rusko (1983), however, failed to consider the effect the softer shoes had on the peak force developed by the muscles under stretch during the eccentric phase. The peak force would have been lower when wearing the softer shoes and the difference in force between the two conditions (soft versus normal shoes) may have increased with speed. Consequently, the amount of elastic energy stored at the end of the eccentric contraction might have been much greater when the subjects wore normal shoes. This would then favor the normal footwear condition in terms of energy expenditure. In addition, the softer footwear may have altered gait mechanics which can also affect
energy expenditure (Morgan, Martin, & Krahenbuhl, 1989). Thus, the authors were probably incorrect to conclude that the interaction of coupling time with fiber type recruitment was the sole mechanism responsible for the results obtained. It is likely that the wearing of specially made soft shoes perturbed other factors in addition to coupling time. Nevertheless, Bosco and Rusko’s study raises the possibility that fiber type may also play a role in how much elastic energy can be stored and reused during a SSC.

**Fiber type**

Several studies have suggested that, under particular conditions, slow and fast twitch fibers differ in their ability to take advantage of muscle elasticity (Aura & Komi, 1987; Bosco et al., 1982; Bosco et al., 1987). Using a special sledge designed to slide up inclined rails, Aura and Komi (1987) examined the effect of muscle fiber distribution on the mechanical efficiency of subjects performing knee extensions whilst seated in the sledge. Efficiency values of the positive work phase were calculated when the subjects performed pure positive work (analogous to a squat jump) and when they preceded the positive work phase with active lengthening of the extensor muscles (analogous to a counter-movement jump). To define the muscle fiber distribution, muscle biopsies were taken from the vastus lateralis muscle (a knee extensor) of each subject. From the biopsy information, two groups of six subjects were formed — a fast twitch (FT) group (63.8% ± 5.9% FT fibers) and a slow twitch (ST) group (38.0 % ± 6.1% FT fibers).

For the purely concentric condition, no significant differences between the efficiency values for the two groups existed (16.4% and 17.1% for the ST and FT groups respectively). When the concentric contraction immediately followed an active stretch, however, the ST group were significantly more efficient than the FT group (36.4% and 33.2% for the ST and FT groups respectively). The authors put forward two possible explanations for the results obtained. First, they suggested the ST fibers might undergo greater myoelectric potentiation due to the stretch reflex because they have been shown
to have a larger number of muscle spindles than FT fibers (Barker et al., 1974). The EMG results reported, however, did not support this claim. Aura and Komi’s second suggestion was that, in an active state, the ST fibers are functionally able to resist a stretch for a longer period of time because their cross-bridge lifetime is longer than that found in FT fibers. A longer stretch would allow for a better storage and reuse of elastic energy. This suggestion is feasible but, before one could put greater faith in this, one would need to know the respective coupling times in each group. If the coupling time in the FT group had turned out to be longer than the cross-bridge lifetime of FT fibers, and the coupling time in the ST group shorter than the cross-bridge lifetime of ST fibers, then the proposal would have more credence. However, the investigation failed to measure coupling time, and so their claim could not be substantiated.

Also, the quantification of the difference in cross-bridge attachment times between ST and FT fibers has not been well documented. Aura and Komi (1987) referred to the study of Curtin et al. (1974) to suggest that ST fibers had longer attachment times. In fact, Curtin et al. (1974) only discussed the mean attachment times of the cross-bridges in isolated sartorius muscles of the frog, and made no distinction between the ST and FT fibers. Once the attachment times of both ST and FT fibers have been clearly established, it would be worth repeating the study of Aura & Komi (1987), but with the following modification: coupling time should be measured and varied within subjects so that the interaction between coupling time, fiber type, and the elastic properties of muscle could be better assessed. It is predicted that, at the shortest possible coupling time, the FT group would be just as efficient than the ST group.

Coupling time has previously been measured in conjunction with fiber type to determine the effect of fiber type on stored elastic energy in jumping (Bosco et al., 1982). Bosco et al. (1982) had 14 subjects perform jumps with and without countermovement and with small and large knee angular displacements on a force platform.
The average positive ground reaction force difference (ΔF) between counter-movement jump and static jump conditions was chosen as a parameter to reflect the potentiation due to the pre-stretch. The amount of elastic energy stored at the end of the pre-stretch was represented by the ground reaction force developed at the end of the stretch (-F).

Coupling time was measured from electrogoniometer records of the knee joint angle; it was taken as the length of the phase when no change in knee angle occurred. During this time, it was presupposed that the knee extensors were neither lengthening or shortening. Subjects were analyzed for fiber type and categorized into FT (56.1% ± 9.0% FT fibers) and ST (37.4% ± 8.4% FT fibers) groups by extracting muscle biopsies from the vastus lateralis muscle.

