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Plyometric vs. Isometric Training Influences on Tendon Properties and Muscle Output

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ABSTRACT

The purpose of this study was to concurrently determine the effect that plyometric and isometric training has on tendon stiffness (K) and muscle output characteristics to compare any subsequent changes. Thirteen men trained the lower limbs either plyometrically or isometrically 2–3 times a week for a 6-week period. Medial gastrocnemius tendon stiffness was measured in vivo using ultrasonography during ramped isometric contractions before and after training. Mechanical output variables were measured using a force plate during concentric and isometric efforts. Significant ($p < 0.05$) training-induced increases in tendon K were seen for the plyometric (29.4%; 49.0 < 10.8 to 63.4 < 9.2 $N \cdot mm_{-1}$) and isometric groups (61.6%; 43.9 < 2.5 to 71.0 < 7.4 $N \cdot mm^{-1}$). Statistically similar increases in rate of force development and jump height were also seen for both training groups, with increases of 18.9 and 58.6% for the plyometric group and 16.7 and 64.3% for the isometric group, respectively. Jump height was found to be significantly correlated with tendon stiffness, such that stiffness could explain 21% of the variance in jump height. Plyometric training has been shown to place large stresses on the body, which can lead to a potential for injury, whereas explosive isometric training has been shown here to provide similar benefits to that of plyometric training with respect to the measured variables, but with reduced impact forces, and would therefore provide a useful adjunct for athletic training programs within a 6-week time frame.

KEYWORDS: tendon stiffness, rate of force development, exercise

Introduction

Previous studies have shown that rate of force development (RFD) has a significant relationship with sporting events requiring high-power output (22, 24). During these dynamic explosive activities, there is a limited amount of time available to produce force, and therefore, the rate at which force is generated becomes very important. To develop force, a muscle must first take up the slack within the tendon. Therefore, a tendon that is less stiff would result in an increased time in which to develop force. Rate of force development has been seen to increase after relatively short periods of training (6 weeks) (16); this is thought to be caused by enhanced neural drive in the early phase of muscle contraction (9). Within this time period, it is also possible that changes in tendon stiffness could occur. Michna (17) reported changes in the degree of alignment of collagen fibers within the tendons of rodents after physical loading after just 1 week. Recent methodologic developments have enabled the elastic characteristics of human tendons to be measured in vivo using ultrasonography (7). This technique was used by Kubo et al. (12), who found increases in medial astrocnemius tendon stiffness in humans after 8 weeks of resistance training. As tendon stiffness increases, RFD should improve, because force transmission from muscle to bone would be more rapid (23). This has been shown by Bojsen-Moller et al. (3), who found a positive correlation between tendon stiffness and RFD.

Many previous studies have used different methods of training to improve RFD, including plyometric training (16), resistance training (1), and isometric training (11, 13). However, no attempt to compare the efficacy of plyometric vs. isometric training with respect to improvements in RFD and changes in tendon K has previously been made.

METHODS

Experimental Approach to the Problem

Subjects were randomly allocated into 1 of 2 groups and were trained for a period of 6 weeks. One group was trained isometrically and the other plyometrically. Testing was completed before and after the 6-week training period. The main dependent variables measured in this study were medial gastrocnemius tendon stiffness (K), jump height, and RFD.

Subjects

Thirteen men, with a mean age of 23 ± 6 (SD) years, a height of 179.8 ± 5.2 cm, and a body mass of 76.8 ± 6.1 kg, participated in the study and were assigned to either the plyometric or isometric training group. During the study, no additional training was undertaken by the participants. Before selection, all subjects were screened for evidence of previous lower limb injury and habitual activity. The study was approved by the Salford University Institutional Ethics Committee, and all subjects gave their written informed consent to participate in the experiment. The study conformed to the principles of the World Medical Associations Declaration of Helsinki.

Procedures

Training. The isometric training consisted of repetitions of maximal one-legged explosive isometric plantar flexions, and the plyometric training consisted of repetitions of maximal one-legged straight-legged drop jump. The training volume was progressively increased over the 6-week period, from 2 sessions a week consisting of 3 sets of 15 repetitions in the first week to 3 sessions a week consisting of 4 sets of 20 repetitions in the final week. Before training, subjects were adequately warmed up by performing several submaximal repetitions of their training exercise.

