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Effect of Foot Intrinsic Muscle Strength Training on Jump Performance

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ABSTRACT

Fifteen subjects, 21–62 years old, participated in a 6-week toe flexor strengthening program using the archxerciser. Pre- and posttraining data for toe strength, vertical jump height simultaneously using the Just Jump and Vertec, and horizontal jump distance were collected for both control and exercise legs. Post hoc paired sample *t*-tests ($p < 0.05$) indicated significant improvement in all categories. This supported the hypothesis that the unconventional method of strength training the toe flexors should be considered a valuable adjunct in a training program designed to enhance vertical or horizontal jump ability. The relationship of different testing methods was also assessed. A Pearson correlation coefficient showed a significant (0.001 level) correlation when simultaneously using the Vertec and Just Jump to quantify vertical jump performance. A significant (0.01 level) correlation between individual performance in the vertical and horizontal jump was also identified. These results indicate that the tester is not restricted to a single testing device or method for assessment of jump performance.

Key Words: toe strength, vertical jump, horizontal jump, training response

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Introduction

Jumping ability, whether horizontal or vertical, is a critical element in many recreational and competitive sports activities. Therefore, the improvement of jumping ability is highly desirable in order to maximize athletic performance, which is required as part of a skill (rebounding in basketball, catching overhead balls, and spiking a volleyball) or as its own event (long jump, triple jump, and high jump).

This topic has been extensively explored in the literature. The relationship between leg/hip strength and vertical-jump performance has been assessed isometrically (7, 17), isokinetically (2, 10, 26), and isotonically (17). Biomechanical analysis of form (19, 22) and the effects of arm and countermovement on vertical jump (12) have previously been presented. The training effects of depth jumping (3, 16, 27), vertical jump periodization cycles (8), and plyometric training (1, 5, 9, 13) have been studied.

Since jumping requires muscle contraction across multiple joints, progressive resistance training has focused on multiple areas, with the traditional focus being the extensors of the hip, knee, and ankle. Robertson and Fleming (21) found the contribution of each of these muscle groups to be 40, 24.2, and 35.8 %, respectively, during a vertical jump. Harman et al. (12) showed that the arms contributed a mean 10% to takeoff velocity during the vertical jump. This was similar to the effect reported by Luhtanen and Komi (15).

When analyzing jump performance, there is yet another link in the closed kinetic chain that has gone largely uninvestigated—the contribution of the foot intrinsic musculature. There is a paucity of information on this subject. Djshov, as cited by Vorbjev (24), suggested that maximal jumping performance could be achieved by equally training the muscles of the foot. Kokkonen et al. (14) showed a significant improvement in toe strength ($p < 0.01$) and vertical jump ($p < 0.05$) following a 12-week training program that utilized a toe-finger exercise device adapted to a Cybex machine for strength training sessions and testing.

Although muscle size and maximum force is small in comparison to muscle groups such as the quadriceps femoris or gluteus maximus, the combined contribution of the flexors of the foot (flexor digitorum longus, flexor digitorum brevis, quadratus plantae, flexor hallucis longus, flexor hallucis brevis, adductor hallucis, abductor hallucis, flexor digiti minimi brevis, abductor digiti minimi pedis, interossei dorsalis pedis, interossei plantares, and lumbricales pedis) was hypothesized to positively translate into improved jump performance.

The primary purpose of this study was to determine what effect a strengthening program for the flex-

or muscles of the metatarsophalangeal and interphalangeal joints would have on toe flexor strength and on performance of vertical and horizontal jump. An additional purpose of this study was to determine the correlation between performance of a standing 1-leg broad jump and 1-leg vertical jump. A positive correlation between the 2 tests would support interchangeability in future studies. Vertical jump performance was simultaneously quantified using both the Vertec apparatus and Just Jump (Probotics, Inc., Huntsville, AL) mat and hand computer. A significant correlation would support interchangeable use of the 2 devices.

Methods

Subjects

A sample of convenience was selected from the clinical and office staff of a rehabilitation clinic. This sample consisted of 9 men and 6 women who were 21–62 years of age. Subjects were informed of the benefits and risks of the study. Each signed informed consent in accordance with the guidelines of the Physiotherapy Associates Institutional Research Review Board. Subjects completed a pretest questionnaire detailing demographic information, activity level, and any pertinent injury history.