For small knee angular displacements (55.3 ± 10.1 degrees), -F was greater in the FT group than the ST group (30.2 ± 4.8 compared with 25.9 ± 4.8 N/kg of body mass). It was assumed, therefore, that the FT group had a greater potential for storing mechanical energy in the eccentric phase which could be used to augment the concentric contraction. No significant difference was obtained, however, between the relative potentiation effect (ΔF/-F) for the two groups in the small knee angular displacements. This was explained in terms of the relationship between the cross-bridge attachment-detachment cycle and coupling time. The small amplitude jumps had a relatively small coupling time of only 18.9 ms. It was argued that this time period was so short that the cross-bridges in FT, as well as ST fibers, did not have time to detach before commencement of the concentric contraction. Both groups, therefore, were able to recover a similar percentage of the total elastic energy developed during active lengthening.

On the other hand, large amplitude jumps (87.3 ± 13.1 degrees) were characterized by a longer coupling time (44 ms), and significant potentiation differences were observed between ST and FT groups. Although -F was similar in each group
(16.2 ± 2.6 N/kg (FT) and 16.9 ± 3.5 N/kg (ST)), \( \Delta F \) was significantly greater in the ST group, suggesting that fiber type was an important determinant of potentiation due to pre-stretch under these conditions (\( \Delta F/F \) ratios were 24% and 17.1% for the ST and FT groups respectively). Bosco et al. (1982) postulated that the long coupling time enabled the ST fibers to retain more of their elastic energy for use in the concentric phase as their cross-bridges were able to remain attached for a longer period of time. Thus, the authors concluded that slow and fast twitch fibers may benefit differently from the stretch-shortening phenomenon. Bosco et al. (1982) did not report, however, how the differences in potentiation affected the jump in terms of performance. From the force plate data, jumping height and mechanical power could have been calculated. Such dependent variables are important in order to establish the practical ramifications of the effect of fiber type in the SSC. Nevertheless, the studies discussed above suggest that the interaction of fiber type with coupling time might influence an individual’s use of muscle elastic properties.

**Resonance**

If a damped mass-spring system is subjected to a periodic force, the magnitude of force required to achieve a given amplitude is minimized when the forcing frequency matches the natural frequency of the system (Shorten, 1987). Under this condition, the system is said to resonate. Evidence has been presented suggesting that the motor system can take advantage of resonance by matching movement frequencies with the natural frequency of the SEC (Bach, Chapman & Calvert, 1983; Denoth, 1985, Taylor, 1985). Viscoelastic models of the musculoskeletal system imply that resonant movement frequencies exist at which maximal mechanical output can be achieved with minimal energy expenditure (Bach et al., 1983; Cavagna, 1970). More direct evidence comes from human hopping experiments in which steady state oxygen consumption is measured while subjects hop in place on a force platform at different frequencies.
(Taylor, 1985). The results of these experiments demonstrate that the role of elastic energy is maximized and that of metabolic energy is minimized when subjects hop at their natural frequency of oscillation (resonant frequency). The resonance concept may therefore provide an alternative explanation — as opposed to theories using gait mechanics — for why oxygen consumption is minimized at a specific stride length/frequency in running. An optimum stride length/frequency has been observed by several researchers (e.g. Cavanagh & Williams, 1982; Martin & Morgan, 1992).

Executing movements at resonant frequencies may also benefit performance in power events. Using a two-link mechanical model representing the upper arm and forearm, Denoth (1985) demonstrated that optimal performance of a simple throwing task is achieved when the system is in resonance. The maximum height that a shot was thrown occurred when the effective frequency of contractile component activity coincided with the natural frequency of the SEC. Future research should investigate if similar findings occur with human subjects.

Certainly, more work needs to be done in this area. However, initial results suggest that resonance is a factor to be considered when trying to maximize the effectiveness of the SSC.

**Skill/practice Level**

Research indicates that groups of athletes engaged in power events have a greater ability to use stored elastic energy when trying to maximize performance than those athletes who participate in endurance sports. Bosco and Komi (1982) compared seventy-eight males from different sporting backgrounds by analyzing their maximal performances in the static jump and counter-movement jump. The men were divided into eight groups — physical education students, nationally ranked middle distance runners, nationally ranked karate practitioners, soccer players of international level, volleyball players of international level, nationally ranked long, triple, and high jumpers,
and nationally ranked ski jumpers. The improvement in jump height in the counter-
movement jump condition over the static jump condition was greatest in the ski jumpers
(Δh = 11 cm) and least in the physical education students and middle distance runners
(Δh = 5 cm). High jumpers increased their jump performance by 7.5 cm, long jumpers
by 7.3 cm, volleyball players by 6.2 cm, and karate practitioners by 5.5 cm. These data
strongly suggest that athletes who regularly train for explosive power are better able to
maximize the effect of the SSC.

