University of Alberta

The effects of a short-term plyometrics program on the running economy and Achilles tendon properties of female distance runners

by

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Abstract

This study examined the effects of plyometrics on running economy, performance, and Achilles tendon properties in female distance runners. Seventeen University athletes matched by running economy were randomly assigned to an experimental group that received supplementary plyometrics training (n=9) or a control group that performed run-training only (n=8). Subject attrition led to a final sample of twelve runners (6 experimental, 6 controls).

Measurements were made pre-post an 8-week training period. Running economy was measured as oxygen consumption at three submaximal speeds, performance as time to run 3000 meters, and Achilles tendon properties were estimated via ultrasound during ramp, quasi-isometric plantar flexion to maximum on an isokinetic dynamometer.

No significant differences were found between the two groups after eight weeks because of poor subject compliance and excessive variability in ultrasound measurements. The results are inconclusive as to the effect of supplementary plyometric training on running economy, performance and Achilles tendon properties.

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Chapter 1

Introduction

Running performance is closely linked to running economy (52). Running economy is the oxygen cost of running, typically measured as the rate of oxygen consumption at a predetermined submaximal speed. This key marker for distance running performance appears to have been conceived as an indicator for metabolic factors, but the concept also includes mechanical factors (16, 17). One such mechanical factor in running is the elastic recoil of tendons. It has been shown, for example, that the Achilles tendon returns approximately 35% of the energy it stores upon foot contact (1) (see Plate 1-1). In addition, running economy is correlated to the stiffness of the medial gastrocnemius tendon and the compliance of the vastus lateralis tendon as measured directly via ultrasound (4). There have been a few studies that have shown that plyometrics improves running economy and/or performance (54, 58, 63, 65). However, no studies have simultaneously measured changes in performance and running economy with possible changes in tendon properties measured via ultrasound. The aim of this study is to clarify the growing evidence for performance gains in distance running due to plyometric training by focusing on key adaptations of tendinous structures as a potential physiological mechanism. In addition, a plyometric training study has not yet been done exclusively on female runners.

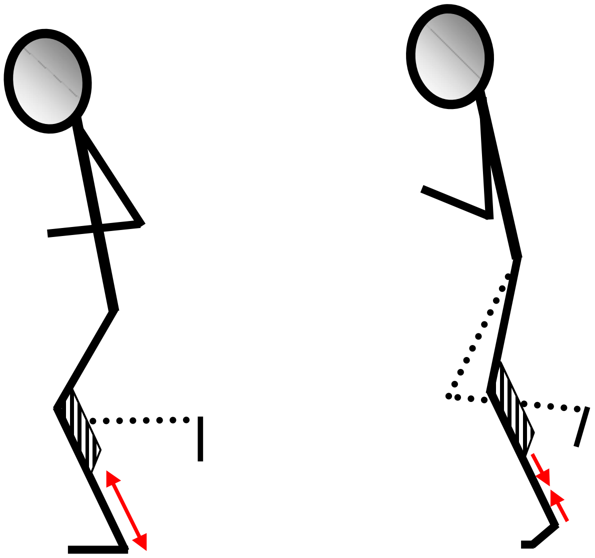

Plate 1-1. Diagram of Achilles tendon stretch on foot contact (left) and subsequent recoil to assist take-off during running (right).

Purpose

The aim of this study was to investigate the effects of a short-term plyometrics program on the running economy, running performance, and Achilles tendon properties of competitive, female, university distance runners. It was hypothesized that running economy will improve along with running performance in a three-kilometer time trial as well as increases in maximum Achilles tendon elongation, tendon force and tendon stiffness after an eight-week training period.

Significance

Plyometrics has been used in distance running with some success (54, 63). This study made an attempt to derive from previous studies the most effective and convenient set of plyometric drills that would produce a result. That is, these drills or combination of drills may be regarded as convenient to use, requiring minimal time or equipment, having a low risk for injury or soreness, while maintaining the desired training effects.

There is some disagreement about the effect of plyometrics on Achilles tendon stiffness. It is not clear whether plyomertics or plyometric-like training leads to an increase in stiffness (11, 63, 68) or a maintenance of stiffness due to a mutual and proportionate increase in tendon force and elongation (20, 36). This study sought to provide new information in this area by contributing results from an actual sport-performance training protocol.

Delimitations

This study examined the effects of an 8-week plyometrics program on the running economy and running performance of female distance runners. It also examined changes in the properties of the Achilles tendon as a potential physiological mechanism. Female runners from the University cross country team who were 17 to 27 years of age were tested for running economy on a treadmill, running performance over 3000 meters, and Achilles tendon elongation via ultrasound, before and after eight weeks of regular run training or regular run training supplemented with plyometrics.

Limitations

Though the sample was made up of female runners from the same team, there were individual differences in running ability. The present study also assumed that despite these differences, the athletes would be at the same relative training level at the start of the indoor track season, carrying peak fitness from the conclusion of the cross country running season. In addition, the sample size was 12 participants after dropouts, subject compliance was insufficient for half of the experimental group, and the regular run training varied among subgroups of runners within the team structure. Some previous injuries prior to the participation in this study may have also affected some athletes' running performance results. Finally, schedule and varsity training restrictions did not allow the standardization of the pre-exercise or pre-testing state of athletes. A brief interview at the start of each running test was used to at least account for possible confounding factors.

Definitions

Running economy is expressed in four ways: absolute running economy (L • min^{-1}), relative running economy (ml • kg^{-1} • min^{-1}), allometric-scaled running economy (ml • kg^{-75} • min^{-1}) (8, 64) and speed-consolidated running economy (ml • kg^{-1} • km^{-1}) (18, 24).

Achilles tendon force (N) is the estimate of the "strength of pull" of the Achilles tendon during a ramp, quasi-isometric plantar flexion to maximum voluntary contraction on an isokinetic dynamometer. It is calculated from joint rotation torque (N • m) and estimated Achilles tendon moment arms (mm) that are based on leg lengths and ankle joint angles (22).

Achilles tendon elongation (mm) is represented by the change in length of the medial gastrocnemius tendon and aponeurosis distal to the site of measurement, measured as close as possible to the myotendinous junction and measured simultaneously with joint rotation torque.

Tendon stiffness (N • mm^{-1}) is the relationship of the change in tendon force and the change in tendon length or elongation.

Ankle joint rotation (°) is the degree of plantar flexion along the sagittal plane.

Chapter 2

Review of Literature

Running economy and plyometrics

Distance running performance is linked to three classic physiological measures: aerobic power, lactate threshold and running economy. Of these, running economy is the least studied (19) and can be the most attune to the coupling of metabolic and mechanical factors in running. Running economy refers to the oxygen cost of running. This is expressed as the amount of oxygen consumed per kilogram of body weight per minute ($ml \cdot kg^{-1} \cdot min^{-1}$) at a predetermined, often submaximal running speed. Running economy can also be expressed as the amount of oxygen consumed per kilogram of body weight to run one kilometer ($ml \cdot kg^{-1} \cdot km^{-1}$). The latter expression yields somewhat constant values across a range of speeds (18, 24) and encourages averaging into one consolidated measurement; conceptually, this has the advantage of coupling metabolic and mechanical factors into one number. This consolidated measure, however, can hide non-significance at some of the predetermined running speeds and can ignore any nuances of running economy related to speed, as oxygen cost is also known to be linked to the running speed at which measurements are taken, especially when dealing with runners of differing ability or event specialization (15). Generally, the closer the testing speed is to the runner's typical race pace, the better the running economy. It is therefore argued that the most relevant measure of running economy is at race speed, rather than at arbitrary submaximal speeds which is what is often done (8). On the other hand, using submaximal speeds establishes a VO_2-speed slope. Saunders et al. (58) argue that improvements in running economy from mechanical adaptations lead to a change in the VO_2-speed slope, while improvements from metabolic adaptations (such as those achieved in altitude training) are seen across all submaximal speeds. Other than speed, factors thought to affect running economy have included running technique, anthropometric variables such as height, weight, limb and foot lengths, calf thickness and even shoe weight (2).

Running economy has also been defined strictly as the *metabolic* power to run a particular speed (67). This conception of running economy is congruent with the rationale for scaling oxygen consumption to 66% or 75% of body weight, since metabolic rate does not increase with body weight on a scale of 1 (8, 64).

Plyometrics is a form of explosive strength training that overloads the stretch-shortening cycle. Its use for power sports has expanded to include endurance events, particularly distance running. Plyometrics has been known to improve vertical jump height (47), which correlated weakly with 10-kilometer run performance in a heterogenous group of trained male and female runners ($r = -0.605$ and -0.618 with and without countermovement, respectively) (61). Training studies using plyometrics on distance runners have shown that plyometrics can improve running economy (65) often without concomitant changes in measures related to aerobic metabolism such as VO_2max or lactate production (54, 58, 63). Only these four studies in the current literature have shown improvements in running economy after a plyometrics intervention, with two—Paavolainen et al. (54) and Spurrs et al. (63)—also measuring and showing improvements in running performance over 5000 and 3000 meters, respectively.

All four training studies used control groups that were, for the most part, limited to run training and experimental groups that performed supplementary drills in plyometrics (with or without explosive weight training). Paavolainen et al. (54) and Saunders et al. (63) employed sprints over 20 to 100 meters and fast feet drills to shorten contact time, respectively. They also both equated run training for both groups as well as total training volumes by time. The two other studies (58, 65) merely kept run training constant over time per individual. The experimental periods used were either 6 or 9 weeks, with athletes training 2-3 days per week, except for those of Paavolainen et al. (54) who had approximately 8-9 training sessions in a week. The plyometric training programs varied among the studies as much as the distance running programs did, likely due to the level of the runners involved, ranging from regular to elite runners. (Mean VO_2max varied from 52.2 to 71.1 $ml \bullet kg^{-1} \bullet min^{-1}$). A summary of these training studies appears in Table 2-1.

With regard to the speeds used in measuring running economy, only Spurrs et al. (63) found that running economy improved at all test speeds. The other three studies (54, 58, 65) found improvements only at the highest speed. This is an expected result since plyometrics is a form of power training, and in theory, some drills overload the stretch-recoil cycle more forcefully and rapidly than what is required in slow, endurance running. In addition, the elastic components of the muscle-tendon unit are utilized more at higher velocities (14).

Table 2-1. Summary of training studies involving plyometrics and running economy.

STUDY	SUBJECTS	TRAINING TYPE	TRAINING VOLUME	TRAINING INTENSITY	Test Speeds (Reported Significant Improvements)		
					m/s	km • h^{-1}	miles • h^{-1}
Paavolainen et al. (1999) Equivalent volumes, i.e. reduced running for plyo group	Highly trained runners 18 males E=10 (less 2) C=8 (less 2)	Plyometrics with Sprint drills and Weight Training	15-90 mins., 8-9 sessions a week, 9 weeks (Significant changes in 3 and 6 weeks)	Con-ecc-con single-leg work and Drop jumps, sometimes weighted	3.67 (4.17)	13.2 (15.0)	8.3 (9.4)
Turner et al. (2003) Run vs. Run+Plyo	Regular runners 8 males, 10 females E=10 (less 1) C=8 (less 2)	Pure plyometrics	3 days a week, 6 weeks	No Con-ecc-con single-leg work No drop jumps	2.68 (3.13) (consolidated running economy using three speeds)	9.6 (11.3)	6.0 (7.0)
Spurrs et al. (2003) Run vs. Run+Plyo	Experienced runners 17 males E=8 C=9	Pure plyometrics	2-3 days a week, 6 weeks	Con-ecc-con single-leg work on Week3, 4 and 6 (3x a week) Drop jumps from Week4 (3x a week)	(3.33) (3.89) (4.44)	(12) (14) (16)	(7.5) (8.8) (10.0)
Saunders et al. (2006) Equivalent volumes, i.e. additional stretching, core work for controls	Elite runners 15 males E=7 C=8	Plyometrics with Fast feet drills and Weight Training	30 mins., 3 days a week, 9 weeks	Con-ecc-con single-leg work from Week1 (once a week) No drop jumps	3.89 4.44 (5.00)	14 16 (18)	8.8 10.0 (11.3)
Lathrop (2001) [unpublished thesis] Run vs. Run+Plyo	High School Runners 13 males, 3 females E=7 C=9	Pure plyometrics	15-20 mins., 2-3 days a week, 6 weeks	Con-ecc-con single-leg work from Week3-6 (ave. 1.5x a week) Drop jumps on Week5 and 6 (once a week, total 4 and 6 jumps)	N/A Used relative speeds: 2 miles per hour (0.89 m/s; 3.2 km • h^{-1}) slower than calculated lactate threshold speed		

The slightly incongruous results of Spurrs and colleagues (63) (6.7% improvement at 12 km • h^{-1}, 6.4% at 14 km • h^{-1}, and 4.1% at 16 km • h^{-1}) may be attributable to measurement error, as running economy for similar subjects have been shown to vary 1-2% under controlled conditions (48). The information in Table 2-1 suggests that depending on the level of runners in the experiment (and hence the degree of stress they can be subjected to), significant improvements in running economy and performance can be gained from plyometrics sessions of about 30 minutes, 2-3 days per week, in about 6 weeks. This minimum is easily within popular recommendations for plyometric training volume (55). However, the precise degree of stress that will induce an adaptation cannot be clearly generalized from four diverse experimental samples and training interventions. Using a simplistic approach, the two studies that show the highest percent improvement in running economy (54, 63) seem to heavily overload the stretch-shortening cycle, as epitomized by two indicators: the use of drop jumps which was sometimes weighted in one study (54) and single-leg exercises that use a full concentric-eccentric-concentric contraction cycle (e.g. hops). In contrast, the two training interventions with minimal reported gains in running economy used more movement-based drills such as bounding or skipping; and any full concentric-eccentric-concentric cycles were performed with two legs or not performed often enough with one leg. The use of similar low training intensities may have also been a key reason why no significant results were found in an unpublished study of sixteen high school cross country runners (38). This study used a six-week plyometric intervention and yielded no significant differences between improvements of experimental and control groups in 3200-meter running performance and running economy measures over time. On the other hand, the intense training protocol of Paavolainen and colleagues (54) may have led to subject attrition, in contrast to the other training studies (58, 63, 65). Subject drop-out due to illness or injury occurred only in this study, though rates were similar for control and experimental groups (2 of 10 and 2 of 12, respectively).

Note that training effectiveness is evaluated above based on percent improvements in running economy—which, in the study by Paavolainen et al. (54)—was measured during over-ground running via a portable telemetric oxygen analyzer. All the other studies performed measurements on a motorized treadmill. While it is reasoned that running economy measured on a treadmill is highly correlated with over-ground running economy (57), it is still conceivable that improvements in submaximal VO_2, especially those wrought by mechanical adaptations, are detected differently when running on a treadmill than over ground.

Only Paavolainen et al. (54) and Spurrs et al. (63) measured actual running performance in addition to running economy. Paavolainen et al. (54) showed a 3.1% increase in 5000-meter time trial performance in highly trained male distance runners (mean $VO_2max = 64.4\ ml \bullet kg^{-1} \bullet min^{-1}$) while Spurrs et al. (63) showed a 2.7% increase in 3000-meter time trial performance in experienced male runners (mean $VO_2max = 57.7\ ml \bullet kg^{-1} \bullet min^{-1}$). Both studies recorded these improvements outside of any changes in metabolic variables such as VO_2max and lactate threshold.

Broadly, one possible mechanism behind improved running economy and performance with plyometrics is neuromuscular adaptation. In the study by Paavolainen et al. (54), three 200-meter laps within the 5000-meter time trial were run at a fixed speed, and the experimental group shortened their average foot contact time after the training period, compared to controls. The authors view this finding as a sign of neuromuscular adaptation. Other biomechanical measures such as ground reaction forces, stride frequency and stride length showed no changes; however, these biomechanical variables were measured while running velocity was held constant.

Another possible mechanism involves changes in muscle-tendon properties, specifically those that maximize the stretch-recoil cycle (63, 65). It has been shown, for example, that the foot can return as much as 17% of the energy it absorbs upon landing, while Achilles tendon recoil can re-generate as much as 35% of the energy it absorbs, all in the absence of metabolic energy contribution. It is likely that this energy-returning property of the Achilles holds true for other tendons as well (1).

Muscle-tendon stiffness, running economy and plyometrics

Tendon stiffness is the change in force applied by a tendon per change in length ($N \cdot mm^{-1}$). It can be estimated globally using the sinusoidal perturbation technique or estimated more accurately with dynamometry and ultrasound as the slope of the relationship between measured tendon force and length. High tendon stiffness is thought to be detrimental to elastic recoil and is more suited to force transmission or increased rate of force development (33, 34). However, tendon stiffness has been shown to be related to running economy (4) while three of the five muscle-tendon studies involving plyometrics have shown increases in tendon stiffness (11, 63, 68), with the other two demonstrating increases that were not statistically significant (20, 36).

Briefly, the sinusoidal perturbation technique is an indirect measure of the elastic properties of a limb. It involves loading the contractile elements isometrically and then providing an additional known load to create a detectable fluctuation in force on a load cell. The assumption is that contractile and non-contractile elements of a limb (or limbs) behave like a damped spring system. The isometric contraction, plus the admonition not to move, isolates the contractile elements of the limb, so that any fluctuations in force recorded on the load cell may be attributed to the non-contractile elements (and perhaps to some involuntary neural response). The global stiffness measures of the muscle-tendon system are then estimated from the weight of the load as well as the timing or frequency of the load fluctuations (63, 66).

Ultrasound provides a more direct method of measuring tendon movement or length change. Tendon movement is visualized from real-time ultrasound echoes while force measurements are recorded on a force plate or dynamometer. Typically, changes in force are measured with changes in tendon length during a ramp isometric contraction (21).

Using the sinusoidal perturbation technique, the study by Spurrs et al. (63) found a training effect for the stiffness of the muscle-tendon structures in both legs of the experimental group, but only at the highest load which related to the maximum stiffness value of the leg. The group of runners who performed plyometrics showed an increase in the stiffness of the non-contractile elements of the both left and right legs while controls did not. The investigators speculated that because overall stiffness of the elastic components were thought to approximate that of the tendon alone, the enhanced 3000-meter performance of their plyometrics group may have been caused by a specific increase in tendon stiffness and elastic recoil that allowed for an increase in stride length or stride frequency. This partly relates to the finding by Nummela et al. (53) that with fatigue in a 5000-meter run, stride length shortened but stride rate stayed the same even as ground contact times increased, because flight times decreased. However, stride frequency and stride rate were not measured by Spurrs and colleagues (63). Paavolainen et al. (54) showed a similar performance improvement that was not accompanied by any change in stride parameters, only with decreased contact times, but these findings could be due to measurements being taken when running velocity was controlled.

Recent studies have used ultrasound to confirm that muscle-tendon properties are related to running economy (4) or alterable with plyometrics (11, 20, 36, 63, 68).

Arampatzis et al. (4) have shown that there is less stiffness in the tendon structures of the vastus lateralis at low level forces and greater stiffness in those of the medial gastrocnemius for highly economical runners compared to less economical runners. The authors postulate that compliance of the quadriceps muscle-tendon units at low level forces allows muscle fibers to shorten at a slower speed after initial contact so that fewer muscle fibers may be recruited. This happens because much of the shortening of the muscle-tendon unit is achieved through the shortening of the compliant tendon structures, and the slower shortening allowed to the muscle permits it to generate more force per fiber according to the force-velocity relationship. More importantly for this review, highly economical runners display higher gastrocnemius tendon and aponeurosis stiffness compared to their less economical counterparts. This tendon structure stiffness is accompanied by higher contractile strength and calculated tendon force, so that estimated energy return (measured as the area under the tendon force-strain or force-length curve) is also higher for this group.

In investigating the effects of plyometrics versus isometric strength training on tendon stiffness and muscle performance, Burgess et al. (11) showed a significant increase in the stiffness of the medial gastrocnemius tendon for a group of thirteen men, where presumably six or seven were trained with drop jumps (the number of subjects per group was not reported). An increase in tendon stiffness was detected after only 6 weeks of single-leg drop jump training: 3 sets of 15 repetitions of maximal drop jumps twice a week which progressed to 4 sets of 20 repetitions thrice a week by the final week. This intervention seems to meet the minimum criterion established earlier from training studies for improvements in running economy. However, in this experimental set-up, tendon force values were derived from torque measurements with a ground force plate sensor rather than the more widely used isokinetic dynamometer. Subjects stood on one straight leg over a force plate with their shoulders pinned down by a bar in a modified Smith machine. The investigators' intent was to prevent the heel from lifting, creating a true isometric plantar flexion, but it is reasonable to be sceptical of other forces outside plantar flexion being recorded using this set-up.

In a similar experiment that compared the effects of plyometrics versus weight or resistance training on tendon properties and jump performance, Kubo et al. (36) found that both maximum tendon force and elongation of the medial gastrocnemius tendon increased, but their relationship—tendon stiffness—remained unchanged after 12 weeks of a "plyometric-like" intervention. These investigators used a weighted sled machine to guide movements similar to a drop jump and counter-movement jump using only the ankle joint. The sled was set at a 17-degree angle from horizontal and weighted with 40% of the subject's 1-repetition maximum. This intervention is not equivalent to the demands of plyometric drills, where multiple joint action, body carriage, and issues of dynamic balance require more intense and complex neuromuscular activation (see Plate 2-1). Also, the ten male subjects were reportedly untrained, the comparisons between plyometrics and resistance training were made against left and right limbs, and the jump performance test was done on the sled machine. For these reasons, viewing the results of this study in light of training studies that employ real-life plyometric exercises must be done with some caution.