Testing. Before initial testing, each participant was familiarized with the testing protocol. Participants were tested before and after the 6-week training period on the following unilateral tests: (a) a maximal straight-legged concentric jump; (b) an explosive maximal isometric plantar flexion, and (c) a graded isometric plantar flexion, used in the determination of tendon stiffness. Before testing, participants were adequately warmed up by performing several submaximal trials of the tests. All subjects were instructed to develop force as rapidly as possible during tests a and b. Each participant carried out the sequence of tests in a random order but in the same order before and after training. Each test was carried out 3 times; the average of these tests was used for further analysis.

Measurement of Tendon Elongation and Stiffness. Using a modified Smith machine (UO82; Leisurelines, Leicestershire, UK), the participant stood on a portable force plate (Kistler type 9286A; Hampshire, UK), and the bar was locked at shoulder height so that when the participant stood on 1 straight leg they were effectively trapped between the bar and the force plate; this ensured that when plantar flexion occurred, the heel could not lift off the floor. During the test, the participant was instructed to generate force gradually, reaching a maximum after 3–4 seconds. Tendon elongation measurements were taken during the graded isometric plantar flexion test using ultrasonography as in Magnaris and Paul (14). Corresponding force values to the ultrasound stills were obtained from the force plate output, which were converted into torques about the ankle by multiplying by the length of the moment arm between the ankle joint center of rotation and the center of pressure of force application. This torque was converted into the gastrocnemius tendon force by dividing by the length of the gastrocnemius tendon moment arm as previously determined by Magnaris and Paul (14). Correction for relative muscle physiologic cross-sectional area of the gastrocnemius was applied in the calculation of final forces as per Fukunaga et al. (8). Antagonistic co-contraction torque was determined and corrected for during the measures using surface electromyography as in Magnusson et al. (15). Tendon stiffness was calculated from the slope of the tendon force–elongation relationship, between 60 and 100% of maximum force.

Unilateral Straight Legged Concentric Jump and Explosive Isometric Test. The participant stood on the portable force plate on 1 straight leg with his hands on his hips and jumped straight upward (no countermovement) by plantar flexing. Ground reaction force data was sampled at a rate of 1,000 Hz and recorded using Bioware version 3.2 software (Kistler). These data were exported to Microsoft Excel, where jump height and concentric RFD over the first 150 ms (RFD_{150}). The subject positioning for the isometric testing was identical to that used in the measurement of tendon stiffness.

Statistical Analyses
Two-way ANOVA was used to identify main effects of group and pre- to post test changes for each of the variables measured. α values were set to p= 0.05. Reliability of the measures was determined using intraclass correlation coefficients.

RESULTS
All main findings and reliability data are summarized in Table 1 with mean ± SEM and percent changes.

TABLE 1. Means ± SEM and percentage improvements for selected variables pre- to post training.*

	Isometric			Plyometric			
Variable	Pre	Post	Percent difference	Pre	Post	Percent difference	Reliability (ICC)
Tendon stiffness ($N \cdot mm^{-1}$)	43.9 ± 2.5	71.0 ± 7.4†	61.6	49.0 ± 10.8	63.4 ± 9.2†	29.4	0.82
Concentric RFD ($N \cdot s^{-1}$)	4,113 ± 1,068	4,801 ± 1,033	16.7	5,410 ± 1,026	6,436 ± 1,655	18.9	0.81
Concentric height jumped (m)	0.057 ± 0.005	0.093 ± 0.017	64.3	0.081 ± 0.012	0.128 ± 0.02†	58.6	0.95
Isometric RFD ($N \cdot s^{-1}$)	2,691 ± 478	3,447 ± 300	28.1	3,813 ± 263	4,270 ± 386	14.6	0.73

* RFD = rate of force development; ICC = intraclass correlation coefficient.
† Significant difference from pre- to post training ($p < 0.05$).