One may argue, however, that the degree to which stored elastic energy can be
used is genetically determined and that the sport self-selects the participants at the elite
level. Even though this may be the case, stretch-shortening exercises performed over an
eighteen month training period have proven successful in improving the elastic potential
of the leg extensors of trained high jumpers and volleyball players (Bosco & Komi,
1982). The training program not only improved jumping ability but, in addition,
increased the tolerance for high stretching loads (stretching load was represented by the
height of the best drop jump). Increasing the tolerance for high stretching loads increases
the possibility of storing a greater amount of elastic energy. It appears, therefore, that
neuromuscular training can influence the ability to store and use elastic energy.

A training effect has also been shown to occur in as little as two months when
individuals follow a program of stretch-shortening type exercises. Kyrolainen,
Hakkinen, Komi, Kim, and Cheng (1989) investigated the performance changes of nine
female subjects over a four-month training period. They performed various types of
stretch-shortening exercises three-times-a-week, but also included weight training for
the leg extensor muscles. The greatest changes were observed after only two months of
training. Take-off velocities from the platform of a special sledge apparatus increased
significantly. However, the increase occurred in both the pure concentric work and the
SSC condition, therefore it could not be concluded that the improvements were due
solely to an enhancement of the stretch-shortening effect. Because fat-free weight increased significantly, a substantial portion of the performance improvement may have been due to an increase in force production as a result of muscle hypertrophy. If attention had also been paid to the pre-stretching technique, perhaps a more marked improvement of the elastic mechanism would have been attained.

**Architecture**

Tendons have a greater ability to store elastic energy after being stretched by an external force than do muscle fibers (Alexander & Bennet-Clark, 1977). Muscles with long tendons and short fibers are, therefore, better able to provide elastic energy when subjected to a SSC. Pennate muscles, rather than parallel fiber muscles, tend to have long tendons and short fibers; the triceps surae muscle complex and the quadriceps muscle group are good examples of pennate muscles. Both these muscle groups undergo active lengthening in running and jumping (Ito et al., 1983), thus, each group is well located to store and release elastic energy during these skills. Of the two muscle groups, the triceps surae complex has the greatest degree of pennation and the smallest fiber/tendon length ratio (Alexander 1984; Leiber, 1992). For the same amount of active stretching force, therefore, the triceps surae is more likely to return a greater percentage of elastic energy than the quadriceps during the concentric phase of a SSC.

Recent research has used mathematical muscle models to further investigate how the structure of the musculotendinous unit affects the elastic properties of the unit (Belli & Bosco, 1992; Caldwell, 1995). Computer simulations allow structural characteristics to be modified with ease in order to predict what effect different morphological arrangements might have on the ability to store elastic energy. Using such techniques, Caldwell (1995) investigated the effects of relative fiber/tendon length ratios on CC and SEC mechanical work and energy storage. He found that much more energy could be stored in the SEC of muscles with long tendons and short fibers.
The stiffness of the SEC has also been manipulated using simulation techniques (Belli & Bosco, 1992). Belli and Bosco (1992) compared in-vivo mechanical results of vertical jumps with results from a computer simulation of the same movement. The jumps were performed with and without pre-stretch and, because the subjects' knees were braced, exclusively involved the triceps surae muscle group. The simulation allowed the work of the triceps surae to be partitioned into CC and SEC work. As expected, the work of the SEC was much higher when a pre-stretch was performed, resulting in greater efficiency values for the rebound jumps. However, the authors also manipulated the stiffness of the SEC (using the simulation) to predict how a change in stiffness would affect efficiency. Interestingly, an optimum stiffness was found to exist which minimized the work of the CC. After calculating actual SEC stiffnesses using techniques developed by Cavagna (1970), and comparing these to the optimum predicted by the model, it was suggested that efficiency could be improved by an increase in SEC stiffness.

The results of Belli and Bosco's simulation may have practical implications. It is possible that stretching exercises, designed to increase joint range of motion (flexibility), may alter tendon stiffness (Toft, Sinkjaer, Kalund, & Espersen, 1989). A change in flexibility, therefore, may affect the amount of elastic energy which can stored and returned to the musculoskeletal system during a concentric contraction. Ultimately, the end result would be an effect on certain performance measures. Work by Gleim, Stachenfeld, and Nicholas (1990) and Craib et al. (1994) has shown flexibility to be positively correlated to energy expenditure during submaximal running. Consequently, flexibility, may also be a factor which can affect the degree to which elastic energy is used in human movement.
Flexibility