While Kubo et al. (36) used a sled to isolate the ankle joint in their "jump" tests, Burgess et al. (11) employed a similar performance task in a unilateral maximal vertical jump with an extended knee. Both studies showed more

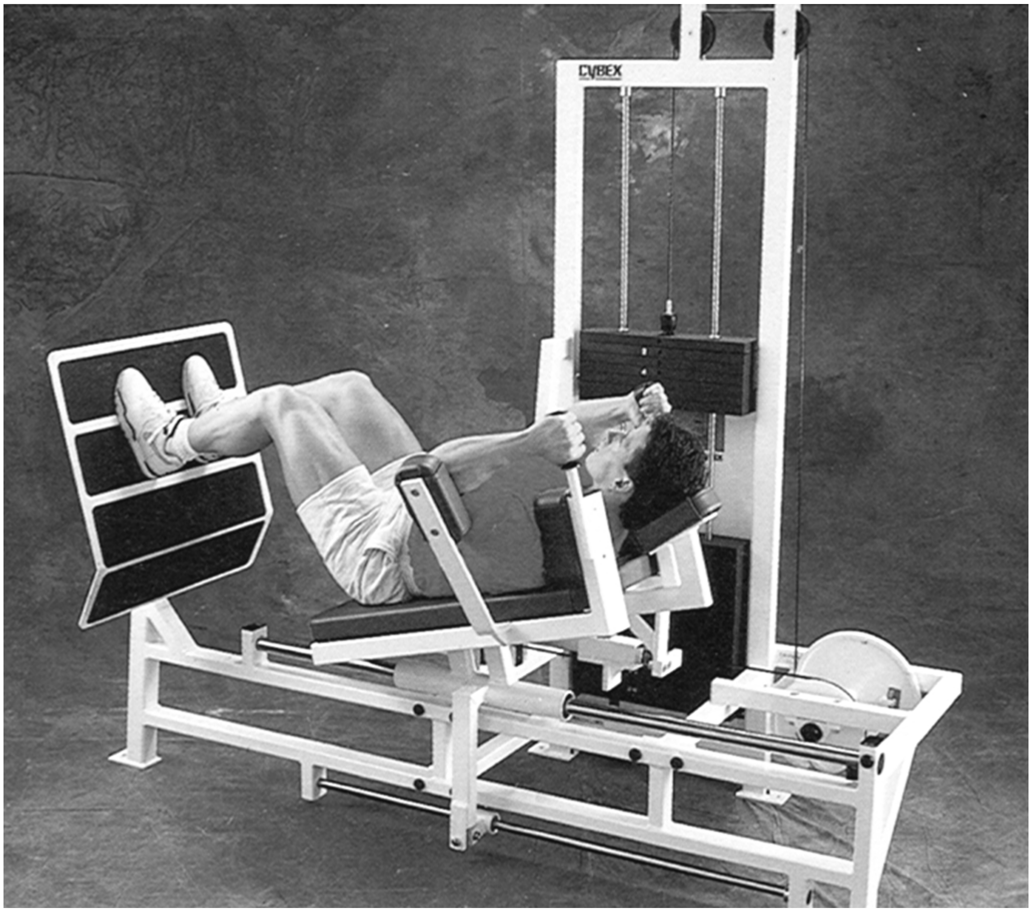

Plate 2-1. Photograph of sledge apparatus (Cybex VR-4100) used in Kubo et al. (36) where the line of movement was tilted from horizontal to 17 degrees. (From: http://www.fullcirclepadding.com/displaypages/admin/Products/SubCategoryimages/cybex%20classic%20leg%20press%204100.jpg, accessed 03 July 2009.)

improvement in jump heights with plyometric training than with concentric-eccentric-cycle resistance training or with isometric training, respectively. The increased jump heights in Burgess et al. (11) correlated mildly to muscle-tendon stiffness. In contrast, Kubo et al. (36) concluded that the jump height gains in their study were due to increased tendon force and elongation, but not stiffness.

Instead of muscle-tendon stiffness, Kubo and colleagues (36) implicated overall joint stiffness in the greater increases in jump heights due to plyometrics, as joint stiffness increased with plyometric training but not with regular resistance training in their study. The researchers hypothesized that this joint stiffness may be due to increases in the passive tension of individual muscle fibers as seen in an 8-week plyometric study by Malisoux et al. (46). In addition, they argue that it is this higher tension in muscle and not tendon stiffness which may have led to the improved running economy and performance in the study of Spurrs et al. (63), where musculo-tendinous stiffness of the ankle joint was measured globally via the sinusoidal perturbation technique.

While Kubo et al. (36) did not show any significant increase in muscle-tendon stiffness of the medial gastrocnemius after plyometrics, their results do involve some increase in tendon stiffness (p=0.109), suggesting that adaptations to increase tendon force may not be as limited as those that increase tendon elongation. From an anatomical and mechanical view, tendon length will have a physical limit dictated by limb length, muscle structure, et cetera, while increases in tendon elongation by itself may be limited as a protective mechanism from ruptures due to excess strain (50). It is therefore conceivable that once maximum tendon elongation has come close to its physical or mechanical limit, internal tendon structures may adapt to accommodate further (and likely small) increases in stiffness to be able to generate more elastic force and recoil, similar to adaptations seen in concentric or isometric resistance training (32, 37). And if stiffness does increase, then it should be matched by an increase in contractile strength, as greater force will be required to pull the stiffer tendon to the same maximal elongation (50). For example, Arampatzis et al. (4) found that highly economical runners possess higher contractile strength of the medial gastrocnemius in conjunction with stiffer Achilles tendons.

Interestingly, the two most recent studies involving an eight-week, 16-session plyometric training program mirror the contradictory findings of Burgess et al. (11) and Kubo et al. (36) with regard to tendon stiffness. Wu and colleagues (68) support the finding that plyometrics increases tendon stiffness, and although they did not report tendon elongation data, they showed significant increases in elastic energy release (measured as the area under the tendon force-elongation curve). This implies that contractile strength or tendon elongation increased separately or together. In contrast, Fouré et al. (20) found that plyometric training increased gastrocnemius musculo-tendinous stiffness but not Achilles tendon stiffness, but they did not report changes in tendon elongation. As with Kubo et al. (36), even if there was no statistically significant increase, Fouré et al. (20) recorded some increase in Achilles tendon stiffness. A look at the reported mean changes suggest greater increases in stiffness for the plyometrics group compared to controls, respectively, at all pre-determined force outputs (80 N, 160 N, 240 N, 320 N): +2.3 N • mm^{-1} vs. +0.7 N • mm^{-1}; +2.2 N • mm^{-1} vs. -1.3 N • mm^{-1}; +1.9 N • mm^{-1} vs. -3.3 N • mm^{-1}; +1.7 N • mm^{-1} vs. -5.3 N • mm^{-1}. Unfortunately, the researchers did not report a specific p-value that can be compared to the non-significant findings of Kubo et al. (p=0.109) (36). This may prove important as an outlier and technical errors with the ultrasound videos reduced the study's sample size from seventeen to thirteen subjects, 6 experimental and 7 controls.

In summary, running economy and performance have been documented to improve with a supplementary plyometrics training program of approximately 30 minutes, 2-3 times a week over approximately 6 weeks; and given that the training intervention provides adequate stress. The amount of stress will depend on the level of training of the athlete, but arguably must involve drop jumps and single-leg exercises with a full concentric-eccentric-concentric contraction cycle. Increased elastic force and recoil of muscle-tendon units, particularly those of the gastrocnemius, may be responsible for this running economy and performance improvement. This may be seen through increases in force production, elongation, and stiffness of the different components of the muscle-tendon unit. Global or whole-limb increases in the stiffness of the muscle-tendon complex in conjunction with improvements in running economy and performance have already been reported. Direct measures of medial gastrocnemius tendon stiffness using ultrasound as well as contractile force have also been shown to be higher in more economical runners. The same direct measures have also shown medial gastrocnemius tendon force, elongation and perhaps stiffness to increase with plyometric training.

This investigation will use the minimum training intervention inferred from the literature to elicit measurable effects. The aim is to study the effects of a real-world plyometric training program on running performance and running economy as Spurrs et al. (63), but also to measure directly the adaptations in musculo-tendinous structures as Kubo et al. (36). In addition, there have been no reported studies of this kind involving female subjects.

Chapter 3

Materials and Methods

Subjects and experimental design

This study used a quasi-experimental design with pre and post measures. Twelve female runners from the University of Alberta Cross Country and Track and Field Team and five female runners from the team's feeder running club volunteered for this study. All volunteers were endurance runners (800m to 5000m events) who trained under the same general program. Subjects were matched by running economy and team training group, and then randomly assigned to a control (n=8) and an experimental group (n=9). Training groups are set by team coaches according to fitness level and the target event distance. The training groups were accommodated in this study to keep run training comparable between control and experimental groups: the experimental group performed plyometric drills in addition to their training group's regular workouts for a period of eight weeks; their matched counterparts in the control group performed regular training without plyometric intervention. All subjects were tested for running economy, running performance and tendon measurements before and after the eight-week training period.

Five university runners dropped out early in the study: three from the experimental group, two due to personal reasons and another due to illness; while two dropped out from the control group, one due to personal reasons and another due to injury. Neither the illness nor injury of the two athletes was related to the plyometric training program or any measurements performed for this study. A series of *t*-tests showed that all running economy measures were still matched after subject drop-outs. The final sample (n=12) consisted of six runners in the control group and six runners in the experimental group.

The mean (±SD) age, height and weight of the final experimental group (n=6) were 18.7 (±5.9) years, 167.1 (±6.4) cm. and 58.3 (±6.0) kg., respectively. Mean (±SD) self-reported running experience was 5.9 (±2.4) years. The mean (±SD) age, height and weight of the final control group (n=6) were 19.4 (±3.1) years, 165.6 (±5.2) cm. and 57.8 (±6.1) kg., respectively. Mean (±SD) self-reported running experience was 7.1 (±4.3) years.

Written informed consent was obtained from all participants and this study was approved by the Faculty of Physical Education and Recreation's Research Ethics Board at the University of Alberta.

Overview

The study consisted of a preliminary familiarization session and two measurement periods before and after an eight-week plyometric training intervention. The familiarization session consisted of 45 minutes of treadmill running for treadmill accommodation (59) and practice in ramp isometric plantar flexion to maximum on a Cybex II isokinetic dynamometer (Cybex II+ and UBXT, Cybex, USA). The pre- and post-intervention measurement periods each consisted of two visits to the laboratory: one visit for tendon force and elongation measurements and another for measurements of running economy and running performance. For each subject, measures of tendon properties were collected before any running test was conducted.

Measurements

All measurements before and after the plyometric training intervention were made using the same protocols and over a period of not more than six days with some exceptions: post-intervention, two athletes from the experimental group were measured 5 and 8 days after the last measurement day due to their personal schedules. All foot and leg length measurements were taken post-intervention within two weeks of the last measurement day with some exceptions: two athletes, one from the experimental group and one from the control group, were measured 24 and 26 days after the last measurement day due to their personal schedules. Treadmill speed and grade were calibrated before, during and after each measurement period (pre- and post-intervention). The metabolic cart system (TrueOne 2400, ParvoMedics, Inc., USA) was calibrated for flow volumes and with gases of known concentration before and after each test. The isokinetic dynamometer was calibrated for torque before each measurement period (pre- and post-intervention). All athletes surrendered their running shoes after pre-intervention measurements and received them at the start of post-intervention measurements to control for effects of footwear on running economy (2).

Running economy

Running economy was measured as the rate of oxygen consumption (VO_2) in the last 1-2 minutes of running during three submaximal bouts on a customized treadmill at level grade. The three speeds used were: 8.0, 9.7 and 11.3 kilometers per hour (5, 6, 7 miles per hour). These were conservatively based on the literature for potential comparisons as well as on the initial treadmill familiarization sessions. A warm-up of eight minutes at the first speed was given. This was followed by five-minute bouts at each of the submaximal speeds, with five minutes of standardized seated recovery in-between. After the last bout, the athletes were accompanied to the indoor track oval, and within 5 or 6 minutes, began their 3000-meter time trial.

To calculate running economy, expired gases were determined and analyzed by the computerized metabolic measurement system. A change in the rate of oxygen inspiration and carbon dioxide expiration of less than 100 milliliters per minute between the third and fourth minutes or the fourth and fifth minutes were used as steady state criteria. Rate of oxygen consumption (VO_2) was averaged over the fifth minute of exercise and normalized by body mass and by body mass$^{-0.75}$ for each of the three speeds. A consolidated running economy value was also calculated based on standard body mass (ml • kg^{-1} • km^{-1}).

Qualitative data on factors that could affect running economy were collected by means of a brief interview. Questions were asked on the following: fatigue and soreness, hours of sleep from the previous night, volume and timing of last meal and/or food intake, and hydration (see Appendix B).

Running performance

Distance running performance was measured as a 3000-meter time trial along the inner lane of a 200-meter indoor track. Subjects were instructed to complete the distance in as little time as possible using their own pacing strategy. No verbal encouragement was given and lap numbers were communicated by the number of raised fingers while the last lap was impassively announced with the words “One more.” Data was recorded to 0.001 seconds with a hand-held stopwatch (Robic SC505, MBI Corporation, USA). Temperature, pressure and humidity readings from an indoor weather system (Davis Perception II, Davis Instruments, USA) were noted immediately before or immediately after the runner started and/or finished the time trial. The secondary variables of stride length and stride frequency were later estimated from video recordings of the 3000-meter time trial (see Appendix C).

Tendon force and elongation

Tendon force was estimated from measured ankle joint torque values during a ramp isometric plantar flexion movement to maximum on the isokinetic dynamometer. Subjects lay prone on the extension table with their left knee extended and their bare left foot strapped to the dynamometer’s foot plate as securely as possible. The foot plate was set at 90 degrees. A digital metronome (Seiko DM-10, Seiko Corp., China) was used to mark a 5-second period of increasing isometric contraction from rest to maximum. Torque readings on thermal paper were later quantified with a standard ruler (Orion, Japan) and the values corresponding to each second (1, 2, 3, 4, and 5) were recorded to the nearest 0.5 N-m. A sixth time point was often added when maximum torque was achieved after 5 seconds; here, both time and torque were recorded and time was recorded to the nearest 0.4 seconds. Torque values were then converted to tendon force estimates using the following equation:

$$F = Tq/MA$$

where F is the estimated tendon force, Tq is the measured torque, and MA is the estimated moment arm of the Achilles tendon. The moment arm was estimated using the method of Spoor et al. (62) and the formula of Grieve et al. (22), so that the moment arm of the Achilles tendon was calculated as a function of the ankle joint angle and tendon elongation predicted as a proportion of leg length. Joint angle during plantar flexion movement was tracked with an electrogoniometer (Penny and Giles, UK), while tendon length was simultaneously visualized via ultrasound. Leg length was measured by a certified exercise physiologist using anthropometric tape (Almedic, Canada) after the post-intervention testing period (see Appendix D).

Tendon elongation was visualized by a radiologist who was blinded to the experimental grouping of the study. A high frequency linear array ultrasound probe (Philips iE33 with L11-3 transducer; Royal Philips Electronics, Netherlands) was set as close as possible to the visualized distal myotendinous junction of the left medial gastrocnemius where a highly visible fascicle attachment to the deep aponeurosis was selected by the radiologist. The movement of this fascicle-aponeurosis cross-point during ramp isometric contraction to maximum was followed by the radiologist without compromising the fixed frame of reference. Echoes of this point were recorded at a sampling rate of 41-50 Hz for seven seconds, the start of which was manually timed with the digital metronome. The echoes were later analyzed using video analysis software (Dartfish Connect 5.0, Dartfish SA, Switzerland). The distance the selected point travelled from time zero to each time point is understood as the elongation of tendon structures distal to the selected point, measured here as Achilles tendon length increase and recorded to the nearest 0.1 millimeter (see Plate 3-1).

Since the dynamometer foot plate does not remain absolutely immobile nor does it completely secure the ankle for a true isometric muscle contraction, corrections were made on the tendon length increases measured from the ultrasound echoes. Tendon length change attributable to ankle movement was subtracted from the measured values. For this, prior measurements were performed in a passive condition, where each subject was asked to relax and the ankle was moved by the investigator. With the ultrasound probe firmly in place, digital still copies of the echoes were made for every two degrees of plantar flexion up to twenty degrees of passive movement. The angle of the ankle was determined with an electrogoniometer (Penny and Giles, UK). The electrogoniometer end-blocks were secured with tape on the lateral and distal aspect of the fifth metatarsal and on the postero-lateral aspect of the fibula. Zero degrees was determined as the position of the ankle when braced against the dynamometer foot plate set at 90 degrees. The digital still echoes were viewed using a standard digital photo viewer (Microsoft Windows 5.1, Microsoft Corporation, USA). Transparency films and pens were used in marking fascicle-aponeurosis cross-points as they “moved” every two degrees on a flat computer screen. These markings were then measured using a standard ruler, referenced against the scale on the ultrasound echo. The distance the selected point travelled

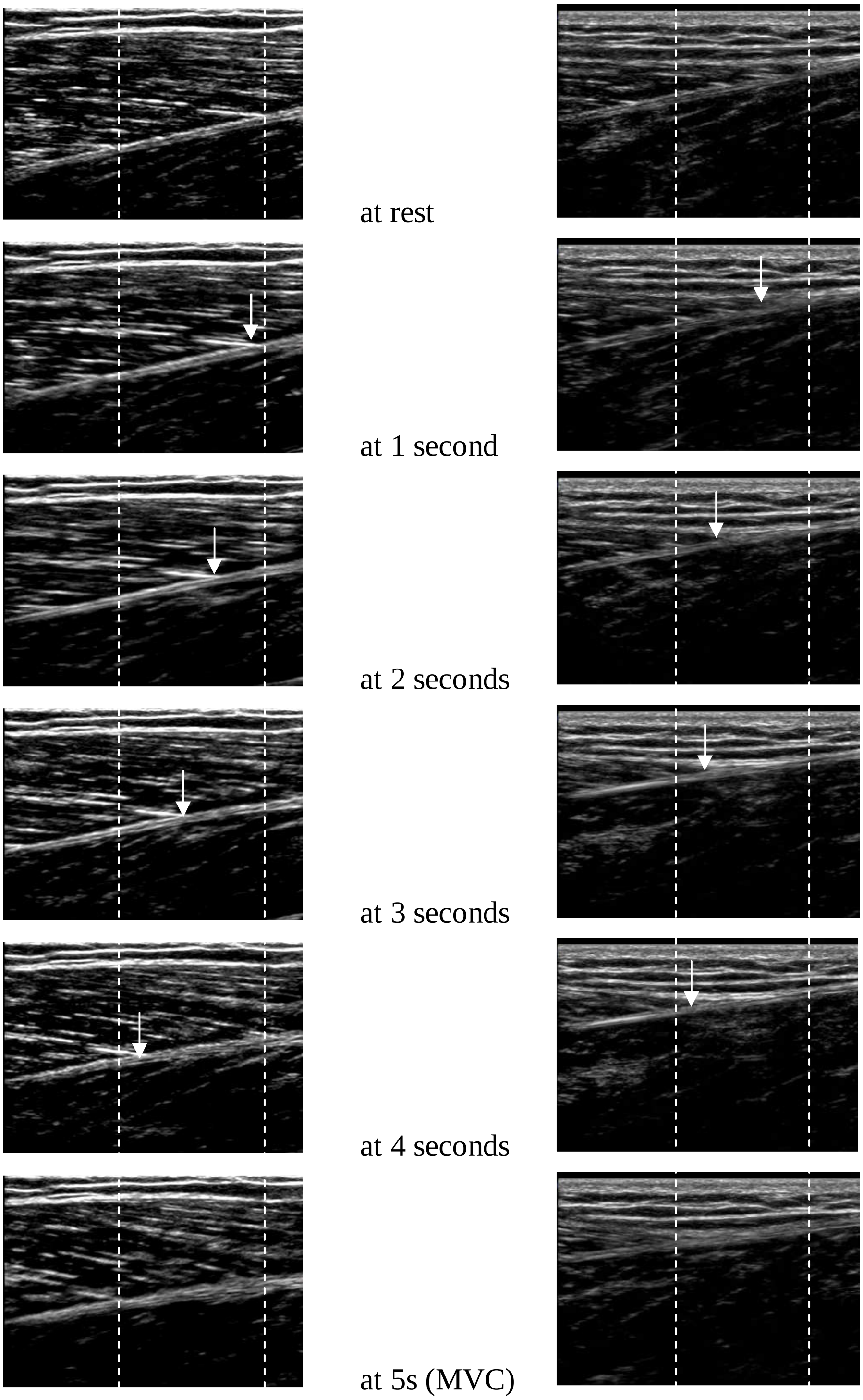

Plate 3-1. Video-captured ultrasonographs of left medial gastrocnemius fascicle-aponeurosis cross-point (left column) and myotendinous junction (right column) of one subject for every second from rest to maximum voluntary contraction (MVC). Distance covered by the right-to-left movement of selected measurement site is defined as the change in length of the Achilles tendon from rest to MVC.

every two degrees from zero to twenty is understood as the elongation of tendon structures distal to the selected point, measured here as Achilles tendon length increase due to ankle movement and recorded to the nearest 0.5 millimeter or the equivalent of ~0.1 millimeters on the ultrasound echoes' 4.4- and 5.2-millimeter scales. The electrogoniometer was kept in place for ramp isometric plantar flexion to maximum. Measurements of ankle angles were taken simultaneously with those of tendon force and elongation and allowed for the subsequent correction. Ankle angles were recorded on a personal computer at a sampling frequency of 120 Hz using custom-made software created in the biomechanics laboratory of the University of Alberta. Plate 3-2 provides a graphical summary of the equipment set-up for tendon measurements and Plates 3-3 to 3-5 show the set-up during a measurement trial.

Measurement trials with complete data and a steady increase in ankle plantar flexion torque were collected for later analysis. Otherwise, the measurement trial was repeated. Three successful trials were performed in the passive condition and a linear regression equation was derived from values from each subject and the origin. Tendon length change values calculated from the equation were used for the correction (subtracted from values in the "isometric" contraction condition). Five successful trials were performed for the ramp isometric contraction condition. The first three trials followed the movement of the fascicle-aponeurosis cross-point close to the myotendinous junction as described above, while two additional trials followed the movement of the myotendinous junction itself and later used for corroboration. These two sets of

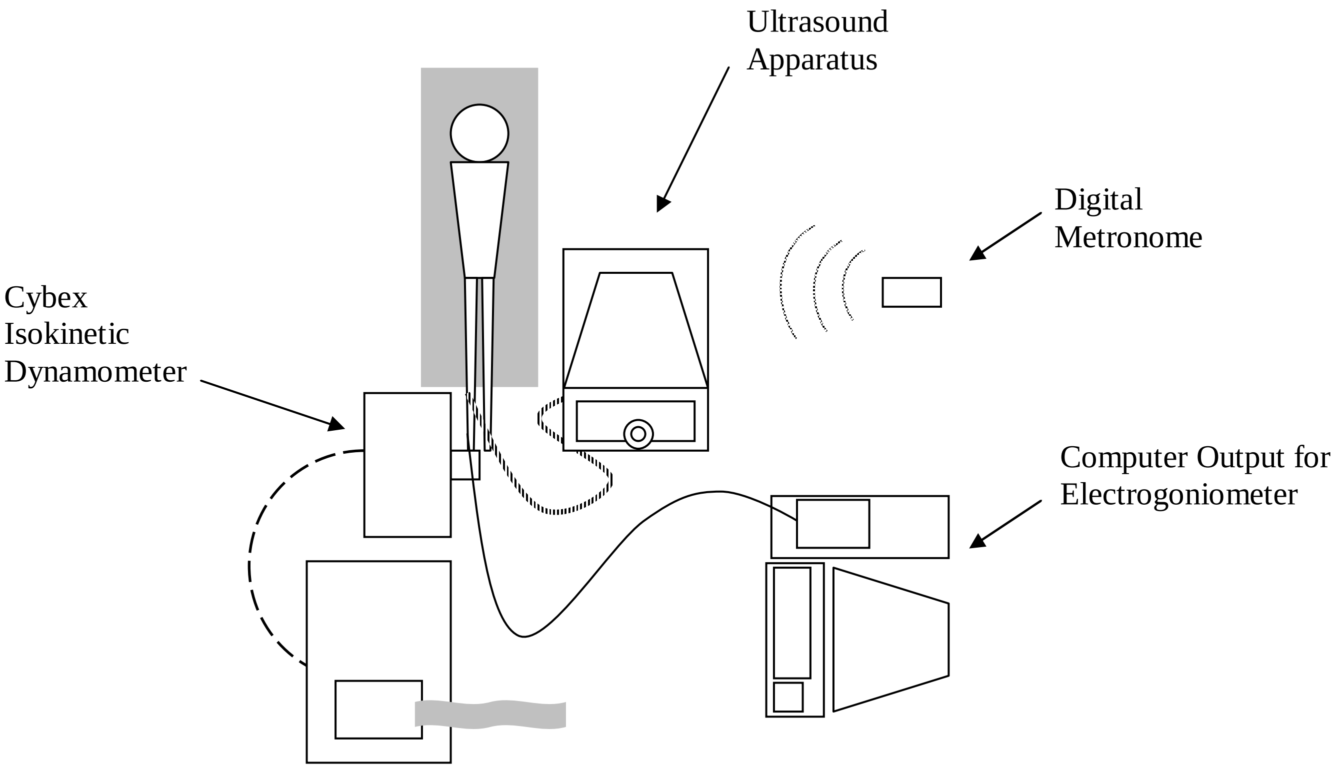

Plate 3-2. Diagram of experimental set-up for tendon force and elongation measurements.