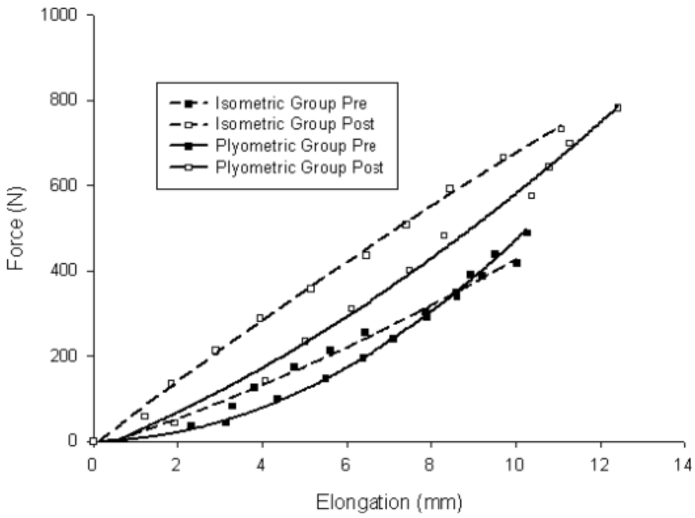

FIGURE 1. Relationship between pre- to postgroup values for medial gastrocnemius tendon force–elongation.

Tendon Stiffness
Figure 1 shows a comparison of force elongation curves for both plyometric and isometric groups for pre- and post training tests. Stiffness of the gastrocnemius tendon increased significantly for both

plyometric (29.4%, from 49.0 ± 10.8 to 63.4 ± 9.2 N·mm^{-1}) and isometric (61.6%, from 43.9 ± 2.5 to 71.0 ± 7.4 N·mm^{-1}) training groups pre- to post training ($p < 0.05$). There were no significant differences between the relative changes of the training groups pre- to post training ($p < 0.05$).

Relationship Between Tendon Stiffness and Concentric Jump Height

The isometric training group showed a trend toward significance (64.3%, $p < 0.059$) with respect to increases in concentric jump height, whereas the plyometric group increased significantly ($p < 0.05$) by 58.6% from the pre- to post training. Concentric jump performance was seen to be significantly associated with tendon stiffness ($r = 0.46$; Figure 2).

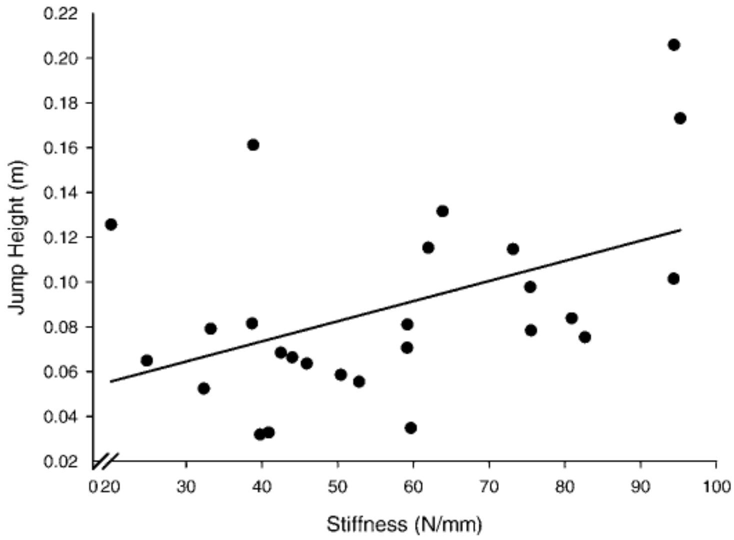

Figure 2. Relationship between tendon stiffness and concentric jump height ($r = 0.46$, $p < 0.05$).

Concentric and Isometric Rate of Force Development

Both training groups showed increases in concentric RFD150 from pre- to post test. However, these increases were not significant for either group (Table 1). Increases of 18.9 and 16.7% were seen for the plyometric and isometric training groups, respectively. In addition, there were no significant differences between the relative changes in concentric RFD of the training groups ($p < 0.05$). Isometric RFD_{150} also showed a similar trend, with increases after training of 14.6 and 28.1% for the plyometric and isometric training groups, respectively.

DISCUSSION

The results show that isometric and plyometric training both significantly increased medial gastrocnemius tendon stiffness ($p < 0.05$). Furthermore, with training, no significant difference ($p < 0.05$) in relative changes of stiffness between the groups occurred. Tendon stiffness values obtained here are in agreement with the literature (13, 20). In general agreement with the percentage increase, Kubo et al. (11) found increases of 58% in the stiffness of the vastus lateralis tendon structures after isometric training compared with 61.6% for the gastrocnemius tendon in this study. Changes of 29.3% for the plyometrically trained group are in general agreement with those of Kubo et al. (12), who found increases in medial gastrocnemius tendon stiffness of 18.8 ± 10.4% after dynamic resistance training.