Running economy, or the aerobic demand of submaximal running, has been associated with distance running success in individuals who are relatively homogeneous in VO$_{2\text{max}}$ (Conley & Krahenbuhl, 1980). This measure of economy can vary among runners possessing similar maximal aerobic capabilities by as much as 30% (Daniels, 1985). Factors such as fiber type, training, gender, fatigue, and various kinematic variables are thought to affect aerobic demand (Morgan, Martin, & Krahenbuhl, 1989); therefore, a number of reasons could account for the large variance in running economy. Recently, flexibility has also been found to be related to economy (Gleim et al., 1990; Craib et al., 1994). Gleim et al. (1990) tested 38 women and 62 men and reported that subjects who demonstrated the lowest flexibility were the most economical over speeds ranging from 1.78 to 3.13 m/s (15 minutes/mile to 8.6 minutes/mile). In nine out of eleven flexibility tests, the “tight” people differed significantly from the “loose”. The authors speculated that tighter individuals may benefit more from the elastic recoil of muscle tissue, thereby reducing the energy required from the CC. Gleim et al.’s data, however, may have been confounded by gender differences, inexperienced subjects, and inadequate treadmill accommodation. The accuracy of running economy measures for such a population must therefore be questioned.

Taking such methodological issues into consideration, Craib et al. (1994) re-examined the relationships between flexibility measures and running economy. Nineteen well trained, male distance runners were measured for trunk and lower limb range of motion and were then properly accommodated to treadmill running before measuring running economy. Their results were in agreement with Gleim et al. (1990) in that the least flexible runners exhibited better economy. However, the only flexibility measures to show a significant correlation with running economy were ankle dorsiflexion ($r = -0.65$, $p<0.01$) and lateral hip rotation ($r = -0.53$, $p<0.02$). Ankle
dorsiflexion inflexibility may benefit economy by enhancing elastic energy return from the Achilles tendon and plantar flexor complex. It has been suggested by several researchers that the plantar flexors act as a major energy-saving mechanism in locomotion (Alexander, 1988; Hof, 1983; Ker et al., 1987). Furthermore, Belli & Bosco (1992) have provided evidence to suggest that the SEC stiffness of the plantar flexors can affect the metabolic cost of the muscle complex and that an optimum stiffness exists. It is possible that individuals exhibiting a higher ankle dorsiflexion inflexibility may be closer to an optimum stiffness which minimizes the requirement for oxygen in the CC.

Although the quadriceps have also been shown to be important contributors of elastic energy, no relationship between knee joint range of motion and economy could be established by Craib et al. (1994). This was because the flexibility test used to quantify knee flexion proved to be inadequate for the purpose of investigating such a relationship. The measurements were not continuous and could not distinguish between participants in terms of flexibility.

Gleim et al. (1990) provided an additional explanation for why less flexible individuals were found to be more economical than those displaying a higher degree of flexibility. Although they found nine measures of flexibility to show a relationship with economy, the two best predictors were the degree of trunk rotation and lateral hip rotation. They hypothesized that individuals who were the least flexible in terms of trunk and hip rotation were more resistant to motion in the transverse plane. This would require less active contraction from the appropriate musculature to neutralize the rotary forces which develop as running speed increases, thus, less energy would be expended.

Although further research is required to either confirm or refute the speculations of Craib et al. (1994) and Gleim et al. (1990), the results of these studies (Belli & Bosco, 1992; Craib et al., 1994; Gleim et al., 1990) raise some interesting questions.
For example, does a change in flexibility within an individual alter the elastic properties of the musculotendinous unit and, therefore, the effect of a SSC? Because the storage of elastic energy is a function of muscle and tendon stiffness (Shorten, 1987), and because acute, passive stretching has been shown to alter the passive stiffness at a joint (Magnusson, Simonsen, Aagaard, & Kjaer, 1996; Toft, Espersen, Sinkjaer, & Hornemann, 1989; Toft et al., 1989), it seems reasonable to speculate that stretching exercises may decrease the amount of elastic energy that can be stored. An increase in flexibility could therefore limit power output and efficiency in skills which utilize a SSC. If this turns out to be the case, such a finding would be important because many athletes regularly include a thorough stretching program as part of their training protocol. As stretching has been promoted as an important measure to prevent injuries (Bryant, 1984; Corbin & Noble, 1980) athletes would then face the problem of assessing how much stretching would be optimal.