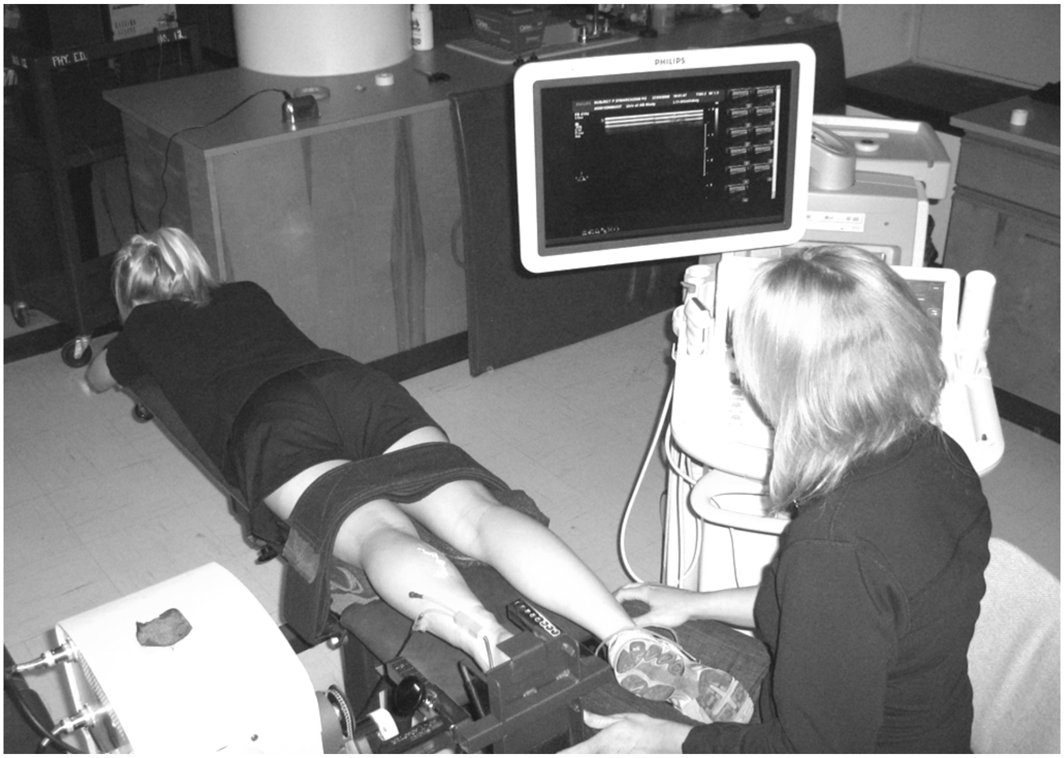

Plate 3-3. Photograph of measurement set-up for data collection via ultrasound.

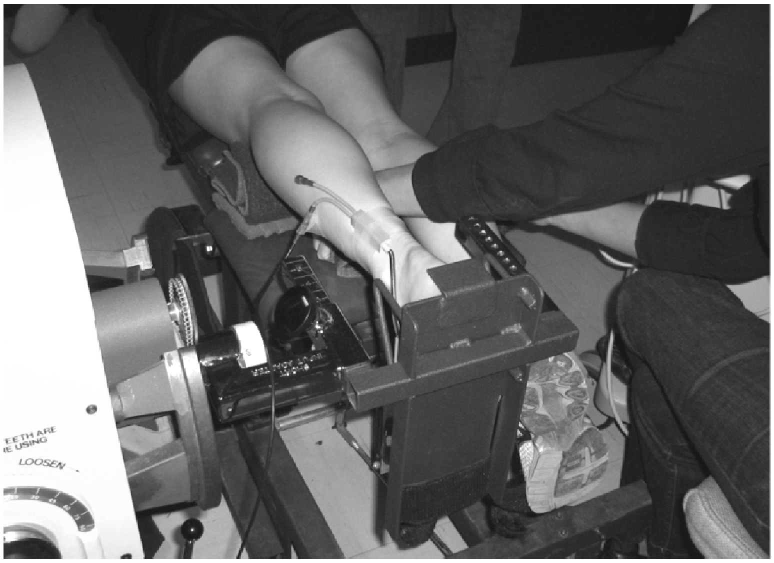

Plate 3-4. Photograph of electrogoniometer and isokinetic dynamometer attachment.

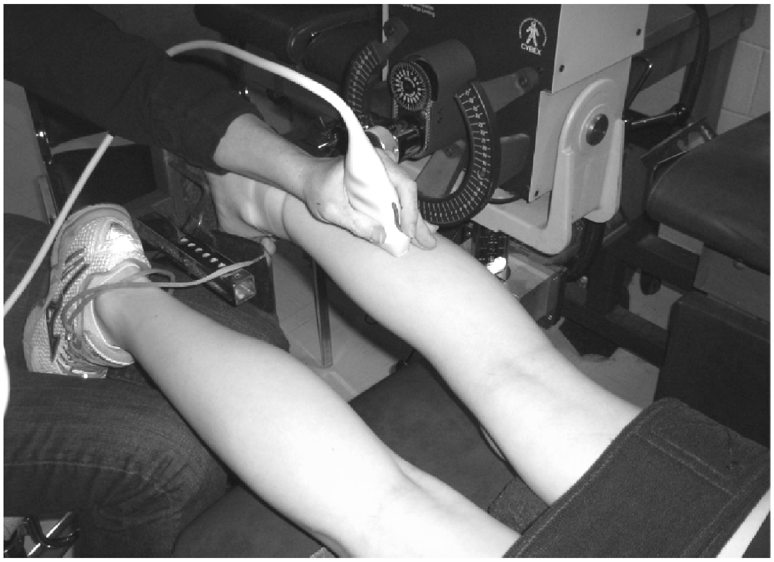

Plate 3-5. Photograph of ultrasound probe position during a scan.

values were fitted separately to a linear regression equation, again forced through the origin. Tendon stiffness was measured as the slope of the regression line of the relationship between estimated tendon force and visualized tendon elongation. It is generally accepted that the tendon force-elongation relationship is quadratic (rate of tendon elongation decreases as tendon force increases), so that the initial intention was to measure the slope of the upper half of the regression curve (50-100% of maximum tendon force) as per Kubo et al. (36). However, data in the present study demonstrated largely linear relationships, so a simple linear regression was used.

Maganaris (40) has criticized the correction method presented above as invalid. He showed that when the ultrasound probe is affixed to the skin, subtracting tendon movement based on ankle rotation results in underestimating tendon elongation, because the leg slides along its long axis during plantar flexion. The movement of the leg and probe attached to it is already of near-equal magnitude to the movement of the Achilles tendon origin at the calcaneus. Therefore, doing away with the correction will actually result in more accurate measurements so long as the probe is securely on the skin, as was done recently by Burgess et al. and Fouré et al. (12, 20). Data in the present study were more reliable without the correction, but were in closer agreement with those reported in the literature when the correction was used. The latter case is in line with Arampatzis et al. (3) who found contrary evidence to those of Maganaris. However, because the present study used a fixed ultrasound measurement site, the correction was not used in the final analysis.

Reliability checks

The reliability of running economy measures was assessed by having three subjects (2 from the control group and 1 from the experimental group) return for a separate testing session more than 34 weeks after the experiment concluded. This was a convenience sample within the study sample. Each runner performed the complete running economy test twice, approximately 48 hours apart (45.5, 48 and 49.3 hours). Individual running economy data for each test speed per subject was used for the analysis. Meanwhile, the reliability of tendon measures was assessed by performing the test twice on five subjects (3 from the control group and 2 from the experimental group) during the post-intervention test period. This was also a convenience sample within the study sample. The re-test was performed after resetting all equipment. This included releasing the subject from the isokinetic dynamometer and upper body extension table, removing the electrogoniometer from the subject's foot, and erasing all skin markings with an alcohol pad. Individual tendon elongation data at each ankle angle in every trial was used for the reliability analysis in the passive condition. In the active condition, tendon elongation data per matched time point in every trial was used in reliability analysis; that is, if a measurement trial had a sixth time point (for a true maximum force) while its corresponding trial did not, data from the sixth time point was omitted. There were three cases or trials when this occurred. Finally, for all experimental measurements involving ultrasound, the elongation estimates measured from the fascicle-aponeurosis cross-point was compared to those measured from the myotendinous junction itself (recall Plate 3-1).

Plyometric training program

Subjects in the experimental group underwent a supervised, eight-week plyometrics program. With the exception of one drill performed on stairs with closed steps, all plyometric drills were performed on a wooden surface. Plyometrics was scheduled Mondays, Wednesdays and Fridays in the first 30 minutes of the regular training session. Runners would jog for approximately five minutes with the entire team before leaving for plyometric drills. These drills were preceded by an active warm-up with all or almost all of the following drills based on the terminology of Boyle (10) in this order: high knee walk, straight-leg front kick walk, high knee skip (A's with hip, knee and ankle angles at 90 degrees), high knee run (often done repeatedly to raise heart rate and core temperature), butt kicks, cariocas (basic, no knee lift), lunge walk (eventually progressed to add backward lunge walk), stiff-legged dead-lift walk, and inch worm. The distance used for each warm-up exercise was determined by the venue. A racquetball court (6.1 × 12.2 m) was used Mondays and Wednesdays while a mirrored dance studio (7.0 × 13.75 m) was available on Fridays. Most warm-up drills were often done over two lengths of the training space.

The plyometric training program is depicted in Table 3-1 and is based on the terminology of Radcliffe and Farentinos (55). The program's design was based on quality over quantity, as well as simplicity. A maximum of four exercises were performed for any given training session. This was intended to remove the burden of learning complex movements in a short period. In every session, each exercise was designed to progress into the next, moving from

Table 3-1. General summary of implemented 8-week plyometric training program (workouts in sets × repetitions).

Training Phase	Week	Workout 1		Workout 2		Workout 3	Workout 4	
		Double-leg Pogo	Single-leg Pogo	Double-leg Bound (Stair)	Single-leg Bound (Stair)	Alternating-leg Bound	Double-leg Drop Jump*	Single-leg Drop Jump*
General Preparation	1	3 × 10		3 × 3-4		3 × 4	1 × 10	
	2	3 × 10		3 × 3-4		3 × 4	1 × 10	
Single-leg Prep/Early Conditioning	3	3 × 10		3 × 3-4		3 × 4	1 × 10	
	4	2 × 10	1 × 10	2 × 4	1 × 2-5	3 × 4	1 × 10	1 × 3-5
Actual Conditioning	5	2 × 10	1 × 10	2 × 4	1 × 5	4 × 4	1 × 10	1 × 5
	6	1 × 10	2 × 10	2 × 4	1 × 5	4 × 4	2 × 5[h]	1 × 10
Actual Conditioning	7	1 × 10	2 × 10	1 × 4	2 × 5-6	4 × 4	2 × 5	1 × 10[h]
	8	1 × 10	2 × 10	1 × 4	2 × 6	4 × 4	2 × 10	1 × 10

[*] Radcliffe and Farentinos (54) use the term “Depth Jump”

[h] Height increased by 5 centimeters.

general elastic strength to concentric strength to eccentric strength as suggested by Mackenzie (39). Pogos were done as a group while the other exercises were performed individually in round-robin fashion, with the wait in line acting as recovery (approximately 15-60 seconds depending on the exercise and the number of athletes). All exercise sets of single-leg drills were preceded by sets that worked both legs as a form of preparation. Athletes were closely supervised by the investigator for maximal effort and correct technique; and feedback was given on each repetition as needed.

From the beginning, the intention was to use the training program as a general guideline. Often, alternate leg bounds were not performed, and occasionally, neither were leg stair bounds. Also, not all warm-up drills would be used in a given session due to the time constraints. Similarly, progressions in training volume or intensity were modified slightly to fit each individual athlete's needs based on constant feedback and observations from the athletes and the researcher.

The initial height of drop jumps was determined with the aid of the reactive strength index (RSI). Briefly, the reactive strength index is the ratio between vertical jump height and contact time during a drop jump. It is considered a measure of the neuromuscular system's ability "to tolerate stretch load and change movement from rapid eccentric to rapid concentric" (51). The experimental subjects performed four maximal jumps on a ground force sensor plate (Bertec 4060A, Bertec Corporation, USA): a counter-movement jump and three drop jumps from a height of 30, 45 and 55 centimeters. The optimum height for drop jump training was estimated from the drop heights that yielded the highest reactive indexes. For practical reasons, a single conservative value was chosen for the entire group: 30 cm for double-leg drop jumps. For the sixth and seventh week of the training program, progression was aided by a similar protocol in selecting heights for single-leg drop jumps as well as in adjusting the height for double-leg jumps.

Each plyometrics session did not last more than thirty minutes, as each athlete had to rejoin the team for official practice. However, extra sessions were held outside of official practice days to make up for cancelled sessions due to public holidays and personal schedules. These sessions were not as constrained by time so all warm-up exercises and plyometric drills were performed. Feedback for sprint, and by extension general running technique, was also offered to the experimental group with the idea that physiological adaptations from plyometric training—whether neuro-muscular or musculo-tendinous—may require some degree of running technique to utilize. Verbal feedback was given after each of four to six 40-meter sprints at close to maximum speed. These full sessions would last for approximately 45 minutes, with an additional 15 minutes when run technique was being coached.

Run training program

The team's regular run training was monitored by observation, and through the coaches' training plans and records as well as training diaries (a Microsoft Excel file) electronically sent and distributed to all research participants. The run training program was designed by the team's coach around speed endurance, using low volumes and high intensities. Athletes were expected to attend team practices on Mondays, Wednesdays and Fridays and adhere to specific workout plans. Over the course of the experimental period, the general weekly pattern followed for those training for 800-meter races was: one session focusing on speed; one session focusing on running at VO_2max using short, fast intervals; and one interval training session that changed about every week, alternating between long intervals (generally 200-800 meters at 3000-meter race pace) and short intervals (generally 100-400m at 800- or 1000-meter race pace). For those training for 1500- to 3000-meter races, the general weekly pattern was: one session focusing on speed; one session focusing on running at VO_2max that changed every week, alternating between short and long intervals; and one interval training session that changed every week, alternating between aerobic and anaerobic intensities. On other days of the week, light recovery workouts were officially prescribed but seemed to be generally understood as optional or variable.

Analysis

Complete data was obtained from 12 subjects for running economy. Data for eleven subjects (E=6, C=5) was used for running performance. Data for ten subjects (E=5, C=5) was used for tendon force and elongation. Incomplete data sets were due to errors in measurement protocol.

A between-group analysis (*t*-test) was conducted after random assignment to check for probabilistic equivalence before plyometric intervention. This was repeated after subject drop-out. For reliability checks, technical error of measurement as absolute values and as coefficients of variation was calculated according to the methods promoted by the Australian Sports Commission (7) and summarized in Appendix E. Tendon variables were additionally analyzed using the intraclass correlation coefficient (two-way mixed effects model average measure reliability with measures of absolute agreement) or *ICC* (3, *k*) as per Shrout and Fleiss (60).

For the primary variables of running economy, running performance, maximum tendon force and maximum elongation and tendon stiffness, a 2×2 factorial repeated measures ANOVA was used. A three-way repeated measures ANOVA was used to evaluate changes in the slope of running economy at three speeds for two groups over time. Absolute (L • min^{-1}), relative (ml • kg^{-1} • min^{-1}), and allometric-scaled (ml • kg^{-75} • min^{-1}) running economy were all tested. A Tukey post-hoc test was intended for any significant F-ratios found. Chauvenet's criterion was used to confirm the presence of an outlier; a secondary analysis without the outlier and utilizing a form of selective comparison was performed on primary variables and stride parameters using the Mann-Whitney test. Percent differences before and after plyometric intervention were used. Statistical significance was set a priori at $p \leq 0.05$ for all analyses. All statistical analyses were performed using SPSS 17.0 (SPSS Inc., USA) and data are reported as mean ± standard deviation, unless otherwise noted.

Chapter 4

Results

The control and experimental groups remained matched for running economy despite subject drop-out soon after the pre-intervention testing period. Excessive variability in tendon measurements was reduced by undoing a failed corrective step. An outlier and issues of subject compliance prompted a secondary analysis of fewer subjects using descriptive statistics and a non-parametric test to explore trends. Descriptive statistics were also used for qualitative data collected before each run test. All line graphs use group means, and error bars represent one standard deviation.

Plyometric training program

During the experimental period, a total of four team practices were cancelled: two due to public holidays and two due to venue availability and/or local race participation of individual runners. This meant that team members had to perform the run workouts on their own, but it also meant cancelling plyometrics sessions since these had to be supervised. There were also individual reasons for missing official team practice hours. Accordingly, a total of 5 plyometric training sessions were scheduled outside of the planned weekdays, in addition to running several multiple sessions in a day (morning and afternoon, or before and after run training) to accommodate individual schedules. Two subjects attended at least 3 special sessions with running technique feedback, one subject attended two, and one subject attended one. Average attendance for plyometric training was 17 sessions, with a range of 11 to 23 sessions attended (or 2.1

sessions per week with a range of 1.4 to 2.9 sessions per week attended). In addition, one athlete with a minor soft-tissue injury (incurred outside plyometric training) was provided a reduced load; specifically, all single-leg work was withheld. This is shown in Figure 4-1.

Run training program

On an individual basis, athletes skipped or altered team training sessions so that any generalizations about the run training program must be made with caution. Half of the research participants returned their training diaries (n=6). Three of these athletes were from the control group and three were from the experimental group. Five were in the 1500m training group while only one belonged to the 800m training group. Only key-workout days were assessed, the three days of the week when the team trained together. The last two of twenty four sessions in the experimental period were excluded due to incomplete data; there was some confusion about the training schedule in the last two days as these fell on the Easter long weekend (Good Friday and Easter Monday). Table 4-1 summarizes run training compliance as interpreted from the returned training diaries. Data from these training records suggest that on average, athletes performed 68% of all scheduled workouts, altered 10% and skipped 14%; also, about 8% of scheduled sessions were spent on other forms of training. Sessions were classified as “altered” when athletes performed run training that was different from the planned team workout, often due to injury, personal reasons or individualization by the coach. This category also includes workout sessions completed a day before or a day after the original schedule. In contrast, sessions were classified as “replaced” when some form of training other than running was performed. This was often resistance or strength training, or cardiovascular training on a bike, rowing machine or elliptical machine, often performed due to injury or personal reasons. Reasons for skipping sessions included illness, injury, and other personal reasons. Categorizing a few sessions involved subjective judgement as some athletes performed extra work on other days that may or may not be considered as a substitute or modification. In addition to the type of extra training performed, the frequency of these sessions varied from never to almost always in the six athletes who recorded their training. The two athletes who did not report any extra training were both in the final experimental group.

Reliability checks

Data pertaining to the reliability of running economy measures are shown in Table 4-2. Self-reported fatigue, soreness, hours of sleep from the previous night, hydration status and volume, timing and type of food intake were comparable between tests except for one subject who reported more fatigue and slightly more hours of sleep prior to the second measurement.

Ranges for temperature, barometric pressure and humidity, respectively, were a constant 22 degrees, 693-704 mmHg, and 3-7% saturation in the pre-intervention running economy tests while they were 19-20 degrees, 700-708 mmHg, and 2-16% saturation in the post-intervention testing period. Therefore, between the two testing periods, runners experienced environmental differences of 2.58 (±0.5) degrees, 6.0 (±5.2) mmHg, and 6.5 (±2.8)%. For the 3000-meter run performance trials, ranges for temperature, barometric pressure and humidity, respectively, were 20-23 degrees, 695-702 mmHg, and 3-14% saturation in the pre-intervention testing period, and constantly 21 degrees, 701-708 mmHg, and 4-19% post-intervention. Environmental differences experienced by athletes between these tests were 0.75 (±0.9) degrees, 6.33 (±2.7) mmHg, and 4.83 (±3.2)%.

Results of reliability testing for tendon variables are presented in Table 4-3. Table 4-4 shows a secondary reliability check using two measurement sites and Table 4-5 presents the variability in ankle joint rotation within subject trials and between subject means as well as by group and sample. These tables are based on data from the main experiment while Table 4-6 shows the results of reliability testing in maximum ankle joint rotation.

Running economy, performance and tendon properties

Values of running economy and running performance before and after the plyometric intervention may be found in Appendix F, where absolute rate of oxygen consumption is presented with body mass and treadmill speed as the derivation of the different calculations of running economy. Measurement protocol errors led to the exclusion of data from one subject in the control group for all analyses involving time trial performance and from one subject each from the control and plyometrics group for all analyses involving tendon properties. A detailed table of tendon variables per measurement site is provided as Table 4-7. Changes in running economy, running performance and tendon properties by group over eight weeks are presented in Appendix G. No significant differences were found.

Allometric-scaled running economy slopes over three treadmill speeds are presented in Appendix H. Absolute ($L \cdot min^{-1}$), relative ($ml \cdot kg^{-1} \cdot min^{-1}$), and allometric-scaled ($ml \cdot kg^{-75} \cdot min^{-1}$) running economy were all examined and no significant differences were found.

Secondary analysis

One subject from the control group revealed that she was relatively detrained at the start of the experimental period. A check using Chauvenet's criterion revealed that pre-post differences in running performance and running economy (allometric-scaled running economy at all three speeds and consolidated running economy) were consistently outliers among the control group (n=5 and n=6), and that this trend was true only for this particular athlete. This subject's data set was removed for the secondary analysis.

In addition, issues of subject compliance gave good reason for two experimental groups, one described as having "partial compliance" and another as having "full compliance". Attendance records were used as a guideline in determining partial or full compliance. A minimum of two plyometrics sessions per week was deemed necessary for any measurable training effect, so this was used as the cut-off for "full compliance" (recall Figure 4-1). Even when reduced-load sessions are considered as sessions attended, results from a Mann-Whitney test support a significant difference between the "partial compliance" and "full compliance" groups in terms of number of plyometric sessions attended (p=0.05). Figure 4-2 shows the distribution of number of sessions attended by athletes from the two training subgroups.