Subjects were included if they satisfied the following criteria: (a) they had no prior history of unresolved pain, injury, or surgery to either the hip, knee, or ankle; and (b) they were currently not taking prescription medication for pain. Subjects classified themselves according to operational definitions set up in a pretest questionnaire. Eight subjects were minimally physically active, which was defined as 3–5 hours of exercise per week; 6 subjects were moderately physically active, which was defined as >5 hours of exercise per week; and 1 subject was a competitive athlete.

Experimental Design and Procedures

All pre- and posttraining test sessions were performed indoors in the same area on a standard linoleum block floor with minimal distractions in order to control for environmental factors. Each testing session consisted of a 5-minute warm-up period on a bicycle. This was followed by 3 supervised stretches in standing of 5–10 second duration for the quadriceps/hamstrings/gastroc-soleus complex bilaterally as demonstrated by the tester to maintain consistency.

Standardized demonstration and verbal instructions were given to each subject prior to testing during the pre- and posttraining sessions. Subjects were given an opportunity to ask questions and were required to correctly return the demonstration of each test leg prior to the actual testing to ensure compliance with the protocol. The study was organized into 3 categories: toe flexor strength, vertical jump, and horizontal jump. Toe flexor strength was always measured first. The order of horizontal and vertical jump testing was randomized by a coin test. The order of the leg sequence for each of the 3 tests was also randomized by a coin toss.

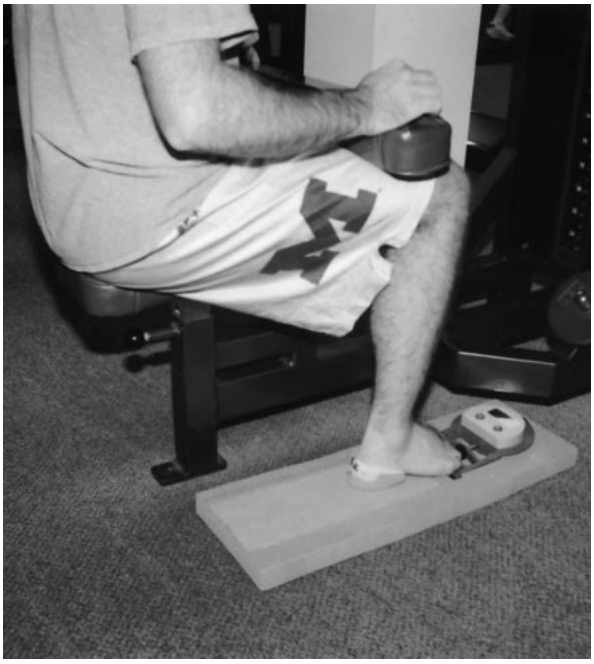

Figure 1. Set-up for toe flexor strength measurement.

To ensure test-retest reliability, every third subject completed the same experimental testing procedure 24 hours following initial pretraining testing.

Toe Flexor Strength. The testing apparatus consisted of a Smedley III Digital Grip Strength Tester (Takei Scientific Instruments Co., Ltd., Tokyo, Japan). Since this device was designed for the hand, modificatons were made that included a thermocork housing. An area was cut out of the housing directly under the toe-gripping slide bar to allow space for the toes to flex without obstruction. The subject was seated on the bench of a Magnum lat pull-down machine (Badger Fitness Equipment, South Milwaukee, WI). This was selected since it provided a stationary surface with seat height and thigh stabilizing pad that were adjustable to individual subject dimensions. Figure 1 depicts the subject's heel resting on the testing apparatus with the foot positioned to allow maximal hallux interphalangeal flexion, approximately 90°, over the toe-gripping slide bar. Once positioned, a heel stop secured by Velcro was placed immediately posterior to the heel to prevent movement of the foot. A 12-inch, 360° goniometer was used according to standard guidelines to position the subject in 90° of hip and knee flexion, with the ankle in 0° of dorsiflexion and with the heel resting on the test apparatus. The thigh-stabilizing pad of the pull-down machine was used to maintain the upper thigh in the aforementioned position during testing. Heel stop and seat height positions were recorded to ensure reproduceability be-