Future research should investigate the effect of both acute and chronic stretching on the use of stored elastic energy in running and jumping. In addition to including stretching exercises as a regular part of a long term stretching program (chronic stretching), athletes often include passive stretching as part of their pre-event warm-up (acute stretching). Such a practice is encouraged because it is widely asserted that if stretching exercises are performed just prior to physical activity, the risk of musculoskeletal injury is lessened (Bryant, 1984; Corbin & Noble, 1980; Shellock & Prentice, 1985). However, the basis for this conjecture has been formed from either anecdotal evidence or from the findings of retrospective studies which have investigated the relationship between injury occurrence and inherent flexibility (Safran, Seaber, & Garret, 1989; Shellock & Prentice, 1985). Convincing evidence to support the belief that acute stretching has a prophylactic effect is therefore lacking. Consequently, it is recommended that studies be conducted to assess the potential benefits of acute
stretching (i.e., injury prevention), in addition to the potential cost (i.e., performance decrement).

A chronic change in joint range of motion might alter the elastic properties of the musculotendinous unit more than an acute change. Sapega, Quedenfeld, Moyer and Butler (1981) have suggested that the range of motion about most joints is limited by connective tissue structures, including those in muscle. To increase joint range of motion, therefore, flexibility exercises should attempt to alter the length of the connective tissue structures. According to Enoka (1994), plastic changes in these structures are required in order to create a permanent increase in length. How such changes affect the elastic properties of these structures remains to be determined. Nevertheless, it could be hypothesized that chronic stretching of elastic tissues causes a reduction in their elasticity. After all, if a spring or an elastic band is stretched beyond the elastic limit, a permanent deformation arises and elasticity is compromised (Tipler, 1991). Consequently, the ability to store and release elastic energy is reduced. Moreover, eccentric strength training has been shown to reduce the compliance of the SEC in the flexors of the human elbow joint (Pousson, Hoecke, and Goubel, 1990); thus, it appears that the elastic properties of muscle and tendon can be physically altered. It would be prudent, therefore, to determine if the capacity to use stored elastic energy is decreased in individuals who demonstrate a significant change in joint range of motion after a long term stretching program. If a significant improvement in the range of motion at specific joints has a deleterious effect on running economy and the potentiating effect of a SSC in jumping, the notion that flexibility can influence the degree to which elastic energy is utilized will be supported.

Conclusions and Hypotheses for Future Research

One of the main goals of this review was to determine the importance of muscle and tendon elasticity to human performance. Both isolated muscle studies and research
with human subjects have demonstrated that muscle and tendon elasticity can significantly contribute to the effectiveness and efficiency of performance through the mechanisms of force enhancement and elastic energy storage. The influence of elasticity is greatest in skills which involve a stretch-shorten cycle such as running and jumping. In these skills, the release of stored energy from the elastic elements of the musculotendinous unit may be responsible for approximately half of the positive work produced.

Storage of elastic energy occurs when the musculoskeletal system makes use of passive forces such as reactive, gravitational, frictional, and inertial forces to stretch the elastic components of muscle. In running and jumping for example, these forces are used to stretch the prime-movers during the eccentric portion of the skill. When a muscle undergoes an eccentric contraction, the energy expenditure of the contractile component is relatively small compared to a concentric contraction (Williams, 1985); thus, elastic energy is associated with a low metabolic cost (Cavagna, 1977). Consequently, the efficiency of positive work production can increase beyond that expected from the transformation of chemical energy into mechanical work by the contractile component. This process exemplifies Bernstein’s (1967) second stage in the development of skilled behavior. According to Berstein (1967), after the learner has organized the degrees of freedom within the neuromuscular system into effective functional units (the first stage), a more economical pattern of movement evolves as the system learns to take advantage of passive forces available in the environment. As well as using passive forces to complement the force generated by the contractile component, the learner develops the ability to employ these forces to passively transfer energy through elastic storage and recovery.

Ideally, a skilled performer should coordinate his or her movement to maximize the use of passive forces. At the elite level, however, differences in the ability to store
and recover elastic energy may account for differences in performance. In submaximal running, the economy of movement has been shown to vary considerably among runners who possess similar maximal aerobic capabilities (Daniels, 1985). It might be that highly economical runners are more adept at employing passive forces for the purpose of generating elastic energy than runners exhibiting low economy. Although studies (for a review see Morgan, Martin & Krahenbuhl, 1989) have shown other factors to affect aerobic demand (e.g., fiber type, training, gender, age, fatigue, and various kinematic variables), future work should investigate if an individual’s ability to use elastic energy is the underlying reason why such a wide variance in running economy exists.

The elastic properties of muscle also appear to affect performance in skills where success is more dependent on power output. Under the influence of passive forces, the elastic behavior of muscle has been shown to enhance the force, work, and power output of a concentric contraction. This is important in skills such as sprinting, jumping, and throwing when trying to maximize performance. In sprinting, a sudden increase in power can occur when an individual approaches maximum speed. This happens to coincide with an increase in the negative work done in each step, suggesting that a greater stretch and recoil of the elastic elements is, at least, partly responsible the power increase. In jumping, power output and jump height are increased when a jump is performed with a pre-stretch rather than jumping from a static position.