Training may cause an increase in tendon stiffness caused in part by increased tendon cross-sectional area; however, a recent review by Buchanan and Marsh (5) reported that the current literature does not provide conclusive evidence to support this theory. Kubo et al. (13) suggested that increases in tendon stiffness after training could be caused by alterations in the internal structures of tendons brought about to compensate for the mechanical weakness induced by the stress of repeated loading during training. In support of this, a study by Michna (17) reported changes in the degree of alignment of collagen fibers within the tendon of rodents after physical loading.

Plyometric training produced nonsignificant increases of 18.9 and 14.6% in RFD measured concentrically and isometrically, respectively. These increases are in line with those reported by Spurrs et al. (21) after 6 weeks of plyometric training.

Isometric training produced an increase in both isometric (28.1%) and concentric (16.7%) RFD. The percentage increase in isometric RFD is in agreement with the findings of Duchanteu and Hainaut (6), Behm and Sale (2), and Kubo et al. (13), who all found isometric training to increase isometric RFD. However, research has suggested that dynamic RFD tests provide a more valid assessment of RFD than isometric tests (19), in that they are more functional and show greater correlations with various performance measures (22).

There are a number of factors that may play an important role in the force production and RFD. Neural components can affect the production and rate of production of force, because both frequency and quantity of neural firing can be modified with training. Although in this study we did not detect any changes in neural efficiency (data not shown), quantity of EMG did increase, suggesting no changes in synchronization but increases in firing frequency.

In theory, RFD should improve as tendon stiffness increases, because force transmission would be more rapid (23). A significant correlation has previously been reported between tendon stiffness and rate of torque/force development (4). Similarly, in this study, it was noted that there was an association between tendon stiffness and RFD, although the association did not reach levels of significance (data not shown). Hence, changes in tendon stiffness with training should provide an important mechanism to allow improvement in the rate of force development. Aagaard et al. (1) have recently shown that during the very early phase of the force generation (≈40 ms from onset), RFD is related less to the maximal force generating capacity (MVC) and more to the twitch properties of the muscle, RFD becoming more associated to the MVC with increasing time. These findings could also be explained in part by the effect of tendon stiffness. As force is developed, the curvilinear nature of the tendon force elongation curve can result in an increase in stiffness that would be expected to differentially affect RFD. Although not significant, increases were seen in RFD, with tendon stiffness possibly playing a major role in the observed increase.

Concentric jump height increased for both isometric (64.3%) and plyometric (58.6%) groups, with the plyometric group showing a significant increase ($p < 0.05$). In agreement with this study, plyometric training has been previously shown to significantly increase vertical jump performance (4, 16). The jump height here that consisted of a concentric plantar flexion effort on a single leg was also shown to be significantly correlated with tendon stiffness, in that stiffness could explain 21% of the variance in jump height.

In conclusion, the results indicate that both explosive isometric training and plyometric training increase tendon stiffness significantly (p 0.05) and to a similar degree. Furthermore, both training groups show trends toward increasing concentric RFD, which has been shown to be associated with athletic performance (19).

In addition, tendon stiffness was shown to be significantly correlated with dynamic performance in terms of concentric jump height, such that stiffness could explain 21% of the variance in jump height. Further studies with larger more heterogeneous groups need to be carried out to allow eneralization of these findings.

PRACTICAL A PPLICATIONS

Isometric training (6 weeks) in a standing position has been shown to significantly increase tendon stiffness and RFD, showing similar increases to plyometric training. Isometric training, therefore, seems to improve not only isometric performance but also has a cross-over effect of improving concentric performance as evidenced by increased jump height. Plyometric training has been shown to place large stresses on the body, caused by large impact forces on landing, which can lead to a potential for injury (10) and has also been reported to cause muscle soreness (18). Other methods of training, which provide similar training effects, but with reduced impact forces would therefore be beneficial to many athletes. This study has shown that isometric and plyometric training causes significantly similar increases in tendon stiffness and muscle output parameters. These results have important implications in the consideration of training protocols and during rehabilitation where controlled loading may be needed. Explosive isometric training can be used to supplement traditional methods of developing RFD (e.g., plyometric training) and to increase tendon stiffness for optimal force transmission for sports requiring increases in jump height and rapid dynamic efforts while moderating the injury risk. In summary, specific protocols could be designed and implemented within a time frame of 6 weeks to improve RFD using isometric training for a number of different sporting activities.

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