Moreover, two of the three subjects in the partial compliance group had minor injuries, so that performance was affected aside from plyometric training compliance, with one subject reporting after her post-intervention time trial that she had “never run that slow since Grade 10”. The third subject in the “partial compliance” group missed plyometric training sessions due to frequent competition and actually improved her 3000-meter time trial performance. This subject had a highly individualized run training program. Therefore, data from this group are presented as descriptive statistics but are excluded from comparisons using non-parametric statistical tests.

Group means and standard deviations of running economy and running performance are presented in Table 4-8 for the three groups formed. Changes over time of these variables are also reported as percent differences: group means, standard deviations and 95% confidence intervals are presented in Table 4-9. Positive values are improvements (i.e., lower submaximal oxygen consumption, lower performance time). Running economy and running performance percent differences over time are illustrated by Figure 4-3 and 4-4. Similarly, group means and standard deviations of tendon variables are presented in Table 4-10, with changes over time reported as percent differences in Table 4-11. Positive values are improvements (i.e., greater tendon force, elongation and stiffness).

Changes in running economy, running performance and tendon properties over eight weeks for the three groups are presented in Appendix I. Running economy slopes are shown in Appendix J.

Figure 4-5 depicts percent differences in the secondary variables related to stride, after the percent differences over time of paced running and sprinting stride parameters were normalized to reflect their relative contribution to the run performance trial (14 laps and 1 lap, respectively). Figure 4-6 is the same graph using individual data and excluding the partially compliant group.

Non-parametric statistics between the control group and the full compliance group showed no significant differences. Given that the sample size of the experimental compliant subgroup is low (n=3), the following non-significant differences are reported: the full compliance group showed a higher time trial performance difference versus the control group (p=0.101) as well as a higher stride frequency difference during paced running (p=0.101); also, tendon stiffness measured at the fascicle-aponeurosis cross-point decreased more for controls (p=0.077) but this suggestion is not corroborated by tendon stiffness measured at the myotendinous junction (p=0.724), and maximum tendon elongation increased more for controls (p=0.077) but this suggestion is not corroborated by maximum tendon elongation measured at the myotendinous junction (p=0.289).

Qualitative data

A summary of subjects' self-reports on training/physical state just before run tests is shown as Table 4-12. It presents some factors that may have potentially affected running economy measures and running performance. The factors were flagged based on comparisons of subjects' responses in the two time points (pre- or post-plyo). With regard to meal-timing, the time elapsed after food intake was considered with the volume of food taken which is not reported. Information on the most recent training session was not processed due to incomplete and highly variable data.

Table 4-13 uses the assumption that self-reported factors affected running economy and performance by completely preventing any improvement, so that descriptive comparisons can be made between predictions and outcomes. Running economy outcomes were determined based on percent change minus relative technical error of measurement (2.2% for allometric-scaled measures according to the reliability check). Time trial outcomes were based on previously reported variability (1.3%) in a group of fast women runners participating in cross country and road races of 2500 to 12000 meters over a similar time period (25). Positive values are improvements (i.e., lower submaximal oxygen consumption, lower performance time). Due to the small sample size, descriptive statistics are presented. For running economy outcomes, 5 or 7 out of 12 cases refute the hypothesis that self-reported factors affected the measurement (outcome is opposite of prediction, including better performance after no change was predicted); so that also 5 or 7 out of 12 cases support the hypothesis that self-reported factors affected the outcomes (outcome is same as prediction, including worse performance after no change was predicted). For running performance outcomes, only 4 out of 11 cases refute the hypothesis that self-reported factors affected the measurement.

Finally, none of the subjects were of the opinion that their menstrual cycle was a factor in the running economy and performance tests, in addition to recent work showing that tendon properties are not affected by hormonal changes related to the female reproductive cycle (13, 30).

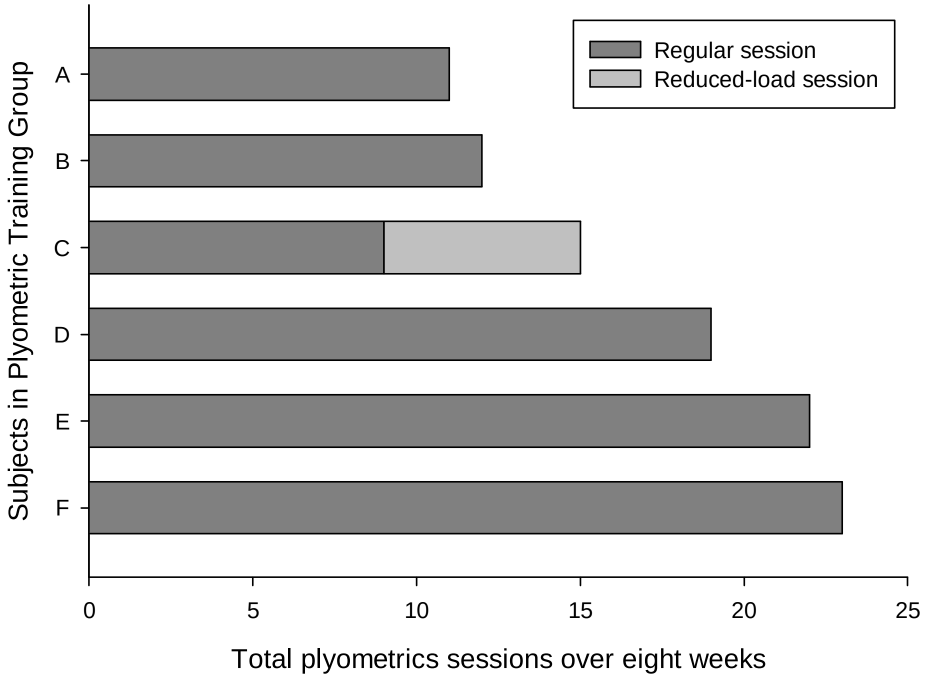

Figure 4-1. Compliance to plyometric training of members of the plyometric training group in number of sessions attended out of 24 total sessions (n=6).

Table 4-1. Compliance to run training of members of the control and plyometric training groups who completed training diaries in number of assigned sessions followed, altered, replaced or skipped (n=6). Values are presented as Mean (Range).

Category or descriptor of training session	Number of training sessions (out of 22) Mean (Range)
Followed	15 / 22 (12-20)
Altered	2.17 / 22 (0-6)
Replaced	1.83 / 22 (0-5)
Skipped	3 / 22 (1-5)

Table 4-2. Results of reliability testing for running economy measures (n=3 × 3 speeds).

Running Economy Measures	Mean Values		Technical Error of Measurement (TEM)	Coefficient of Variation (Relative TEM)
	Test 1	Test 2		
Absolute (L • min^{-1})	1.76	1.76	0.04	2.5%
Relative (ml • kg^{-1} • min^{-1})	29.83	29.88	0.68	2.3%
Allometric (ml • kg^{-75} • min^{-1})	39.80	39.84	0.86	2.2%

Table 4-3. Results of reliability testing for tendon measures via fascicle-aponeurosis cross-point (final variables, n=5; passive condition, n=5 × 10 angles × 3 trials; active condition, n=5 × 5-6 time points × 3 trials).

	Intraclass Correlation Coefficient (ICC)	ICC p-value	Technical Error of Measurement (TEM)	Coefficient of Variation (Relative TEM)
Final Tendon Variables				
(before re-correction)				
Maximum Force (N)	0.970	<0.001	113.79	7.2%
Maximum Elongation (mm)	0.680	0.173	2.78	19.0%
Stiffness (N • mm^{-1})	0.575	0.203	25.30	22.5%
(after re-correction)				
Maximum Force (N)	0.970	<0.001	113.79	7.2%
Maximum Elongation (mm)	0.930	0.007	1.57	8.0%
Stiffness (N • mm^{-1})	0.901	0.005	7.99	10.1%
Passive Condition				
Elongation (mm)	0.969	<0.001	0.84	14.9%
Active Condition				
Elongation (mm) (before re-correction)	0.874	<0.001	2.52	29.4%
Elongation (mm) (after re-correction)	0.947	<0.001	1.95	16.1%

Table 4-4. Results of reliability analysis between fascicle-aponeurosis cross-point and myotendinous junction measurement sites (n=10).

Final Variables (after re-correction)	Mean Differences		Technical Error of Measurement (TEM)		Coefficient of Variation (Relative TEM)	
	Pre	Post	Pre	Post	Pre	Post
Maximum Force (N)	107.05	147.10	105.54	116.38	6.2%	7.3%
Maximum Elongation (mm)	1.11	1.65	1.17	1.41	6.0%	7.3%
Stiffness (N • mm^{-1})	52.35	33.44	58.16	32.12	49.7%	32.7%

Table 4-5. Coefficients of variation for maximum ankle joint rotation per subject, by group, and overall (per subject, n=5 trials; by group n=5 subjects per group; overall, n=10).

Group	Subject	Maximum Ankle Joint Rotation (degrees) Mean (SD)		Coefficient of Variation	
		Pre	Post	Pre	Post
Control	A	10.6 (1.9)	8.1 (1.8)	18.4%	22.5%
	B	6.6 (0.4)	7.7 (0.8)	5.5%	10.3%
	C				
	D	8.1 (0.4)	8.8 (1.9)	4.8%	21.7%
	E	8.1 (0.4)	7.9 (0.9)	5.2%	11.4%
	F	5.8 (1.2)	11.4 (2.4)	20.1%	21.0%
Group Values		7.8 (1.8)	8.8 (1.5)	23.4%	17.5%
Plyometric	G				
	H	5.8 (0.8)	7.9 (0.6)	14.2%	7.0%
	I	11.4 (1.2)	9.2 (0.6)	10.5%	6.2%
	J	7.2 (1.0)	10.0 (1.5)	13.8%	14.8%
	K	8.2 (0.7)	10.1 (0.8)	8.6%	8.4%
	L	4.6 (0.7)	9.1 (1.0)	14.7%	11.4%
Group Values		7.4 (2.6)	9.3 (0.9)	34.7%	9.6%
Sample Values		7.6 (2.1)	9.0 (1.2)	27.7%	13.4%

Table 4-6. Results of reliability testing for maximum ankle joint rotation (n=5).

	Mean Values		Technical Error of Measurement (TEM)	Coefficient of Variation (Relative TEM)
	Test 1	Test 2		
Maximum Ankle Joint Rotation (degrees)	9.5	7.8	3.2	37.0%

Table 4-7. Tendon variables measured in trials using two different measurement sites before and after an 8-week plyometrics program (n=10).

Group	Subject	Maximum Force (N)				Maximum Elongation (mm)				Stiffness (N • mm^{-1})			
		Fascicle trials		Myotendinous junction trials		Fascicle trials		Myotendinous junction trials		Fascicle trials		Myotendinous junction trials	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Control	A	1880.4	1213.7	1753.8	1177.5	16.92	14.57	15.78	13.54	111.1	83.3	90.9	83.3
	B	2068.0	2180.5	2260.6	1916.8	16.54	23.99	18.09	19.50	125.0	90.9	90.9	90.9
	C												
	D	1405.7	1158.5	1594.2	1034.7	9.84	21.46	11.16	19.22	142.9	52.6	90.9	40.0
	E	909.7	1189.8	936.2	1336.2	10.92	15.47	11.23	15.83	83.3	76.9	71.4	100.0
	F	1212.7	1575.8	1218.1	1457.7	19.40	18.91	19.49	17.49	62.5	83.3	58.8	58.8
Group Mean		1495.3	1463.7	1552.6	1384.6	14.72	18.88	15.15	17.12	105.0	77.4	80.6	74.6
(SD)		(476.2)	(435.0)	(508.8)	(337.3)	(4.1)	(4.0)	(3.8)	(2.5)	(32.2)	(14.7)	(14.8)	(24.7)
Plyometric	G												
	H	1468.1	1746.4	1802.5	1690.5	19.09	22.70	23.43	21.98	76.9	76.9	58.8	62.5
	I	1838.8	1471.3	1839.4	1611.2	25.74	16.44	25.75	18.64	71.4	83.3	90.9	83.3
	J	2626.3	2608.1	2489.2	2465.6	28.89	33.04	27.38	31.99	90.9	76.9	83.3	111.1
	K	1355.1	1343.4	1303.2	1182.4	18.97	11.13	18.25	12.31	71.4	90.9	71.4	76.9
	L	2047.6	1962.9	2054.4	1679.2	24.57	18.62	24.65	16.79	83.3	100.0	111.1	90.9
Group Mean		1867.2	1826.4	1897.8	1725.8	23.45	20.39	23.89	20.34	78.8	85.6	83.1	85.0
(SD)		(507.7)	(498.9)	(430.2)	(463.4)	(4.3)	(8.2)	(3.5)	(7.4)	(8.4)	(9.9)	(19.8)	(18.0)
Sample Mean		1681.2	1645.0	1725.2	1555.2	19.09	19.63	19.52	18.73	91.88	81.52	81.86	79.78
(SD)		(503.8)	(480.9)	(480.0)	(422.5)	(6.1)	(6.1)	(5.8)	(5.5)	(26.1)	(12.6)	(16.5)	(21.1)

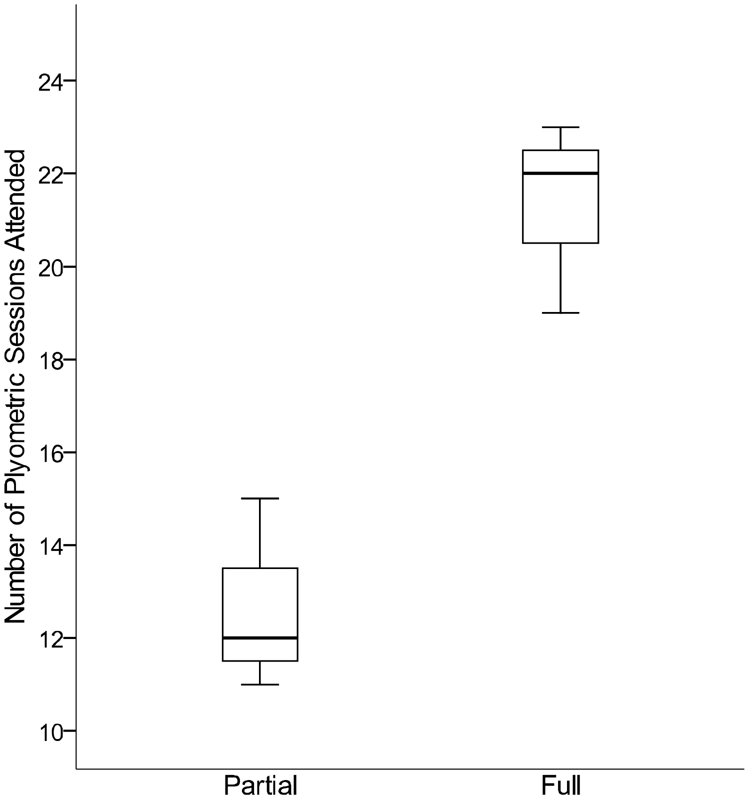

Figure 4-2. Distribution of plyometric training sessions attended for partial compliance (n=3) and full compliance (n=3) plyometric training groups. Significant difference at $p \leq 0.05$.

Table 4-8. Running economy and performance variables for control, partial compliance and full compliance plyometric training groups before and after an 8-week plyometrics program (running economy: n=5, 3, and 3 respectively; 3000-m time: n=4, 3, and 3). Values are presented as Mean (SD).

Group	Allometric-scaled Running Economy (ml • kg^{-75} • min^{-1})						Consolidated Running Economy (ml • kg $^{-1}$ • km^{-1})		3000-m time (s)	
	8.0 km • h^{-1}		9.7 km • h^{-1}		11.3 km • h^{-1}					
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Control Group	34.7 (0.95)	33.9 (1.49)	41.3 (1.66)	40.6 (2.48)	48.6 (2.12)	48.5 (2.85)	193.9 (6.88)	191.3 (10.15)	719.34 (46.22)	713.77 (36.71)
Partial Compliance	34.6 (2.57)	34.3 (0.18)	40.0 (4.51)	39.7 (1.10)	44.9 (5.44)	45.6 (3.37)	186.8 (19.07)	187.0 (5.69)	689.58 (29.43)	711.18 (61.27)
Full Compliance	37.6 (3.39)	36.8 (3.01)	43.1 (4.01)	42.8 (3.43)	49.9 (4.33)	49.7 (5.79)	203.9 (18.37)	201.8 (18.40)	753.21 (32.47)	731.32 (35.47)

Table 4-9. Running economy and performance variables as percent improvement for control, partial compliance and full compliance plyometric training groups over an 8-week plyometrics program (running economy: n=5, 3, and 3 respectively; 3000-m time: n=4, 3, and 3). Values are presented as Mean ± SD (95% confidence interval, CI).

Group	Allometric-scaled Running Economy (ml • kg^{-75} • min^{-1})			Consolidated Running Economy (ml • kg^{-1} • km^{-1})	3000-m time (s)
	8.0 km • h^{-1} Mean ± SD (95% CI)	9.7 km • h^{-1} Mean ± SD (95% CI)	11.3 km • h^{-1} Mean ± SD (95% CI)	Mean ± SD (95% CI)	Mean ± SD (95% CI)
Control Group	2.4 ± 3.77 (-2.3 to 7.1)	1.7 ± 2.98 (-2.0 to 5.4)	0.1 ± 4.35 (-5.3 to 5.5)	1.4 ± 3.36 (-2.8 to 5.5)	0.9 ± 1.67 (-1.2 to 2.9)
Partial Compliance	0.6 ± 7.62 (-18.3 to 19.5)	-0.2 ± 10.65 (-26.7 to 26.2)	-2.0 ± 5.68 (-16.1 to 12.1)	-0.7 ± 8.00 (-20.5 to 19.2)	-3.0 ± 4.63 (-14.5 to 8.5)
Full Compliance	2.0 ± 2.26 (-3.6 to 7.6)	0.4 ± 3.49 (-14.7 to 15.4)	0.5 ± 8.58 (-20.8 to 21.8)	0.9 ± 4.99 (-11.5 to 13.3)	2.9 ± 1.16 (0.03 to 5.81)*

*Statistically significant at $p \leq 0.05$.

Table 4-10. Tendon variables for control, partial compliance and full compliance plyometric training groups before and after an 8-week plyometrics program (n=4, 2, and 3 respectively). Values are presented as Mean (SD).

Group	Maximum Tendon Force (N)		Maximum Tendon Elongation (mm)		Tendon Stiffness (N • mm^{-1})	
	Pre	Post	Pre	Post	Pre	Post
Control Group	1566.0 (518.72)	1435.6 (497.09)	13.56 (3.70)	18.87 (4.58)	115.58 (25.12)	75.95 (16.56)
Partial Compliance	1653.5 (262.10)	1608.8 (194.54)	22.42 (4.71)	19.57 (4.43)	74.18 (3.88)	80.13 (4.53)
Full Compliance	2009.7 (636.47)	1971.4 (632.48)	24.14 (4.97)	20.93 (11.14)	81.89 (9.82)	89.28 (11.62)

Table 4-11. Tendon variables as percent improvement for control, partial compliance and full compliance plyometric training groups over an 8-week plyometrics program (n=4, 2, and 3 respectively). Values are presented as Mean ± SD (95% confidence interval, CI).

Group	Maximum Tendon Force (N)	Maximum Tendon Elongation (mm)	Tendon Stiffness ($N \bullet mm^{-1}$)
	Mean ± SD (95% CI)	Mean ± SD (95% CI)	Mean ± SD (95% CI)
Control Group	-4.2 ± 28.71 (-49.9–41.5)	-5.3 ± 5.88 (-14.7–4.0)	39.6 ± 35.75 (17.3–96.5)
Partial Compliance	-0.5 ± 27.54 (-247.9–246.9)	2.8 ± 9.14 (-79.2–84.9)	-6.0 ± 8.42 (-81.6 to 69.7)
Full Compliance	-1.9 ± 1.94 (-6.7–2.9)	3.2 ± 6.45 (-12.8–19.2)	-7.4 ± 18.56 (-53.5 to 38.7)

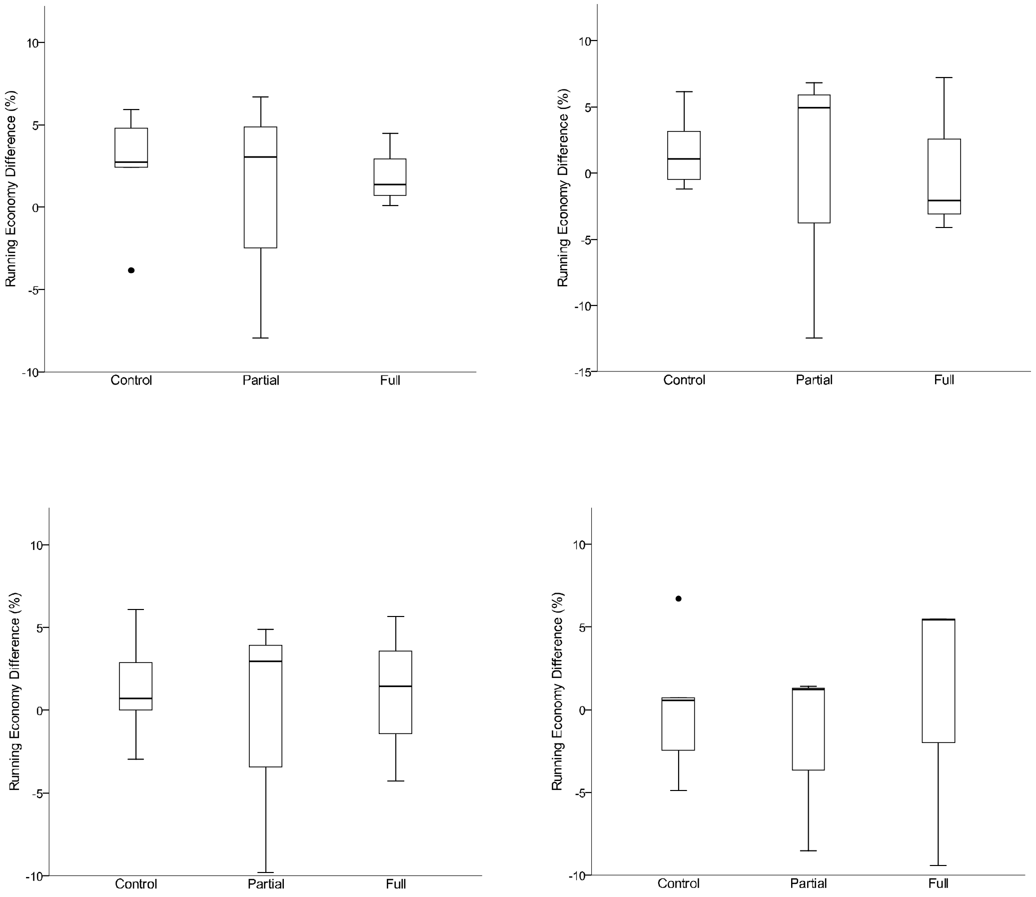

Figure 4-3. Percent differences in running economy measures for the control (n=5), and partial compliance (n=3) and full compliance (n=3) plyometric training groups over an 8-week plyometrics program. Clock-wise from top-left: allometric-scaled rate of oxygen consumption at 8.0 km • h^{-1}, 9.7 km • h^{-1}, 11.3 km • h^{-1}, and consolidated running economy. Descriptive statistics only.