Movement technique is probably an important determinant in maximizing the effect of muscle elasticity in skills which rely on a high power output. For example, in sprinting, Cavagna et al. (1971) showed differences in the ability of trained sprinters to increase power output through the recovery of stored elastic energy. Thus, even at the elite level, it appears that technique refinement can increase the effects of muscle elasticity. Because the research in this area is scant, future work should investigate if
the role of elastic energy can be increased by manipulating the pattern of movement both at the novice and expert levels. Also, it would be interesting to focus such work on throwing skills in addition to running and jumping. Typically, running and jumping have been the skills investigated and not skills such as the javelin throw, shot putt, and the baseball pitch.

Biofeedback may be one means of achieving the most favorable pattern of movement to elicit the maximum effect from a stretch-shorten cycle. Electromyography might be an appropriate biofeedback tool because similar variables influence the degree to which the stretch reflex and elastic mechanisms are activated. Not only does a pre-stretch enable elastic energy to be stored, it can also increase muscle activation levels through the stretch reflex mechanism.

Two important modulating factors that affect both the stretch reflex and elastic mechanisms are coupling time and the rate of pre-stretching. Myoelectric and elastic potentiation increase with an increase in pre-stretch velocity and a decrease in coupling time. Consequently, in skills involving a stretch-shortening cycle, a judicious movement strategy would be to maximize the velocity of the pre-stretch and to minimize the time between the eccentric and concentric phase. Future work, therefore, might include coupling time and pre-stretch velocity, in addition to the integrated EMG signal, as feedback parameters when attempting to optimize the pre-stretching technique.

The phenomenon of resonance should also be considered when attempting to maximize the contribution of elastic energy through technique optimization. Although there is a paucity of research into the effect of performing movements at resonant frequencies, initial work suggests that the effect of muscle and tendon elasticity may be enhanced if the frequency of contractile component activity matches the natural frequency of the system. More work is required, however, to establish if the resonance
phenomenon can be applied to improve performance in both aerobic and power dependent anaerobic skills.

In addition to technique manipulation, training the neuromuscular system with a long term program of stretch-shortening exercises will probably increase an individual’s ability to store and recover elastic energy. Neuromuscular training can increase an individual’s tolerance for high stretching loads which, in turn, increases the possibility of storing more elastic energy. It would be prudent, therefore, to include both technique optimization procedures and specific stretch-shortening exercises in any training program designed to improve an individual’s ability to take advantage of the stretch-shortening phenomenon.

One type of exercise that the majority of athletes usually encompass in their training programs is passive stretching. Stretching is performed to increase joint range of motion or flexibility. There is a possibility, however, that excessive flexibility may negatively impact performance in skills which take advantage of muscle and tendon elasticity. Increasing joint range of motion requires lengthening connective tissue structures which cross the joint. It seems reasonable to speculate, therefore, that the elastic properties of muscle may be modified by imposing a structural change through passive stretching. In most materials, excessive stretching permanently deforms the material and causes elasticity to be compromised. If this holds true for the musculotendinous unit, the storage and recovery of elastic energy will also be compromised. Because of the practical importance of this issue, it is recommended that future research should investigate the effect that both chronic and acute passive stretching has on the elastic properties of muscle and, consequently, performance.

Although not easily manipulated like flexibility and the other modulating factors so far discussed, muscle fiber type and architecture are also factors which may influence the degree to which elastic energy can be used. Fiber type may affect the ability to recover...
elastic energy from the elastic elements at the end of an active stretch. Due to a longer cross-bridge lifetime, slow twitch fibers might be able to recover a greater percentage of stored elastic energy than fast twitch fibers. Muscle architecture, on the other hand, dictates the amount of energy which can be stored, as well as recovered. Tendons have a greater ability to store elastic energy than do muscle fibers; muscles with long tendons and short fibers are therefore more capable of storing energy than muscles with long fibers and short tendons. Consequently pennate muscles rather than parallel fiber muscles are usually better providers of elastic energy.

An exact method of quantifying the storage and recovery of elastic energy, however, remains elusive. Nevertheless, it is clear that the role of muscle and tendon elasticity in human movement is an important one; with the assistance of passive forces, this property can complement and enhance a muscle's contractile properties. As a result, humans have the potential to increase their movement efficiency, force production, work output, power output, and performance in activities which incorporate a stretch-shorten cycle. The degree of enhancement is dependent on several factors which can modulate the effect of muscle and tendon elasticity. Future research should investigate the optimal management of these factors so that the exploitation of the stretch-shortening phenomenon can be maximized.