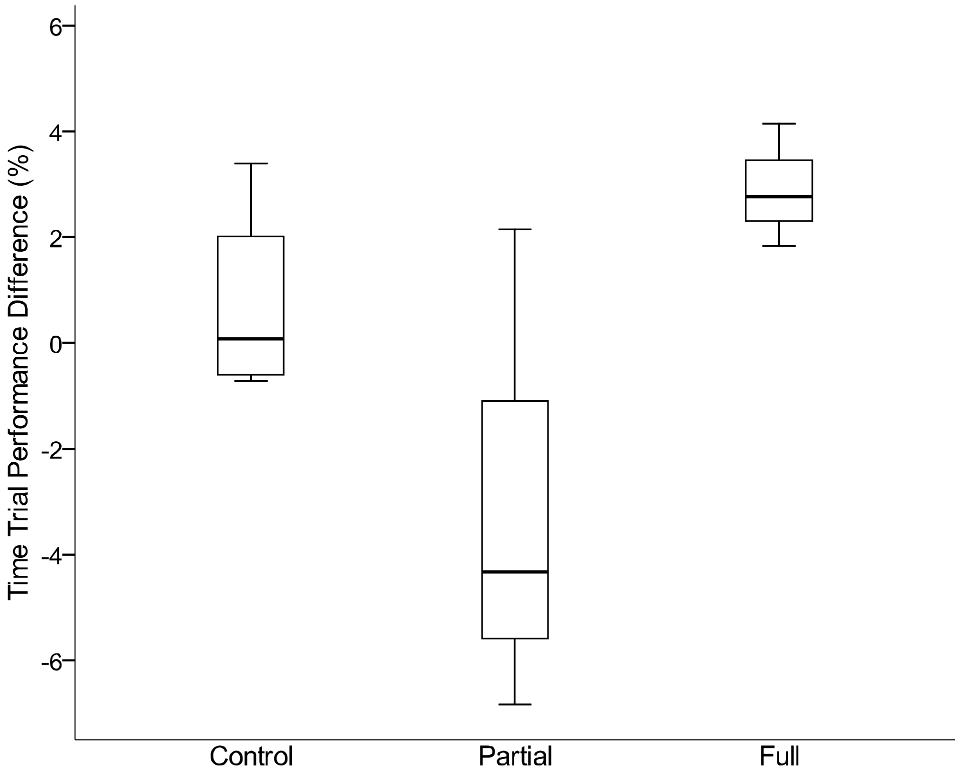

Figure 4-4. Percent differences in running performance measures for the control (n=4), and partial compliance (n=3) and full compliance (n=3) plyometric training groups over an 8-week plyometrics program. Descriptive statistics only.

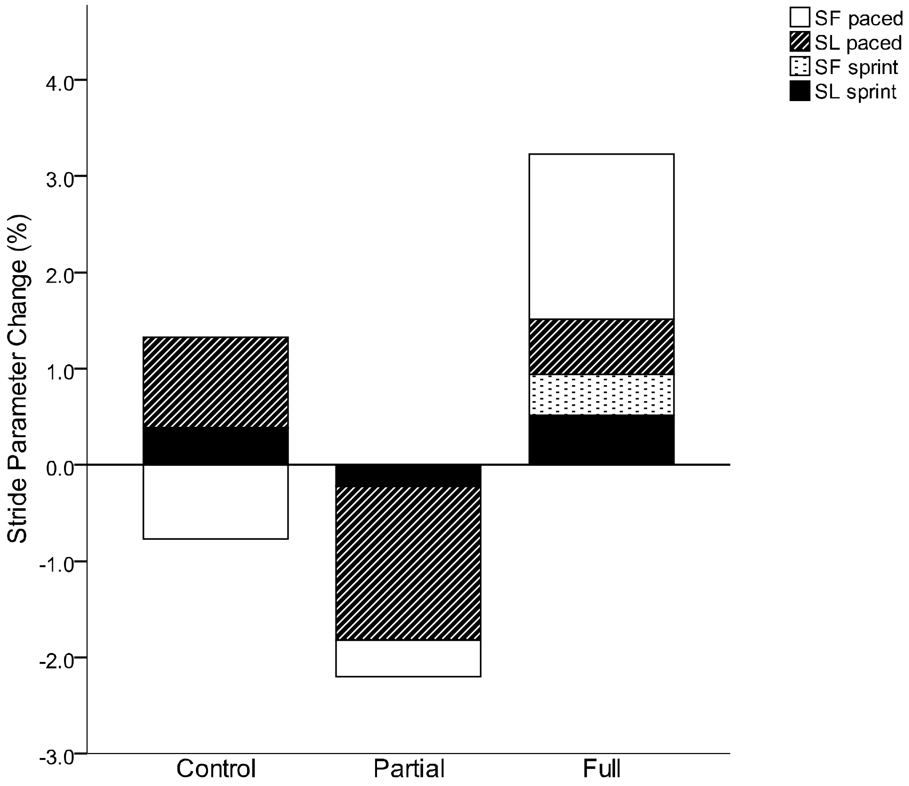

Figure 4-5. Percent differences in measures of stride parameters for the control (n=4), and partial compliance (n=3) and full compliance (n=3) plyometric training groups over an 8-week plyometrics program. SF=stride frequency, SL=stride length, paced=paced running (first 14 laps), sprint=sprint running (last lap). Adding the relative contributions of each parameter approximates the percent change in time trial run performance. Descriptive statistics only.

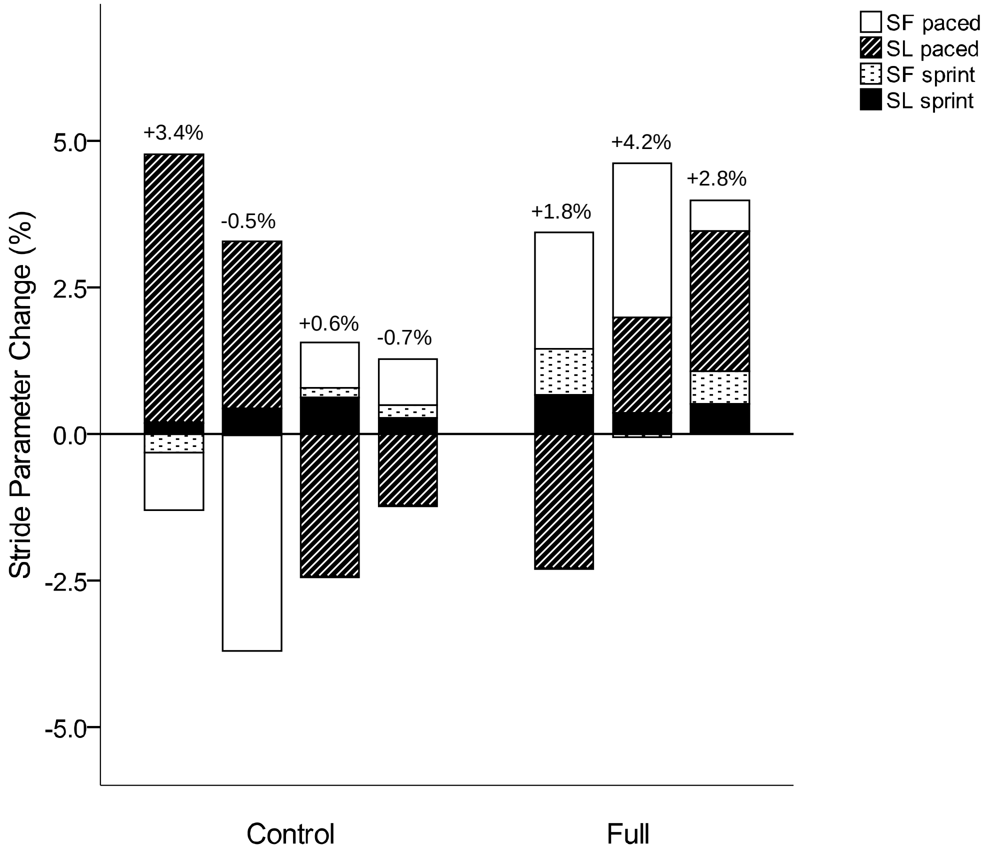

Figure 4-6. Individual analysis of percent differences in measures of stride parameters for the control (n=4) and full compliance plyometric training group (n=3) over an 8-week plyometrics program. SF=stride frequency, SL=stride length, paced=paced running (first 14 laps), sprint=sprint running (last lap). Adding and subtracting the relative contributions of each parameter approximates the percent change in time trial run performance. Descriptive statistics only.

Table 4-12. Summary of self-reports on physical states prior to run tests with flagged potential confounders.

Group	Subject	Fatigued or sore?		Hours of sleep (previous night over normal)		Hours since last food intake (meal or snack)		Hydration	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post
Control	A	Normal (sniffles)	a bit fatigued*	7 / 7.5	7.5 / 7.5	2.5	1.75*	ok	a bit thirsty*
	B	Normal (stiff legs)	a little sick, tired*	7.5 / 7	6.5 / 7	3	1.5*	ok	not ok*
	C	Normal	Normal	7 / 7.5	7.5 / 7.5	1	2.75	a little dehydrated*	ok
	D	Normal (a bit tired)	bit of cold, allergy	8 / 7.5-8	7.5 / 7.5-8	3.5	3	ok	ok
	E	Normal	tired, sore muscles*	6.5 / 6.5	10 / 6.5	3.75	1.75*	ok	ok
	F	a bit fatigued*	Normal	7 / 7	7 / 6	1.5	2.5	ok	ok
Plyometric	G	a bit fatigued	a bit fatigued (headache)	9 / 9	9 / 9	1.5	3.75	ok	ok
	H	a little sore (localized)	a bit fatigued, injured knee*	7.5 / 8	8 / 8	1.75	1*	a little dehydrated*	ok
	I	Normal	sore abs, injured ankle*	8 / 7	10 / 7	3	2	a little dehydrated*	ok
	J	a little sore (localized)	a little sore, a bit tired	7.5 / 8	8.5 / 6	2	no breakfast*	ok	ok
	K	a little sore, tired*	a bit sore (localized)	6 / 5	6.5 / 5	2.5	2.25	ok	ok
	L	tired*, sore (localized)	a bit sore (localized)	6 / 8*	8 / 8	2.75	3.5	a little dehydrated*	ok

*Potential confounders in test-retest.

Table 4-13. Table of predictions and outcomes assuming that potential confounders affected the run tests categorically.

Group	Subject	Categorical Prediction	Outcomes			
			Allometric-scaled Running Economy (ml • kg^{-75} • min^{-1})			3000-m time (s)
			8.0 km • h^{-1}	9.7 km • h^{-1}	11.3 km • h^{-1}	
Control	A	Worse	Better (+5.9 %)	Better (+6.2 %)	Better (+6.7 %)	
	B	Worse	Better (+4.8 %)	Better (+3.2 %)	No change (+0.7 %)	No change (-0.7 %)
	C	Better	Better (+2.7 %)	No change (-1.2 %)	No change (+0.6 %)	Better (+3.4 %)
	D	No change	Better (+2.4 %)	No change (+1.1 %)	Worse (-2.5 %)	No change (-0.5 %)
	E	Worse	Worse (-3.8 %)	No change (-0.5 %)	Worse (-4.9 %)	No change (+0.6 %)
	F	Better	Better (+14.5 %)	Better (+14.7 %)	Better (+9.5 %)	Better (+6.2 %)
Plyometric	G	No change	Worse (-7.9 %)	Worse (-12.5 %)	Worse (-8.5 %)	Better (+2.1 %)
	H	Worse	Better (+3.0 %)	Better (+5.0 %)	No change (+1.2 %)	Worse (-6.8 %)
	I	Worse	Better (+6.7 %)	Better (+6.8 %)	No change (+1.4 %)	Worse (-4.3 %)
	J	Worse	No change (+0.1 %)	Worse (-4.1 %)	Worse (-9.4 %)	Better (+1.8 %)
	K	Better	Better (+4.5 %)	Better (+7.2 %)	Better (+5.5 %)	Better (+4.2 %)
	L	Better	No change (+1.4 %)	No change (-2.1 %)	Better (+5.4 %)	Better (+2.8 %)

Chapter 5

Discussion

The main result of this study indicates that after eight weeks, there is no difference between run training with supplementary plyometrics and run training alone in a group of 12 female University runners with regard to running economy, running performance, and Achilles tendon properties. Unfortunately, this research suffered from issues of attrition and poor compliance so that this finding is inconclusive. In addition, while measurements of running economy and performance were fairly straightforward and reliable, the same cannot be said of the measurement of tendon properties via ultrasound. A larger sample size and better control of sources of variability in tendon measurements are the two primary recommendations for future research.

After controlling for compliance, it was found that subjects who performed plyometric training at least twice a week improved running performance but not running economy. As a group, these subjects improved more than those who performed only run training, although this is not supported by statistical analysis due to the small sample size. In addition, future research might further explore a potential link between performance gains from plyometric training to an increase in stride frequency.

Plyometric training and run training

Plyometric training was consistent in the three athletes categorized with "full compliance" (Subjects D, E and F, Figure 4-1). The training adjustments in plyometrics due to schedule, venue, and individualization were negligible.

Specifically, schedule and venue only dictated the inclusion of stair bounds and alternate-leg bounding or slightly affected the time for in-depth feedback in jumping or landing technique; individualization dictated only that one athlete performed depth jumps 5 centimeters higher. Unfortunately, while controlling for compliance makes plyometric training consistent and meaningful, it unbalances the equivalence of run training groups by having one or two in the control group training for 800-meter races without any counterparts in the experimental group.

Information from returned training diaries indicates the athletes' compliance to the run training schedule (see Table 4-1). This conclusion is applied to all the research participants despite the 50% return rate of training diaries because attendance records confirm that those who did not complete their training diaries were regularly at practice during team training days. It is the extra training outside of the fixed run training calendar that was variable (and in half of the sample, unknown), which may have influenced results. This possibility, however, is not very likely. For one, based on the training diaries, none of the athletes performed extra work in the form of plyometric exercises, not even the experimental group due to the requirement of strict supervision. Most of the extra work was unstructured recovery runs or other cardiovascular work, with one athlete performing some resistance and core muscle training. In addition, two of the participants in the fully compliant plyometric training group did not do any extra work at all apart from regular run training and supervised plyometrics. Therefore, with plyometrics limited to the experimental group, any extra training should primarily benefit the control group's performance, if at all.

Ultrasound measurements

Maximum tendon elongation, maximum tendon force, and tendon stiffness were examined on three levels: comparison with previously reported values in the literature, comparison between consecutive tests on the same subject (inter-test reliability check), and comparison between the two measurement sites involving the fascicle-aponeurosis cross-point and the myotendinous junction (inter-site reliability check). The main source of error seems to be inter-individual variability, specific but not limited to the manner in which the test movement (ramp isometric plantar flexion to maximum) was performed. The final conclusion is that the tendon measurements were too variable to be useful.

Reliability

Given that the range of values reported in the literature varies according to methodological differences, the results of the present study are best compared with recent work by Kubo et al. (36), who used a similar ultrasound methodology to track changes in tendon properties after a plyometric intervention. Kubo et al. (36) reported stiffness values of 129.0 (±35.8) N • mm^{-1} before and 154.0 (±55.2) N • mm^{-1} after a mechanistic plyometric intervention. The present study's range of tendon stiffness for subjects who underwent plyometric training was 71.4 to 100.0 N • mm^{-1} when estimated using a fascicle-aponeurosis cross-point and 58.8 to 111.11 N • mm^{-1} when estimated using the myotendinous junction. These stiffness values underestimate those of Kubo et al. (36) possibly because of tendon elongation that is unattributed to ankle joint rotation; otherwise, the values would be comparable. Also, Kubo et al. (36) accounted for antagonist coactivation of the tibialis anterior. When coactivation is unaccounted for as in the present study, Achilles tendon force tends to be underestimated by 2.6% (44) or 4.3% (6). Meanwhile, the range or spread of the measurements resembles more closely the results of Burgess et al., who used a substantially different measurement set-up (11).

The present study's reliability test results (Table 4-3) showed that stiffness measurements via fascicle-aponeurosis cross-point in the present study suffer from a typical error of 10.1% (7.99 $N \cdot mm^{-1}$), so that an increase of more than 22.60 $N \cdot mm^{-1}$ is required to achieve significant change at an approximate 95% confidence level. This value is within the mean change reported in the weight or resistance training condition of Kubo et al. (127.9 ± 25.8 to 165.9 ± 43.7 $N \cdot mm^{-1}$) which was significant at $p<0.05$ (36). The intraclass correlation coefficient (ICC) of Kubo et al. was 0.89 (32, 36), while Burgess et al. (11) reported a similar ICC of 0.82 for their different set-up. A reliability study by Mahieu (45) using a method similar to that of Kubo et al. and the present study yielded intraclass coefficients of 0.82 and 0.80 for the left and right leg, respectively. The present study's reliability test produced a comparable ICC of 0.90. In addition, the present study's relative error for stiffness was 10.1%, compared to Mahieu's 15.9% and 13.0% for the left and right leg, respectively. Despite the seeming reliability of the present study's stiffness estimates based on these indices, scepticism is directed towards the stiffness measurements because the previous reports measured inter-day (36) and "inter-week" (45) variability, while the present study was limited to taking two measurements in succession. In addition, the present study's reliability test was performed as a check later in the experimental period when testers have likely improved their technique.

Because the reliability check was performed late in the study, measurements taken in the pre-intervention period may have suffered more variability than what is shown by the reliability indices. One possible indication of this is the closer agreement between stiffness measurements at the fascicle-aponeurosis cross-point with those at the myotendinous junction in the period after plyometric intervention compared to the period before (see Table 4-4). Stiffness estimates from the two sites vary by approximately 49.7% before training, but only by about 32.7% after the training intervention. In addition, these high numbers reveal that the two measurement sites do not consistently produce comparable tendon stiffness estimates as a whole. An examination at the individual level confirms this, with the presence of some non-systematic and sometimes dramatic differences in tendon stiffness estimates between the two measurement sites (see Table 4-7).

Interestingly, maximum tendon elongation and maximum tendon force were consistent between the two measurement sites, varying respectively by an average of 6.0% and 6.2% before and 7.3% and 7.3% after the plyometric training period (Table 4-4). The consistency of tendon elongation between measurement sites suggests that the two sites are comparable for this measure. This is counter to previous reports that tendon elongation measured at the myotendinous junction is less than what is measured at the aponeurosis (6, 35, 49). The discrepancy could be due to measurement error or the fact that the present study utilized a fascicle-aponeurosis intersection as close as possible to the myotendinous junction. In any case, in a static measurement set-up where a fascicle-aponeurosis cross-point can be tracked manually by an experienced technician, the use of the myotendinous junction is not recommended as a measurement site. It appears to be more subject to deformation during muscle contraction and more difficult to discernibly track along a single, narrow path, as also observed by Muramatsu et al. (49). In the current discussion, reliability between measurement sites is used merely to gain insight into the reliability of the ultrasound measurement in general. The other measured variable, maximum tendon force, is independent of any ultrasound measurement, so that consistent values for this variable merely reflect the consistency of isokinetic dynamometer outputs and electrogoniometer readings in the first three trials against the last two.

Unfortunately, the actual reliability of maximum tendon elongation measures via ultrasound—regardless of the site used—indicates a highly variable measurement, despite potential practice effects on the testers’ technique (see Table 4-3). Reported coefficients of variation range from 0.4%-11.3% (23, 28, 31, 44, 49, 50, 68) in varied measurement conditions. In the present study, the standardized technical error of measurement of 8.0% is within previous values; however, this implies that an increase of more than 4.4 mm is required to achieve significant change to approximate a 95% confidence level. Or conversely, a change of less than 4.4 mm in maximum tendon elongation is interpreted as no change. In contrast, the study by Kubo et al. (36) found a significant increase in tendon elongation after a plyometric-type intervention with a mean increase of 1.3

mm with ten subjects. In addition, the present study's maximum elongation mean values (range of 9.84 to 33.04 mm via the fascicle-aponeurosis site, Table 4-7) likely overestimate those reported in the literature (range of 5.2 to 24.7 mm) (6, 11-13, 23, 27, 29-31, 33, 36, 40, 42, 44-45, 49-50, 56) because tendon elongation due to joint rotation was not completely accounted for; also, the variability of the present study's maximum elongation measurements (standard deviations from 4.0 to 8.2 mm, Table 4-7) are higher than those previously reported (standard deviations from 0.6 to 5.8 mm, via different sites and techniques) (6, 27, 29, 31, 33, 36, 40, 42, 44, 45, 50, 56). The range of variability in the literature already reflects methodological differences in addition to reported inter-subject variability (27, 35, 49). Lastly, the presence of isolated but unsystematic and dramatic changes in maximum tendon elongation at the individual level in the present study (e.g. 9.84 mm to 21.46 mm after 8 weeks of run training alone, Table 4-7) completes the reasons to doubt the actual consistency of maximum tendon elongation measurements.

Estimates of maximum tendon force in the present study appear reliable. The range of maximum tendon force values of 909.7 to 2608.1 N when estimated using a fascicle-aponeurosis cross-point and 936.2 to 2489.2 N when estimated using the myotendinous junction are consistent with the broad range of previous findings (875 to 3255 N) (13, 23, 29, 42, 44, 50, 56). The trend of reliable maximum tendon force scores, followed by slightly less reliable tendon elongation measures, and even less reliable stiffness estimates (see Table 4-3) is reflected in the reliability study of Mahieu (45), who performed three separate measurements on 21 male and female volunteers, each a week apart at the same hour of day. This trend indicates that variability in measurements using ultrasound is more crucial to control than that of force output. As confirmed in the present study, the extent of the contribution of ultrasound measurements is directly proportional to the variability of the measure. That is, tendon force was calculated outside of ultrasound measures, tendon elongation was measured via ultrasound, and stiffness variables compound the errors in tendon force and elongation measures.

Given the questionable consistency of ultrasound measurements of tendon elongation in the present study, and the fact that tendon stiffness is based on these measurements, all tendon variables are considered invalid in light of the small sample size (n=5). To clarify, the reliability and technical error of measurement of tendon stiffness appear acceptable, except that the context of the reliability test casts doubt on these indices. Given that the reliability testing was likely affected by learning effects, and that it still showed inadequate tendon elongation accuracy from which stiffness is calculated, then the conclusion is to consider ultrasound variables invalid, including tendon stiffness despite seemingly acceptable reliability indices.

Inter-individual variability

The source of variability in tendon elongation seems to lie in inter-individual variability, as also previously reported (27, 35, 49) but specified here, though not limited to, variations in the performance of the experimental movement. This supposition comes from the lower technical error of measurement in the passive condition (0.84 mm) than in the active condition (1.95 mm) (see Table 4-3). Also, experience with tracking tendon movement with ultrasound suggests that the actual measurement of tendon displacement is largely valid. One could easily confirm visually that the video frame of reference did not move while the anatomical landmark was tracked consistently; this was also confirmed by an experienced radiologist. This confidence in the ultrasound visualization and measurement is limited by two considerations previously raised (43): first, the potential for tester error and bias in measuring distances, and second, the assumption that tendon landmark movement is limited to the sagittal plane. In the present study, extraordinary care was taken during displacement measurement, and while bias was conceivable, it was improbable due to the obscure and isolated nature of the task. In addition, most of the measurements were confirmed by an unbiased radiologist. The second concern is more relevant. The commitment to accurately track the tendon-aponeurosis landmark meant movement was sometimes followed manually in three dimensions, while displacement was only measured in two. (Using the myotendinous junction was even more variable, as the measurement site was bigger and subject to more variation in movement, shape and size.) While care was taken to select landmarks that were easy to track along a flat plane, there was definitely variability in the kind of landmarks chosen between and even within subjects.

The tracking of a tendon landmark seems legitimate and measurement of its displacement adequately reliable. However, it is unclear how much of the tendon movement was due to muscle shortening or tendon stretch, and how much was due to ankle joint rotation; and the relative contribution of each is likely variable between subjects or even trials. The use of a correction method from the literature (44, 49, 56) resulted in excess variability, while an alternative approach (40) still overestimated tendon elongation, hinting at still unaccounted for tendon displacement from joint rotation. Conceptually, inflated tendon elongation measurements will lead to underestimated stiffness values. In practice, joint rotation will also be related to the manner of the movement, which can vary between trials, and likely more so, between subjects. In the present study, maximum rotation of the ankle varied within subjects over five trials by an average of 11.6 (±5.6) % before the training intervention, and 13.5 (±6.2) % after the training intervention. (The difference in variability over time is likely tester-related error, probably in the less consistent electrogoniometer attachment during early testing.) Between subjects, the variability of mean scores was 27.7% before and 13.4% after the training intervention. The mean maximum rotation of the ankle in the present study was 7.63 ± 2.21 degrees before and 9.02 ± 1.70 degrees after the training intervention (Table 4-5).

These values seem comparable to those in the literature which report a range of 3.2 ± 0.9-1.8 degrees (41, 44, 49, 56) using a method similar to the present study, while a more accurate method using video cameras reported maximum ankle joint rotations up to 17.8 ± 2.8 degrees (6). The ranges in the present study, 4.6 to 11.4 degrees before and 7.7 to 11.4 degrees after the intervention, also reveal some (isolated) individual differences, given a technical error of measurement of 3.2 degrees (Table 4-6) such that differences greater than

4.5 degrees can be said to be real inter-individual differences at a confidence level of approximately 95%.

The reliability of joint rotation data is an inherent limitation of the method (the electrogoniometer assumes movement along two dimensions) and undoubtedly contributed to the unwanted variability in the initial correction method used. After the failed correction was undone, however, tendon elongation measurements remained more variable in the active condition than the passive condition. This implies that the active movement contributed to the variability in measures, and despite the lack of precision in the measurement, maximum ankle joint rotation can be implicated as one aspect of the exercise movement that varied between individuals tested.

In addition to ankle rotation, knee rotation can influence tendon movement since the gastrocnemius muscle is biarticular; but knee movement was not monitored in the present study and cannot be ruled out. All in all, the level of inadequacy in accounting for tendon elongation due to joint rotation at the ankle or knee may have been different for each subject, contributing to the high inter-individual variability.

Tendon force was also found to be underestimated by as much as 2.6-4.3% when antagonist muscle coactivation was not accounted for (6, 44) as in the active measurement trials of the present study. Again, the manner of the movement—this time in the extent of muscle coactivation—possibly varied between trials, and likely more so, between subjects. Because this coactivation was not accounted for in the present study, the contribution to high inter-individual variability is unknown. Tendon force calculations are also affected by the tendon moment arm. In some studies, the moment arm is assumed to be constant for all subjects at the neutral ankle position (21, 33, 45). The present study is marginally better at accounting for inter-individual variability by estimating the moment arm based on ankle joint rotation and each subject's lower limb length, using formulas determined in previous studies (22, 62). While ankle joint rotation was measured during actual contraction, tendon length at each angle was estimated using a regression formula from cadaver analysis. It has been established that the Achilles tendon moment arm changes from rest to maximum voluntary contraction due to effective muscle belly thickening from contraction, even when ankle angle is controlled (41). Because ankle angle is near impossible to control, the moment arm can also shift along the line of pull, and also with a shift in the point of force application due to forefoot-rearfoot movement and soft tissue deformation (5, 6) or when the leg slides forward along its long axis and shifts the axis of rotation (40). None of these were accounted for in the present study, so inter-individual variability cannot be traced to the variability of the moment arm, which is subject to the different degrees of "thickening" of contracting muscle bellies, the variability in ankle joint rotation and general manner of performing the test movement.

The insufficient stability of the foot in the dynamometer footplate certainly led to the unwanted movement, which may have been excessive beyond correction and variable between subjects of different foot shapes and sizes. In addition, the mechanical compliance of the dynamometer itself must have contributed to the error in tendon force estimation, as previously reported by Arampatzis et al. who used a Biodex dynamometer (5, 6). Based on subjective experience, this dynamometer provides more rigidity than the older Cybex isokinetic dynamometer used in the present study.

Finally, another methodological problem in tendon measurements via ultrasound is the property of tendon structures to increase the tendency to elongate over time as a result of muscular contractions (tendon creep) (6, 42). This measurement limitation may have been aggravated in the present study by not having initial maximal trials for preconditioning. In addition, total number of trials per subject as well as the sequence of measurement trials with complete data varied between subjects and over time.

Running economy

Measurements of running economy were reliable (Table 4-2) and quite similar to those in a previous study involving a group of older women with similar body mass, training frequency and training volume (26). However, previous studies have shown an increase in running economy in as little as 6 to 9 weeks of plyometric training (54, 58, 63, 65). In the present study, there was no apparent change in any of the running economy values, including the slopes of the VO_2-speed relationship (see Appendix H and Appendix J). The only instance of an obvious improvement in running economy values (10 to 15%) was that of the athlete who had joined the study in a detrained state, and whose scores were excluded as outliers (Appendix F, Subject F). This could indicate that running economy may not be as easily altered in trained subjects as published studies may suggest. The only report of unaltered running economy after plyometrics is that of an unpublished thesis (38). It is left to speculation how many other plyometric training studies did not yield changes in running economy and were never reported. Even among published plyometric training research, running economy improvements were not reported at all speeds in three of four studies (54, 63, 65).

The present study's highest submaximal test speed may have been too slow for any effects to be seen in trained University runners. Significant changes in running economy at this speed was found only in a group of regular but not highly trained male and female runners (65). Therefore, better running economy closer to race speed may have been found, and in which case, the VO_2-speed slope would be altered to reflect a non-metabolic adaptation (58).

Another possible reason for the present study's unchanged running economy over time is the small sample size. (The number of subjects in the four published studies range from 7-10 runners in the experimental group and 8-9 runners as controls.) This problem was aggravated by issues of compliance in the plyometric training group.

Running performance

The fully compliant runners in the plyometric training group improved 3000-meter time trial run performance by 1.8, 4.2 and 2.8% (Figure 4-6). These numbers are similar to the 3.1% mean improvement in 5000-meter time (54) as well as the 2.7% mean improvement in 3000-meter time (63) in trained male runners after run training with plyometrics over 9 weeks and 6 weeks, respectively. The sample size in this analysis (n=3) does not guarantee that the confidence interval or even the relatively low variance of the mean improvement is due to a genuine effect or mere chance (see Table 4-9). In addition, non-parametric statistical tests only hint at a difference in performance improvement between the fully compliant plyometrics group and control subjects (p=0.101). For these reasons, a generalization cannot be formed, except perhaps in light of other research or possibly along with a coach's own professional experience.

In the literature, improvements in run performance due to plyometric training have been linked to improvements in running economy (54, 63). This finding was not replicated in the present study. Collected data (Appendix F) demonstrate that the three subjects categorized with "full compliance" did not experience any change in running economy beyond that of normal variability as previously reported (48) or as established in reliability testing (Table 4-2). And yet, descriptive statistics in Figure 4-4 also show that these individuals improved 3000-meter run performance beyond the approximate normal variability of 1.3% found in fast women runners over a similar time frame (25). This may be an indication that running economy measures do not always reflect performance improvements in the short term. Or again, there may have been running economy improvements at the higher speeds which were not covered by testing.

Two general mechanisms are proposed with regard to improvements in running performance (and economy) without concomitant improvements in metabolic performance indicators: those relating to changes in tendon structure properties and those relating to neuromuscular adaptation.

Spurrs et al. (63) proposed that plyometric training increased tendon stiffness and elastic recoil, so that greater forward propulsion was achieved at a lower energy cost, possibly increasing stride frequency or stride length. However, Spurrs et al. did not measure stride parameters. In the present study, tendon measurements were too variable to be meaningful, but performance gains from plyometrics seem to be associated, albeit non-statistically, with increases in stride frequency (see Figure 4-5). This generalization from a small sample size is not strongly confirmed by a scrutiny of individual responses (see Figure 4-6). For the three subjects who were categorized with “full compliance”, stride frequency increased to make up for a decreased stride length, or in addition to an increased stride length. In contrast, the runner who improved performance time in the control group (+3.4%) did so exclusively through increases in stride length, with some decrease in stride frequency. Control subjects who did not exhibit much change over time (-0.5%, +0.6%, and -0.7%) increased stride length but suffered a decrease in stride frequency, or were unable to sufficiently increase stride frequency to offset decreases in stride length.

Paavolainen et al. (54) were one of the first to propose that neural adaptations were responsible for distance running performance, outside of metabolic adaptations. They proposed that the adaptations to explosive strength training that they found were due to enhanced excitatory input to working muscles or reduced inhibitory input, or both. These investigators cited shorter contact times in controlled-velocity running (among other markers) as a possible indication for this neural adaptation. If athletes had been tested at the speed of their improved time trial run, Paavolainen et al. may have also seen increases in stride frequency together with the decrease in contact times, assuming flight times were shorter or the same at a maintained or increased stride length. In other words, the runners may have found the fixed velocity slower, so that they had to increase flight time. In the present study, the individual responses mildly suggest that the addition of plyometrics increased stride frequency to supplement increased or offset decreased stride length. However, contact times and flight times were not measured in the present study. To speculate, if stride length increased (only true for two of three plyometrics subjects), flight time is more likely to increase or stay the same than decrease. Given that stride frequency also increased for these two subjects, it is reasonable to propose that contact time must have been reduced. However, even if the present study were to have an adequate sample size, decreased contact times are still indirect measures of motor nerve activity or neural adaptation.

In the fully compliant plyometrics group, the two subjects who increased stride frequency more than stride length were the two who did not engage in any additional training outside of regular team practice, helping isolate the effects of the plyometrics sessions. However, they were also the two runners who received the most run technique training. This raises the general question of how much performance improvement is attributable to the plyometric training or to the running technique feedback. Put in other terms, in the absence of tendon measurements, the present study cannot make any conclusion if the performance gains were due to changes in the elastic properties of tendon structures or neural adaptations.

In addition, providing feedback to improve running technique likely leads to different degrees of improvement, depending on how efficient the current technique is. It is possible that the athletes in the present study who improved performance by consistently performing plyometrics did not possess effective techniques to begin with. Optimal running is modeled as several cycles of well-coordinated motor neuron activity that optimizes the use of elastic recoil, a hallmark of which is a relatively short ground contact time (9). Therefore, the increases in stride frequency of the three fully compliant runners in the present study may be an indication of improved overall technique, but only because their stride frequencies had room to improve. On the other hand, stride frequency is thought to be almost constant among experienced distance runners regardless of running speed (17). If the performance gains were largely due to improvements in technique, then the training program suggested here may not be as effective for runners who already have efficient technique.

Unlike other studies that measured metabolic markers such as VO_2max and lactate threshold (54, 58, 63), the present study cannot completely rule out the contribution of metabolic adaptations. Arguably, the control group must have experienced the same cardiovascular adaptations, perhaps more so because more athletes in this group went on extra run training outside of team practice hours. Also, running economy did not change for either group, and this metabolic measure is generally accepted to be linked more closely to running performance than VO_2max, if not lactate threshold, in a homogenous group of runners (52, 57).

The present study also cannot rule out any psychological effects that being in the plyometric training group may have provided. While all athletes were encouraged to produce their best 3000-meter run, and their inherent competitive nature seemed to urge them to perform at their best, there could have been extra motivation or confidence on the part of those who received supplementary plyometric training.

Conclusion

The results of the present study are inconclusive with regard to the effect of supplementary plyometric training on running economy, performance and Achilles tendon properties. This was primarily due to issues of subject drop-out and poor compliance as well as the excessive variability in tendon measurements via ultrasound. Increasing the sample size and controlling the sources of variability in tendon measurements should increase the likelihood of detecting improvements in running economy, performance and tendon properties as a result of plyometrics—or provide more certainty when no changes are seen.

Limitations

The main limitation of this study is the small sample size as a result of subject attrition and inadequate compliance. Related to the latter is the problem of controlling the variables of general run training and plyometric training; specifically, keeping these the same between control and experimental groups. Variations in run training due to the team's training groups were accounted for as much as possible after subjects dropped out or failed to adequately comply with the research requirements. However, even if training is successfully kept uniform for all participants, there will still be individual differences in the response to the same training.

Also a potential confounder is the physical or training state of the research participants prior to testing. Activities before testing could not be controlled, although the present study made an attempt to account for these. The descriptive statistics derived from Table 4-12 do not suggest any systematic effect of reported potential confounders on test results.

Another limitation is that treadmill speeds were not higher for the running economy tests. It is accepted that the contribution of elastic recoil increases with running speed (14) so that improvements in running economy may have been found. However, running economy is also generally accepted as linear (15, 16), so that values at slower speeds may already reflect running economy up to higher speeds. Finally, the present research does not make any distinction between plyometric training and running technique feedback to maximize that training.

Recommendations

A proposed sample size of 24 participants was derived from the literature a priori. Two previous studies on the effect of plyometrics on tendon properties used sample sizes of 13 and 10 participants performing a different exercise on each lower limb (11, 36). This is supported by two recent studies that used a sample size of 17 and 19 divided into two groups (20, 68). However, the study with the sample size of 17 eventually analyzed tendon stiffness results from only 13 subjects (6 experimental and 7 controls) due to one outlier and technical reasons pertaining to the usability of some ultrasound videos; this study did not find any significant differences in tendon stiffness measures between groups (20). The four studies that showed plyometrics improved running economy (54, 58, 63,

65) used 7 to 10 subjects in the experimental group and 5 to 9 subjects in the control group. Subject attrition rates in either group were two for every ten or twelve, or one-for-eleven in two studies (54, 65). The other two studies reported no drop-outs (58, 63). It is recommended that future research form two groups with a minimum of 12 subjects each. This should allow for sufficient statistical power across the primary dependent variables as well as protect against possible subject drop-out or non-compliance.

In addition, runners of similar abilities should be studied. If the sample is not homogenous but large enough, categorizing participants according to run performance or economy will control variability as well as gain insight into training effects by running ability. Another possibility is to design a study that separates training with plyometric drills and running technique feedback as independent variables, possibly categorizing subjects according to running technique. However, a larger sample size also means that plyometric training sessions may take longer than the minimal time reported, depending on equipment, venue, and other considerations.

With regard to limiting variability in tendon measurements via ultrasound, the use of a more advanced isokinetic dynamometer should lead to less extraneous movement at the ankle, although Arampatzis et al. also report compliance of the dynamometer itself (5, 6). Perhaps a more serious concern is properly accounting for ankle joint rotation and more accurately isolating tendon force. For this, in addition to high frequency ultrasound, equipment from a biomechanics and/or neurophysiology laboratory is required, particularly video cameras for a more accurate modelling of mechanical forces and moment arms. In addition to video capture and analysis, a plantar pressure insole for point of force application will help locate moment arms, and electromyographic data can account for coactivation of antagonist muscles, as in the set-up used by Arampatzis et al. (5, 6). While seemingly simple, the experimental movement (quasi-isometric plantar flexion to maximum) should be considered a complex biomechanical and neuromuscular event if the goal is a valid measurement of tendon properties. Currently, there are still research designs like the present study that rely on reliable but not necessarily valid measurements to simply track changes over time (20). In the future, true reference values may be established, and three-dimensional models of real-time, task-specific data will likely be employed.

As for running economy measures, higher treadmill speeds may lead to a higher probability of a significant finding, or fewer doubts when there is none. Contact times may also be measured during the run performance trial given the right equipment, rather than rely on mere speculation based on stride frequency and stride length. The same applies to directly measuring motor neuron activity.

Application

This plyometrics program with minimal running technique feedback may help improve performance beyond that of run training alone. In particular, it might be useful for developing more efficient running technique, whether by direct instruction or by physiological adaptations. Although hardly conclusive, it is possible that under this program, runners are more likely to couple improvements in stride length with those of stride frequency. This means potentially developing shorter contact times and an overall technique that optimizes the use of muscle-tendon elastic recoil, for a minimal investment in training time and materials.

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Appendix A

Initial Survey Form

Name: ______________________________ Age: _____

Birthdate: ____________ Years of Running: _____

Have you experienced any form of spinal injury? (Please check one.)

- ☐ Yes.
- ☐ No.

Have you performed structured plyometrics work before? (Please check one.)

- ☐ Not at all.
- ☐ Not in the last year.
- ☐ Not in the last 6 months.
- ☐ Not in the last 3 months.
- ☐ Yes, within the last 3 months.

Have you had any injury to the lower limbs? (Please check one.)

- ☐ Not at all.
- ☐ Not in the last year.
- ☐ Not in the last 6 months.
- ☐ Not in the last 3 months.
- ☐ Yes, within the last 3 months.

Appendix B

Qualitative Questions before Run Tests

SUBJECT

TEST
DATE

RUNNING ECONOMY AND 3000m TIME TRIAL

NOTES:

How are you feeling today?
Feeling fatigued? Sore?

Did you get enough sleep last night?
and/or How many hours of sleep did you get last night?
How many hours do you usually get?

What time was your last meal?
and/or Did you have anything to eat before this test?
or How long since you had something to eat?

Do you feel properly hydrated?
or Do you think you've been drinking enough water?

Do you feel that your menstrual cycle affects
your running performance in any way?

[If answer is YES]
How?
Do you think it affected your peformance in the previous treadmill test and time trial?
Do you think it affects/will affect your performance in this treadmill test and time trial?

*Mark date of test on training diary; note last hard training session.

Appendix C

Measurement Protocol for Stride Parameters

A digital video recorder operating at 60 Hz (GR-DVL9800, JVC, Germany) was set up with a clear view of the last 40-meter straight segment of the track. The start and end of this segment (40-meter mark and start/finish line, respectively) were marked by lines using athletic tape. Additional lines were placed one meter and half-a-meter before and after these two lines (Plate A-1):

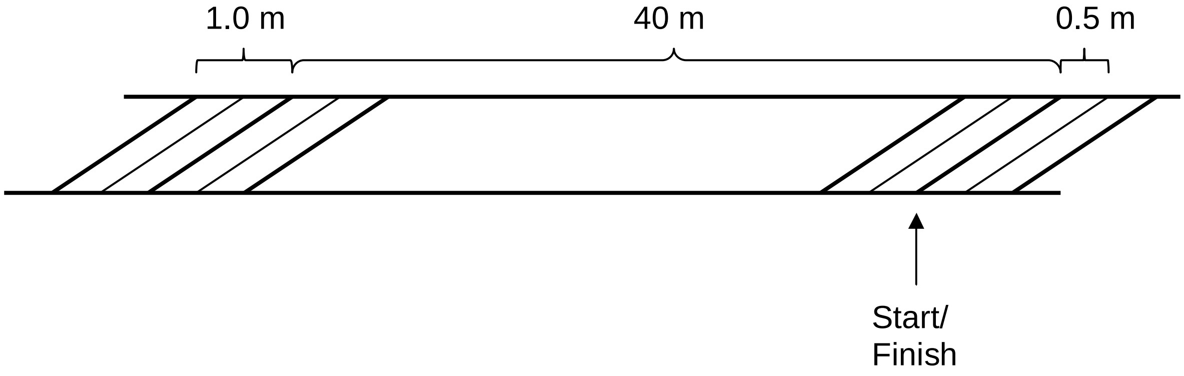

Plate C-1. Diagram of line markers on Lane 1 of an indoor track oval for stride frequency and stride length measurements.

Video analysis was subsequently performed using commercially available software (Studio DV Version 1.2.6.0, Pinnacle Systems, Inc., USA) at 30 frames per second. Stride length was estimated from the number of steps counted within the measured segment (effective distance of 38-42 meters). The same part of the shoe (heel, mid, or toe) was used as reference per measured segment whenever possible. In like manner, the two reference lines chosen showed as similar a relative position to the foot as possible (see Plate 3-2). Therefore, a conservative estimate of the accuracy of this distance measurement is 0.5 meters. Because runners altered their running gait almost immediately after completing the time trial distance, neither of the two lines after the finish line was used for the last lap. Stride length was calculated as follows:

$$SL = DT/FC$$

where SL is stride length in meters, DT is distance travelled in meters, and FC is the number of foot contacts over the established distance. Because the lowest number of steps measured over the distance was 23 (during one runner's sprint to the finish), a conservative estimate of the accuracy of this stride length estimation is within 2.17 centimeters (0.5 meters divided by 23 steps). Stride frequency was estimated using the video recorder's timer and the following formula:

$$SF = (FC/T) \cdot 60 \text{ seconds}$$

where SF is stride frequency in steps per minute, FC is the number of foot contacts over the established distance, and T is time in seconds. Care was taken so that the duration of the measured video segment began and ended with the runner in the same body position—as close as possible to having both knees on the frontal plane during the stance phase.

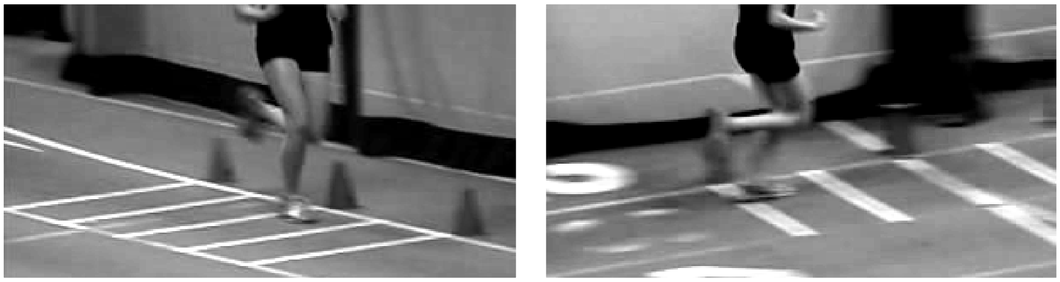

Plate C-2. Video-captured photographs of start and end of stride parameter measurement segment representing one lap, as delineated by foot and body position.

Since measurements were only made over approximately the last 40 meters of each lap, the average estimates of the first 14 laps were considered as the average stride length and stride frequency of the time trial (pacing), and the values of the final lap’s last 40 meters were considered as the stride length and stride frequency of the finishing kick (sprinting).