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Appendix B

Human Subject Approval and Consent Forms
From: Dennis Landin, Chair  
Research Affairs Committee  

To: Research Affairs Committee: Ben Sidaway, Arnold Nelson  

Re: Approval on use of humans and animals for research

Attached are two copies of a research proposal seeking our approval regarding the appropriate protection of humans and animals as research subjects. Please review the summary, abstract, and subject consent form, then mark and sign below (both copies) in appropriate place. Pass on to the next person. Last one to initial, please return to me.
Consent for Participation in an Investigational Study

Subject’s name: ________________________________

Date: ________________________________

I hereby consent to voluntarily participate in the experiment entitled “The acute effects of passive stretching on vertical jump performance” conducted by Andrew Cornwell.

I understand that in order to participate it will be necessary to perform passive stretching exercises designed to stretch the hip and knee extensors. In addition, maximal vertical static and countermovement jumps will be performed on a force platform.

I understand that the above procedures may involve the following risks and discomforts:

1. Discomfort at the knee and hip joints, and in the knee and hip extensor muscles during the stretching procedure.

2. Discomfort and slight trauma due to instability and jarring upon landing from the jump.

I also am aware that I can withdraw my participation at any point in the study and can give verbal notice to the experimenter concerning the degree of discomfort felt during any of the imposed techniques. Upon my verbal request, I can terminate at any point further participation in the study.

I further realize that:

1. All subjects are volunteers

2. I will be informed completely about the nature of the experiment

3. The data obtained from me will be confidential and my identity will not be released without my permission

4. I have the opportunity to ask a question at any point in the study

Subjects signature ________________________________

Witness’s signature ________________________________
Consent for Participation in an Investigational Study

Subject's name: ________________________________

Date: ________________________________

I hereby consent to voluntarily participate in the experiment entitled “The acute effects of passive stretching on the neuromechanical properties of the musculotendinous unit” conducted by Andrew Cornwell.

I understand that in order to participate it will be necessary to perform passive stretching exercises designed to stretch the calf muscles. In addition, maximal vertical jumps using the calf muscles only will be performed on a force platform.

I understand that the above procedures may involve the following risks and discomforts:

1. Discomfort at the ankle joint and in the calf muscles during the stretching procedure.

2. Discomfort and slight trauma due to instability and jarring upon landing from the jump.

I also am aware that I can withdraw my participation at any point in the study and can give verbal notice to the experimenter concerning the degree of discomfort felt during any of the imposed techniques. Upon my verbal request, I can terminate at any point further participation in the study.

I further realize that:

1. All subjects are volunteers

2. I will be informed completely about the nature of the experiment

3. The data obtained from me will be confidential and my identity will not be released without my permission

4. I have the opportunity to ask a question at any point in the study

Subjects signature ________________________________

Witness’s signature ________________________________
Appendix C

Experiment 1 Data and ANOVA Tables
Table C.1  Data Table for Static (SJ) and Countermovement Jump (CMJ) Heights (cm) in the No-stretch (NS) Condition and Static Stretch (SS) Condition.

<table>
<thead>
<tr>
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<th>CMJ</th>
<th>SJ</th>
<th>SJ</th>
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<td>25.38</td>
<td>23.28</td>
<td>22.22</td>
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<tr>
<td>SD</td>
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<td>2.22</td>
<td>2.20</td>
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Table C.2 Data Table for Static (SJ) and Countermovement Jump (CMJ) Peak Vertical Power (W) in the No-stretch (NS) Condition and Static Stretch (SS) Condition.

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<th>SJ SS</th>
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<td>2951.73</td>
<td>2837.58</td>
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<tr>
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<td>3083.84</td>
<td>2997.5</td>
<td>2815.5</td>
</tr>
<tr>
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<td>3504.09</td>
<td>3535.39</td>
<td>3317.6</td>
</tr>
<tr>
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<td>3331.56</td>
<td>3340.66</td>
<td>3214.34</td>
<td>3087.07</td>
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<td>3228.85</td>
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<td>4836.2</td>
<td>4559.83</td>
<td>4569.2</td>
<td>4409.5</td>
</tr>
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</table>

| Mean    | 3561.36| 3474.68| 3383.57| 3271.83|
| SD      | 577.81 | 499.03 | 567.45 | 541.50 |
Table C.3  Data Table for Static (SJ) and Countermovement Jump (CMJ) Peak Vertical Force (N) in the No-stretch (NS) Condition and Static Stretch (SS) Condition.