Appendix D

Measurement Protocol for Leg Lengths

Leg lengths were measured to coincide with Grieve et al. (22) as the distance from the estimated axis of rotation of the left knee to the estimated axis of rotation of the left ankle as viewed on the lateral side of the left leg. Knee axis of rotation was estimated from the medial and lateral epicondyles and actual knee movement while ankle axis of rotation was estimated from the medial and lateral malleoli and actual ankle movement. Leg length measurements were performed three times if the first two measurements were not within 0.2 cm of each other. The two closest measurements were taken and averaged.

Appendix E

Calculation of Technical Error of Measurement

Absolute technical error of measurement (TEM) is the square root of the sum of the squared differences of each test and retest value over twice the number of paired measures:

$$TEM = \sqrt{\frac{\sum d^2}{2n}}$$

where d is the difference between one subject's test and retest measures and n is the number of subjects.

Relative technical error of measurement (%TEM) is absolute TEM normalized against the average of the mean of the first measurement set and the mean of the second measurement set and expressed as a percentage:

$$\%TEM = \left[\frac{TEM}{(M_{1+}M_2)/2}\right] \times 100$$

where M_1 is the mean of the first set of measurements and M_2 is the mean of the second set of measurements.

Appendix F

Collected Data for Running Economy and Performance

Table F-1. Running economy and performance variables before and after an 8-week plyometrics program (running economy variables: n=12; 3000-m performance: n=11).

Group	Subject	Body Mass (kg)		Submaximal VO_2 ($L \cdot min^{-1}$)						3000-m time (s)	
				8.0 $km \cdot h^{-1}$		9.7 $km \cdot h^{-1}$		11.3 $km \cdot h^{-1}$			
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Control	A	57.4	59.8	1.46	1.43	1.73	1.69	2.08	2.02		
	B	57.5	55.9	1.48	1.37	1.71	1.61	2.01	1.94	679.981	684.920
	C	64.3	62.3	1.74	1.64	2.04	2.00	2.45	2.36	776.810	750.400
	D	60.5	59.3	1.60	1.53	1.98	1.92	2.30	2.31	736.682	740.201
	E	44.8	46.6	1.14	1.23	1.36	1.42	1.56	1.70	683.891	679.548
	F	61.4	63.1	1.81	1.59	2.18	1.91	2.43	2.26	780.596	732.531
Plyometric	G	59.7	53.8	1.42	1.38	1.57	1.59	1.75	1.71	661.425	647.242
	H	55.5	55.3	1.48	1.43	1.70	1.61	1.91	1.88	720.143	769.384
	I	54.3	58.6	1.49	1.50	1.79	1.80	2.03	2.16	687.176	716.919
	J	67.0	68.1	1.94	1.97	2.23	2.36	2.50	2.78	783.092	768.711
	K	54.2	51.9	1.64	1.50	1.88	1.67	2.21	2.00	758.540	727.095
	L	61.6	62.0	1.56	1.55	1.78	1.83	2.11	2.01	718.012	698.147

Appendix G

Changes in Primary Variables of Two Groups over Time

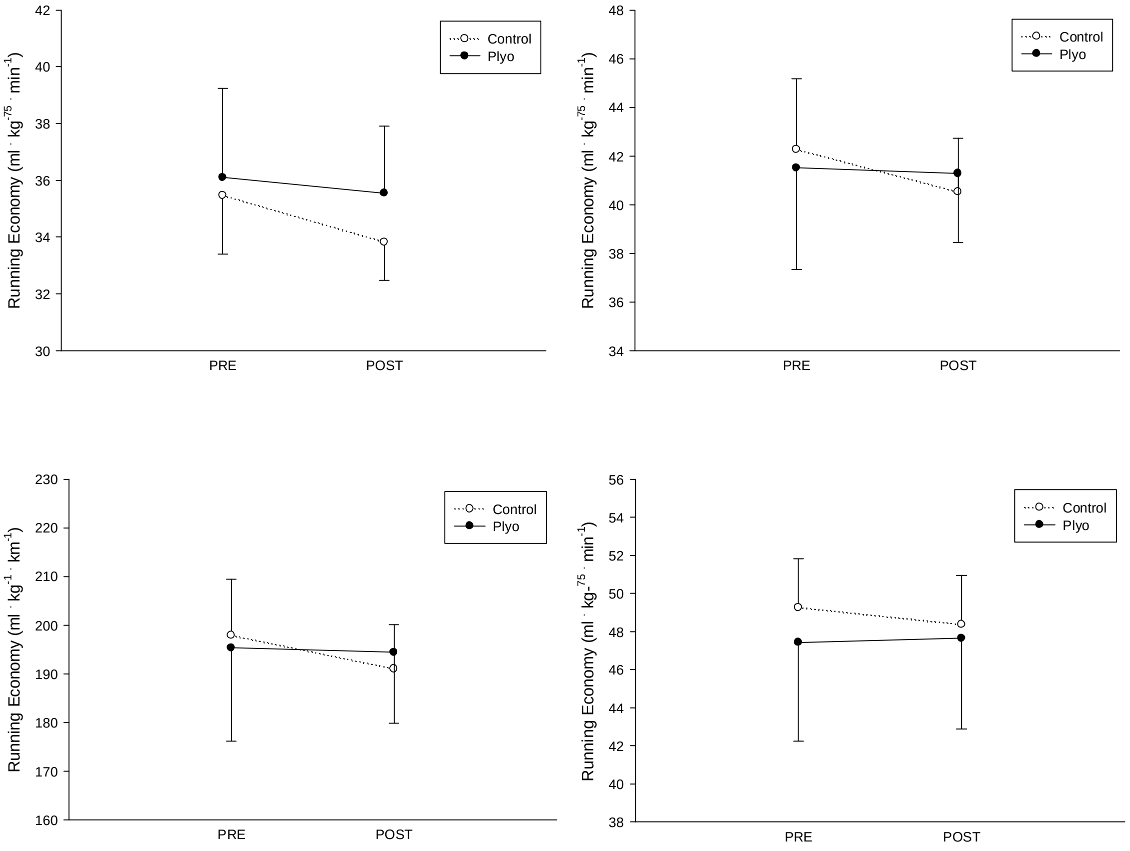

Figure G-1. Running economy measures for the control (n=6) and plyometric training group (n=6) before and after an 8-week plyometrics program. Clockwise from top-left: allometric-scaled rate of oxygen consumption at 8.0 km • h^{-1}, 9.7 km • h^{-1}, 11.3 km • h^{-1}, and consolidated running economy. No significant differences.

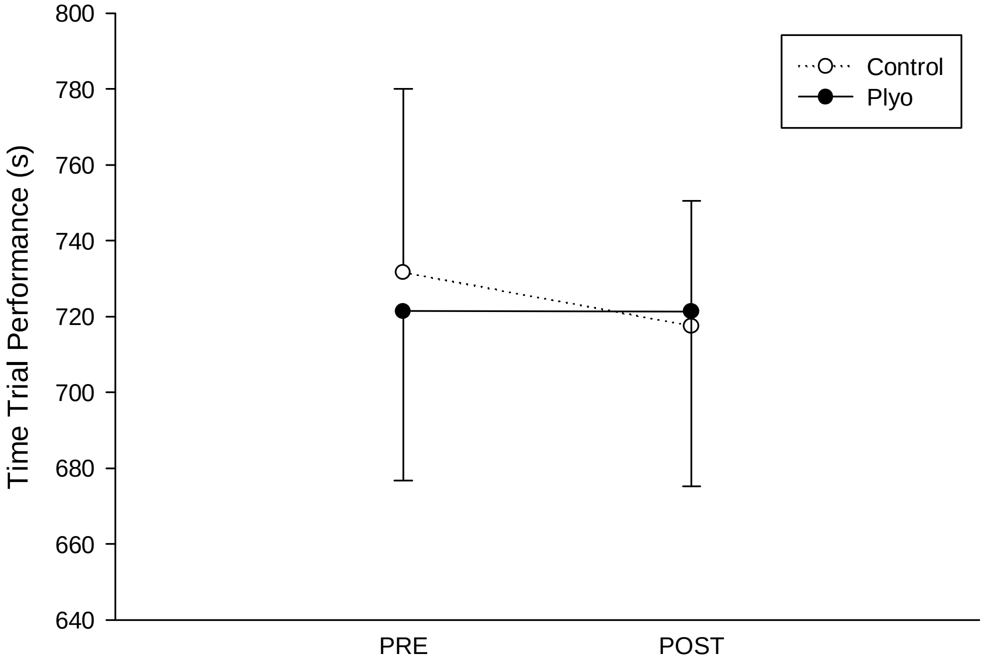

Figure G-2. Running performance measures for the control (n=5) and plyometric training group (n=6) before and after an 8-week plyometrics program. No significant differences.

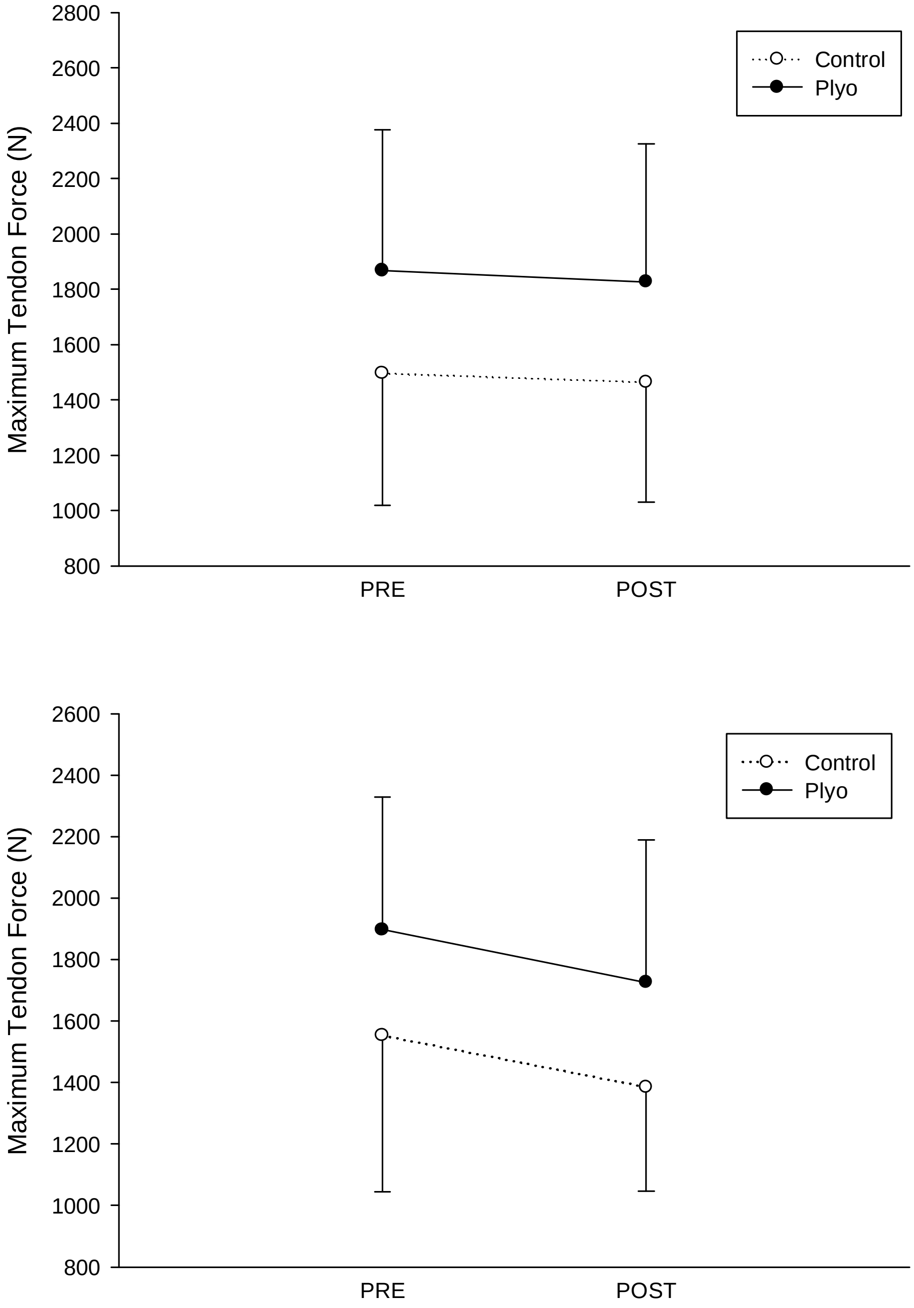

Figure G-3. Maximum tendon force measures for the control (n=5) and plyometric training group (n=5) before and after an 8-week plyometrics program. Top: measurements using fascicle-aponeurosis cross-point. Bottom: measurements using myotendinous junction. No significant differences.

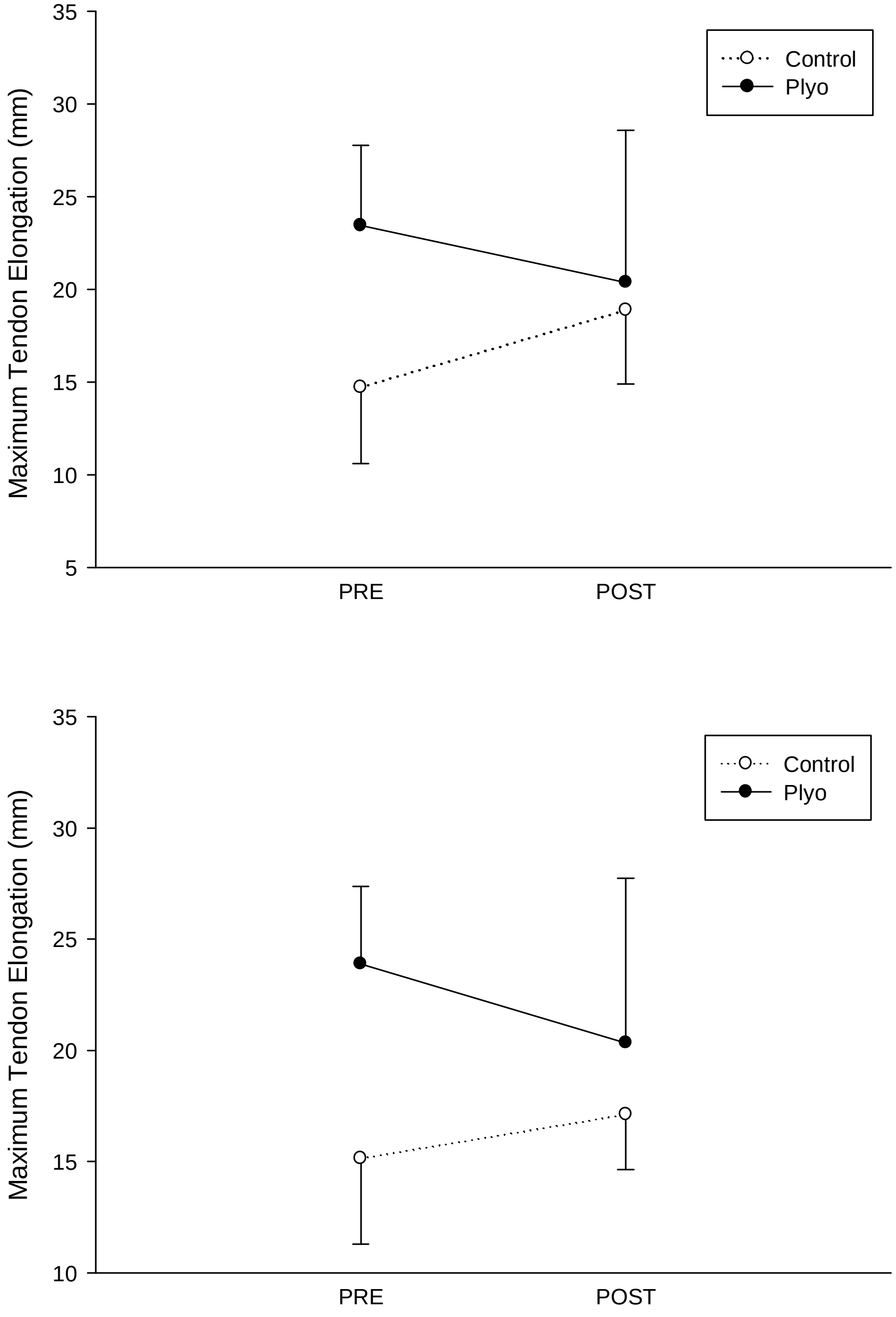

Figure G-4. Maximum tendon elongation measures for the control (n=5) and plyometric training group (n=5) before and after an 8-week plyometrics program. Top: measurements using fascicle-aponeurosis cross-point. Bottom: measurements using myotendinous junction. No significant differences.

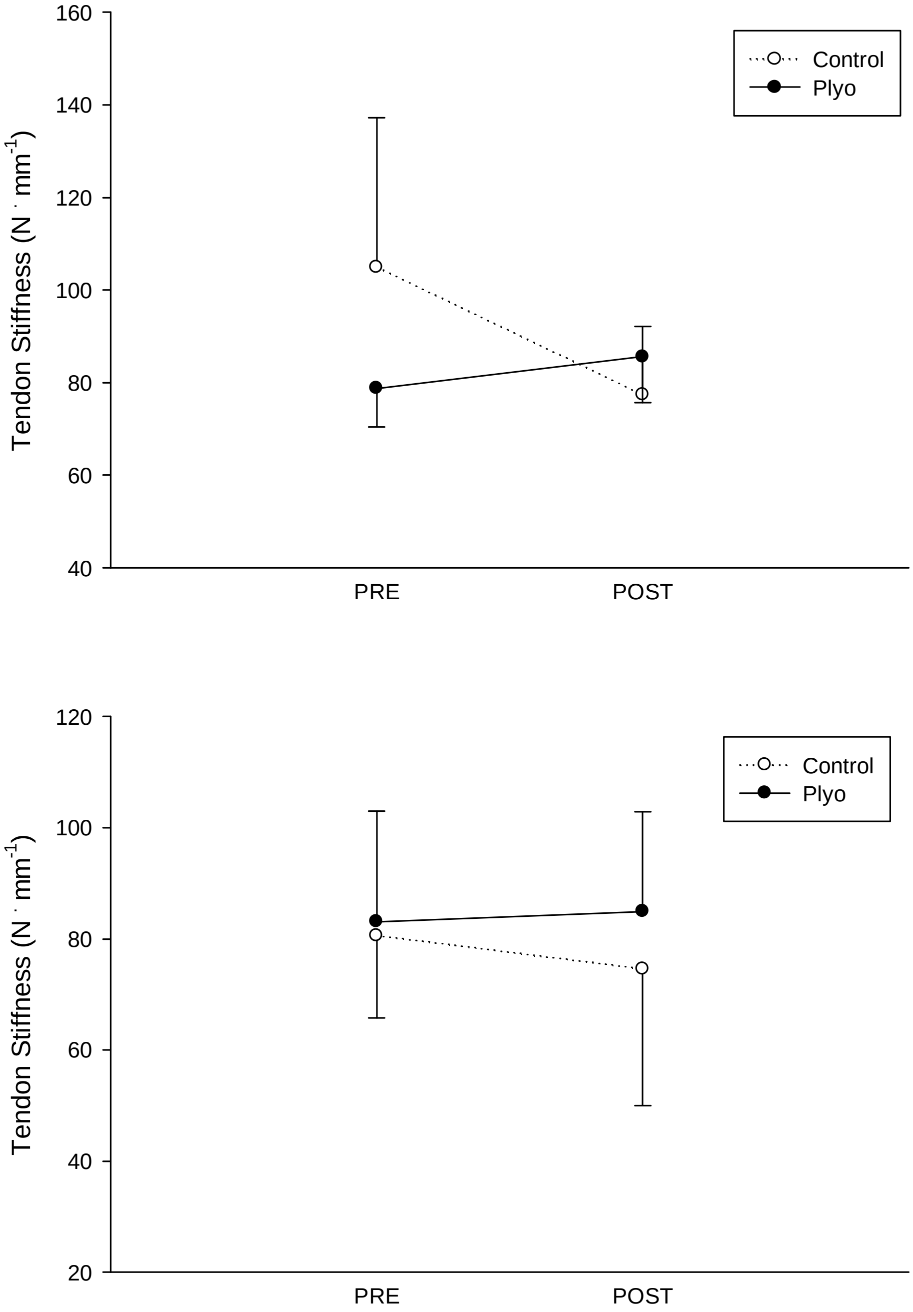

Figure G-5. Tendon stiffness measures for the control (n=5) and plyometric training group (n=5) before and after an 8-week plyometrics program. Top: measurements using fascicle-aponeurosis cross-point. Bottom: measurements using myotendinous junction. No significant differences.

Appendix H

Running Economy Slopes of Two Groups by Time

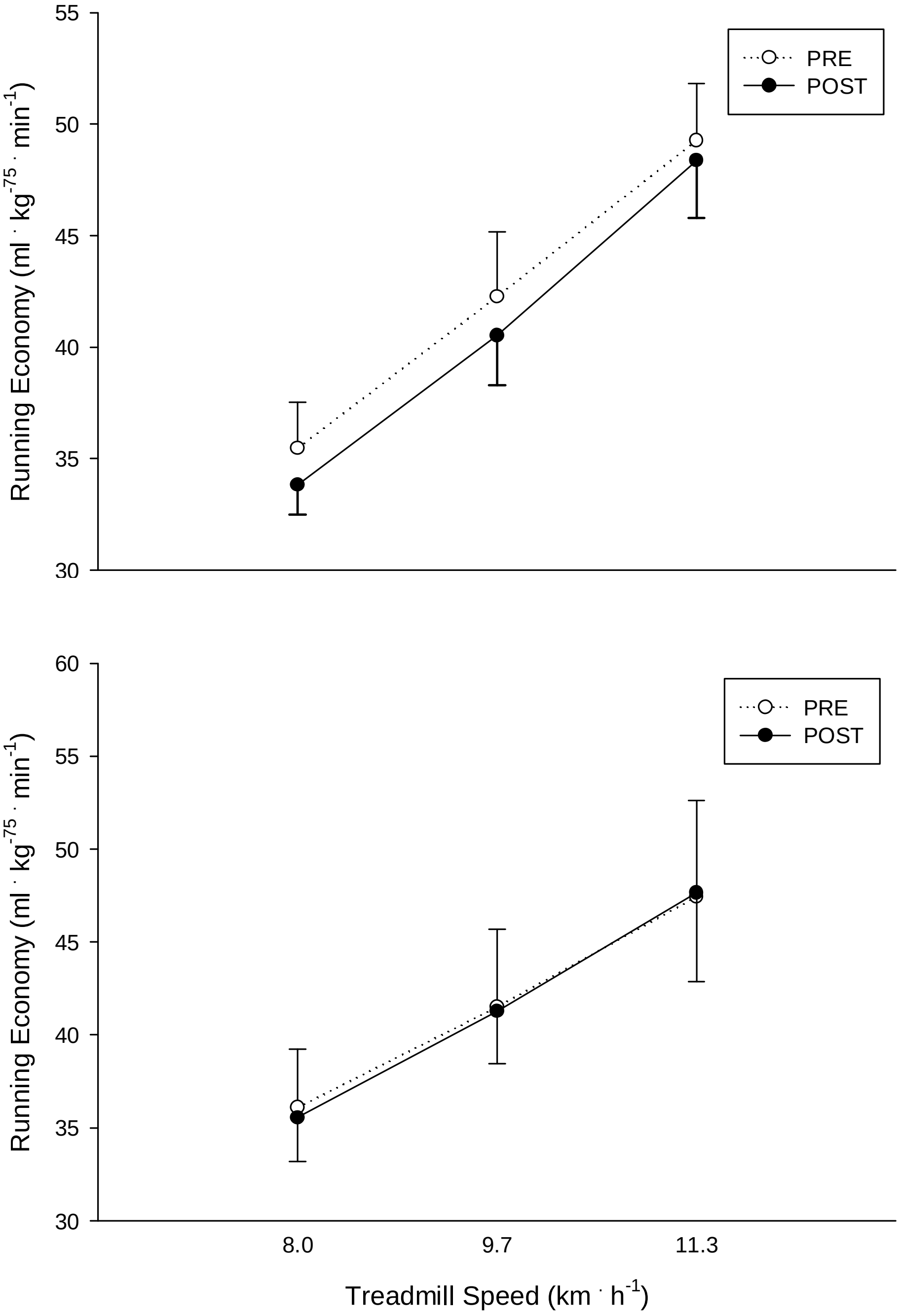

Figure H-1. Allometric-scaled running economy slopes over three treadmill test speeds before and after an 8-week plyometrics program. Top: measurements from the control group (n=6). Bottom: measurements from the plyometric training group (n=6). No significant differences.

Appendix I

Changes in Primary Variables of Three Groups over Time

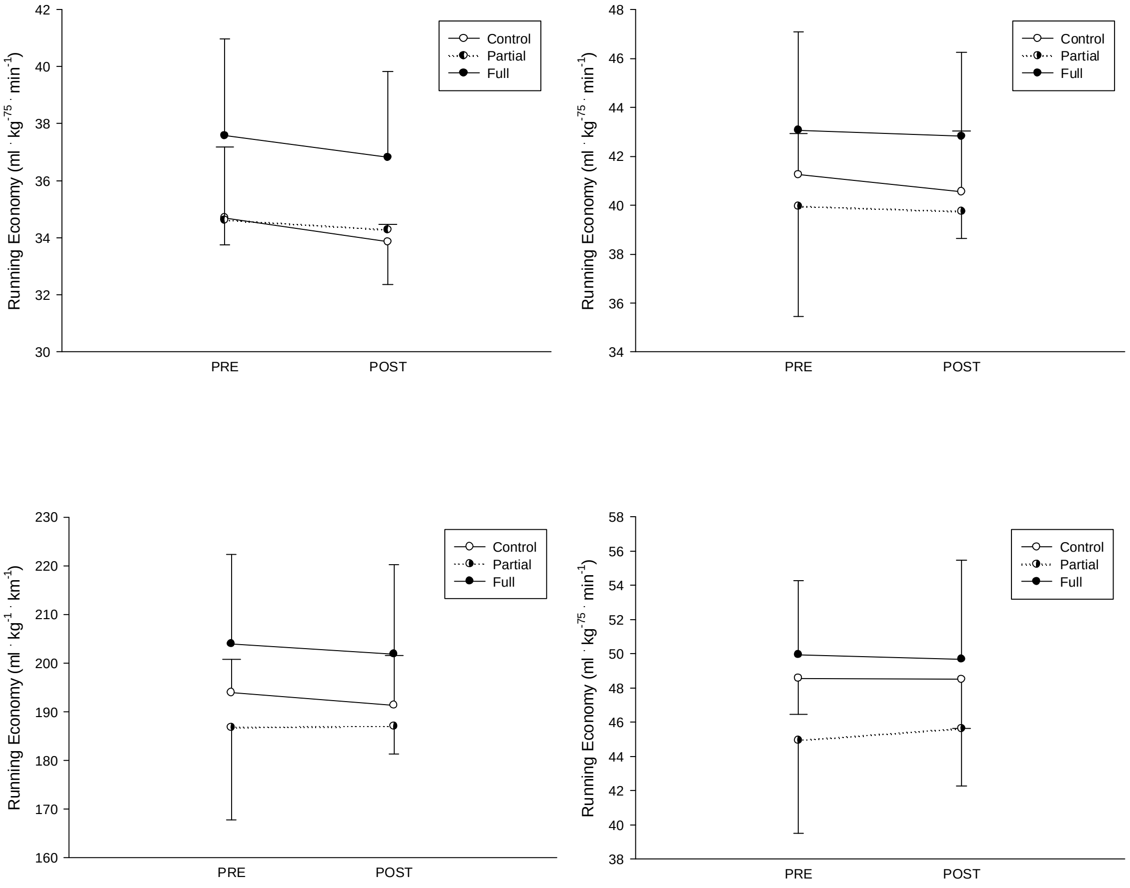

Figure I-1. Running economy measures for the control (n=5), and partial compliance (n=3) and full compliance (n=3) plyometric training groups before and after an 8-week plyometrics program. Clock-wise from top-left: allometric-scaled rate of oxygen consumption at 8.0 km • h^{-1}, 9.7 km • h^{-1}, 11.3 km • h^{-1}, and consolidated running economy. Descriptive statistics only.

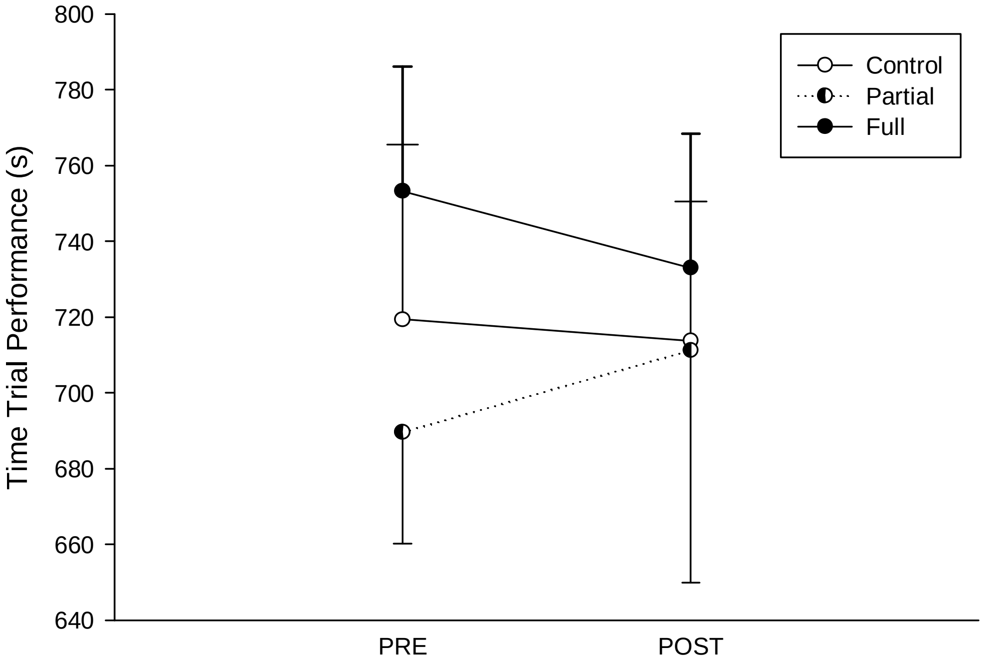

Figure I-2. Running performance measures for the control (n=4), and partial compliance (n=3) and full compliance (n=3) plyometric training groups before and after an 8-week plyometrics program. Descriptive statistics only.

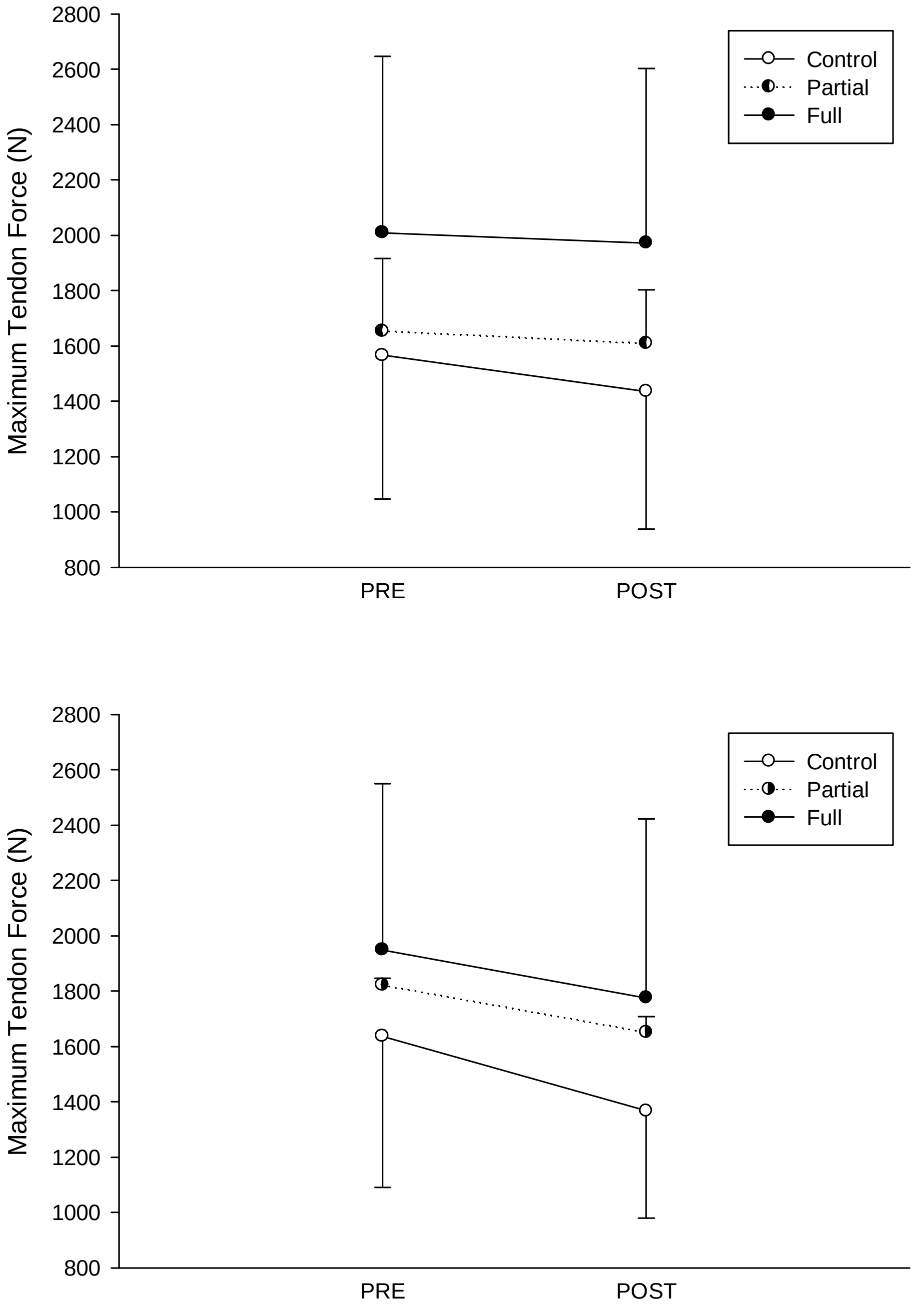

Figure I-3. Maximum tendon force measures for the control (n=4), and partial compliance (n=2) and full compliance (n=3) plyometric training groups before and after an 8-week plyometrics program. Top: measurements using fascicle-aponeurosis cross-point. Bottom: measurements using myotendinous junction. Descriptive statistics only.

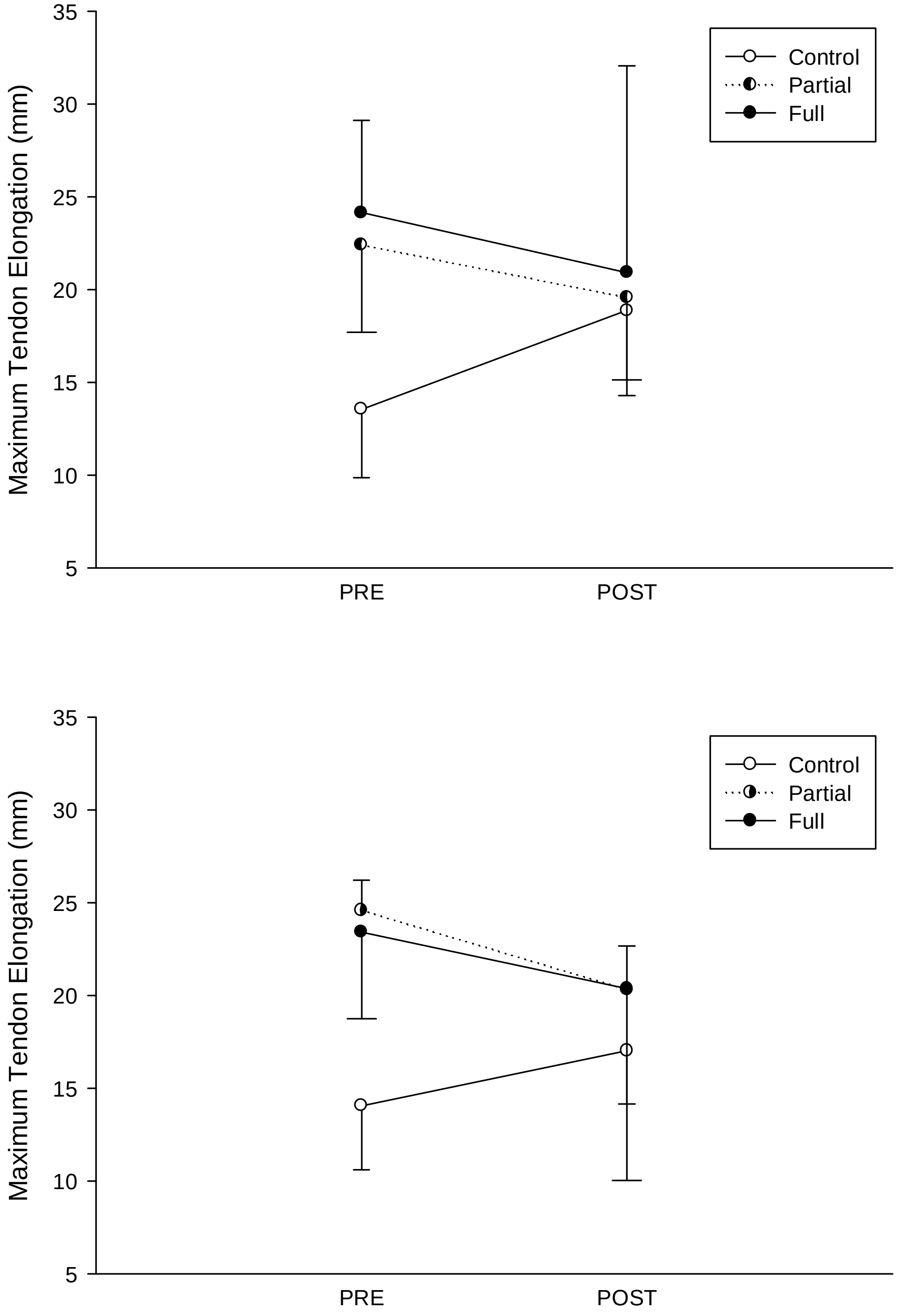

Figure I-4. Maximum tendon elongation measures for the control (n=4), partial compliance (n=2) and full compliance (n=3) plyometric training groups before and after an 8-week plyometrics program. Top: measurements using fascicle-aponeurosis cross-point. Bottom: measurements using myotendinous junction. Descriptive statistics only.

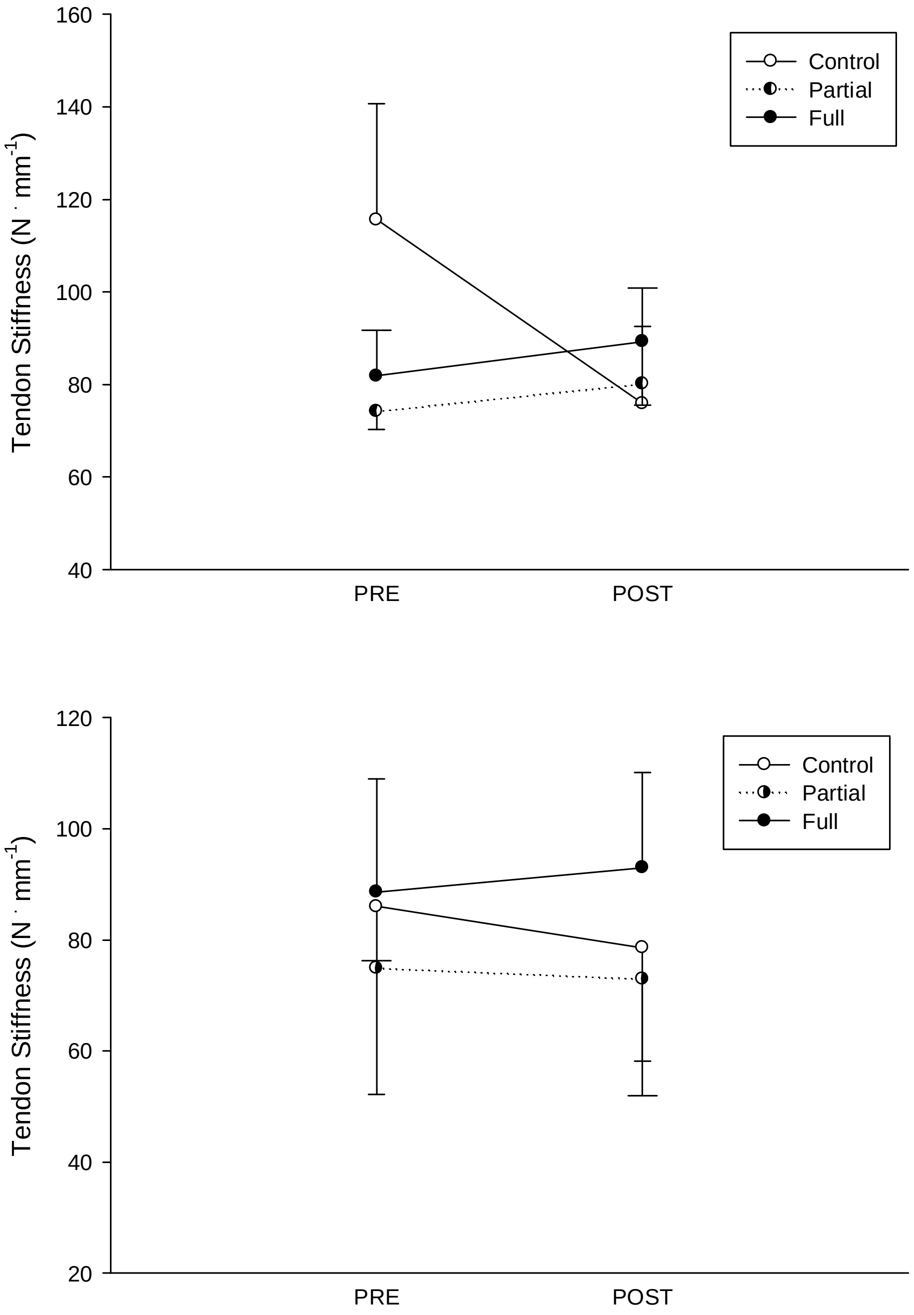

Figure I-5. Tendon stiffness measures for the control (n=4), and partial compliance (n=2) and full compliance (n=3) plyometric training groups before and after an 8-week plyometrics program. Top: measurements using fascicle-aponeurosis cross-point. Bottom: measurements using myotendinous junction. Descriptive statistics only.

Appendix J

Running Economy Slopes of Three Groups by Time

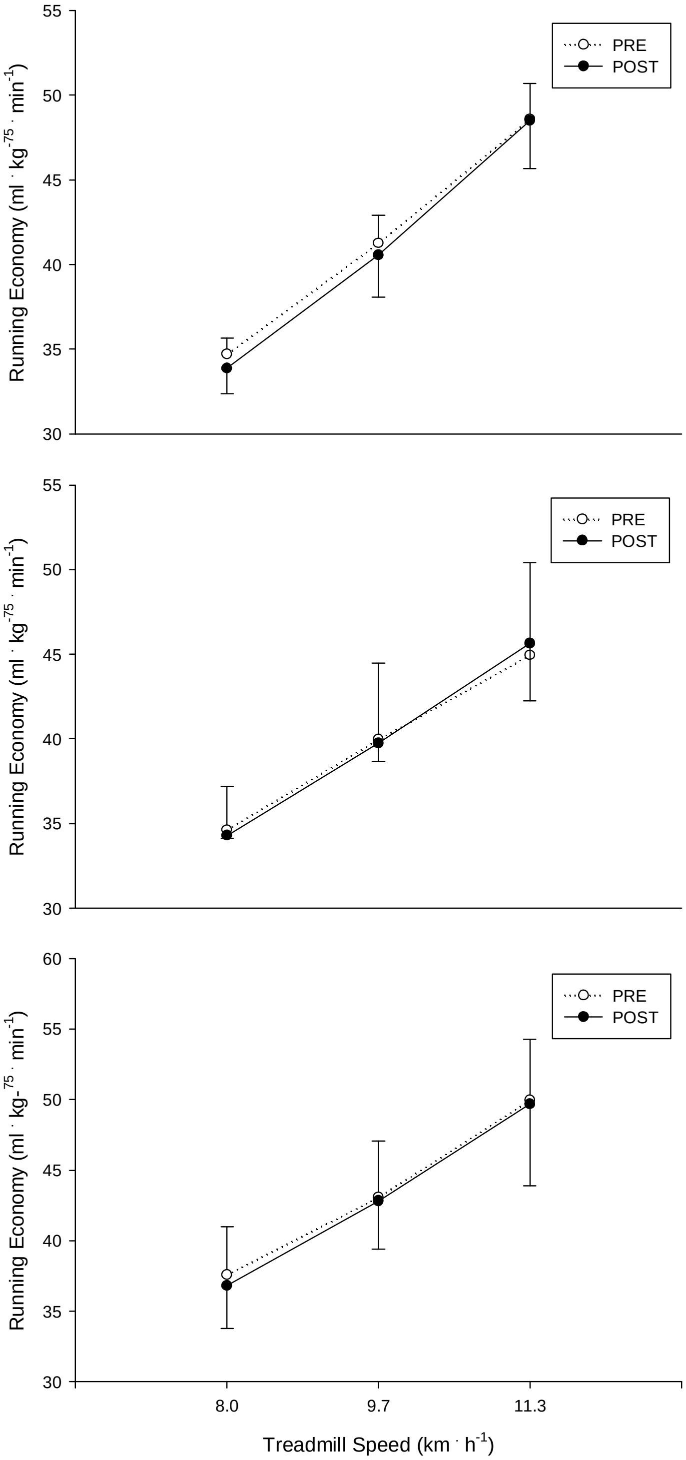

Figure J-1. Allometric-scaled running economy slopes over three treadmill test speeds before and after an 8-week plyometrics program. Top: measurements from control group (n=5). Middle: measurements from partial compliance plyometric training group (n=3). Bottom: measurements from full compliance plyometric training group (n=3). Descriptive statistics only.