<table>
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<th>CMJ SS</th>
<th>SJ NS</th>
<th>SJ SS</th>
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<td>1570.38</td>
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<td>1640.96</td>
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Table C.4  ANOVA Table for Jump Height

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<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
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<td>11.61</td>
<td>11.61</td>
<td>11.66</td>
<td>0.0077</td>
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<tr>
<td>Error (Treatment)</td>
<td>9</td>
<td>8.961</td>
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<td></td>
</tr>
<tr>
<td>Type</td>
<td>1</td>
<td>100.97</td>
<td>100.97</td>
<td>28.37</td>
<td>0.0005</td>
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<tr>
<td>Error (Type)</td>
<td>9</td>
<td>32.026</td>
<td>3.558</td>
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<td></td>
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<tr>
<td>Treatment x Type</td>
<td>1</td>
<td>0.06</td>
<td>0.06</td>
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<td>0.679</td>
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<tr>
<td>Error (Treatment x Type)</td>
<td>9</td>
<td>2.953</td>
<td>0.328</td>
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<td></td>
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</table>

Table C.5  ANOVA Table for Peak Vertical Power

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<th>P</th>
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<td>Error (Treatment)</td>
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<td>87691.1</td>
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<tr>
<td>Type</td>
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Table C.6  ANOVA Table for Peak Vertical Force

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<th>MS</th>
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<th>P</th>
</tr>
</thead>
<tbody>
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<td>Treatment</td>
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<tr>
<td>Type</td>
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<td></td>
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</table>

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<th>SJ BS</th>
<th>SJ AS</th>
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<td>3.71</td>
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<td>1.56</td>
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Table D.1  Data Table for Static (SJ) and Countermovement Jump (CMJ) Heights (cm) Before stretching (BS) and After stretching (AS).
Table D.2 Data Table for Static (SJ) and Countermovement Jump (CMJ) Peak Vertical Power Before Stretching (BS) and After Stretching (AS).

<table>
<thead>
<tr>
<th>SUBJECT</th>
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<th>CMJ AS</th>
<th>SJ BS</th>
<th>SJ AS</th>
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Table D.3   Data Table for Static (SJ) and Countermovement Jump (CMJ) Peak Vertical Force Before Stretching (BS) and After Stretching (AS).

<table>
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Table D4. Data Table for Normalized IEMG (mV) Values for Static Jump (SJ) and Countermovement Jump (CMJ) (both Eccentric (ECC) and Concentric (CON) phases) Before Stretching (BS) and After Stretching (AS).

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<th>AS</th>
<th>BS</th>
<th>AS</th>
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Mean: 0.638 0.632 0.64 0.624 0.655 0.585
SD: 0.24 0.28 0.216 0.222 0.242 0.184
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Table D.5  Data Table for Active Stiffness (kN/m) of the Triceps Surae Muscle Complex Before (BS) Stretching and After Stretching (AS).
Table D.6 Data Table for Ankle Joint Range of Motion (angle in degrees between shank and the horizontal) Before Stretching (BS) and After Stretching (AS) on Both the Jumping and Stiffness Day.

<table>
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Table D.7 ANOVA Table for Jump Height

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Table D.8 ANOVA Table for Peak Vertical Power

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Table D.9 ANOVA Table for Peak Vertical Force

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Table D.10 ANOVA Table for IEMG

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Table D.11 ANOVA Table for Ankle Joint Range of Motion

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Appendix E

Active Stiffness Pilot Data
Table E.1  Pilot Data Table for Active Stiffness (kN/m) of the Triceps Surae Muscle Complex for Five Subjects Measured Using the Original Technique of Cavagna (1970).

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Vita

Andrew Cornwell was born on the 1st of March, 1961, in Pontefract, England. After graduating from the King’s Grammar School, Pontefract, in 1979, Andrew attended Portsmouth Polytechnic in Hampshire, England, where he obtained a Bachelor’s Degree in Civil Engineering. He then worked in London for three years as a Graduate Civil Engineer before returning to college to pursue a master’s degree in Irrigation Engineering at Southampton University, England. For his thesis research, Andrew spent three months in Sri Lanka investigating water seepage losses from irrigation canals. Upon completing this work, Andrew graduated from Southampton in 1987 and returned to London where he took employment as an Irrigation Design Engineer. Soon after, he came to the realization that the Civil/Irrigation Engineering Industry was not his true vocation, and in 1990 he decided to make a career change by embarking on a master’s degree in Exercise and Sports Science at Colorado State University. After graduating from C.S.U in 1992, Andrew moved to Baton Rouge in order to pursue a doctoral degree in Kinesiology at Louisiana State University. Upon completing this program in August 1997, Andrew will take up a post at California State University, Los Angeles, where he will work as an Assistant Professor.
Candidate: Andrew Cornwell
Major Field: Kinesiology

Title of Dissertation: Acute Effects of Passive Muscle Stretching on the Stretch-Shortening Phenomenon

Approved

Major Professor and Chairman
Dean of the Graduate School

EXAMINING COMMITTEE:

Richard J. Myll
Dennis Johnson
Sriram Cheragi
Alan Brummett

Date of Examination:
June 30, 1997