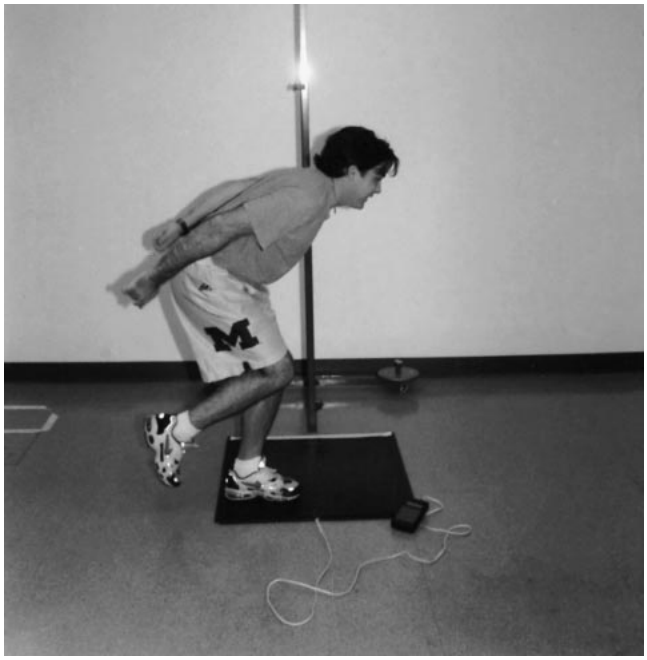

Figure 2. Simultaneous measurement of vertical jump using the Vertec and Just Jump.

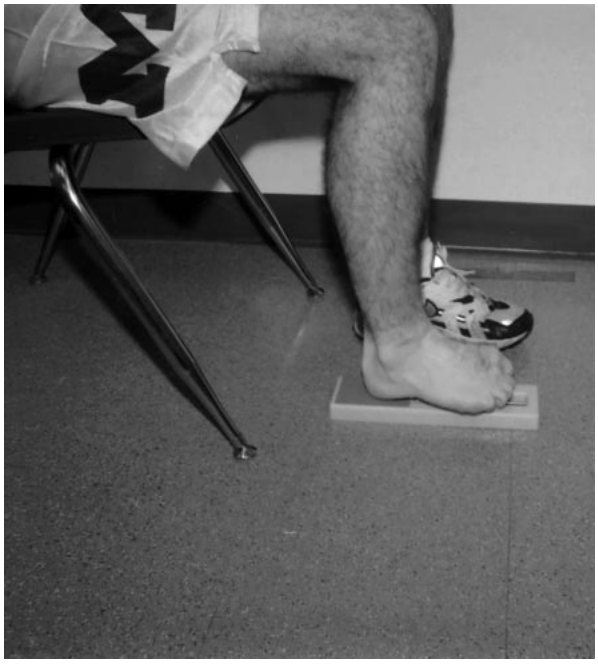

Figure 3. Set-up for toe flexor strength training using the archxerciser.

tween feet and between test sessions. Subjects completed 3 trials, alternating legs and with 30 seconds rest between each test. At the tester's signal, subjects performed maximal toe flexion of all 5 toes against the grip bar by moving the bar as far as possible. An index card placed over the display window eliminated visual feedback of performance. Measurements were recorded as displayed in kg of force.

Horizontal Jump. Subjects stood on the designated leg with the heel positioned on a floor marker. They were instructed to perform a maximal effort incorporating arm swing and countermovement, which is defined as a ''quick bend of the knees during which the body's center of mass drops before being propelled'' (12). Subjects were instructed to land on both legs for safety. The distance between the floor marker to the first point of contact of the heel of the designated leg was recorded in centimeters using a metric measuring tape. Subjects alternated legs with 30 seconds rest between jumps until 3 jumps were completed on each leg.

Vertical Jump. Vertical-jump data were simultaneously measured with 2 devices for each jump (Figure 2). The Vertec (Sports Imports, Columbus, OH) consists of plastic swivel vanes arranged at half-inch increments attached to a metal pole. Markings with sequential numbering for ease of recording results were made below each vane. Subjects stood on the mat of the Just Jump, which is attached to a hand-held computer. Its computer timer records ''air time'' by starting when a subject leaves the mat and stopping upon return to the mat. A mathematical equation translates time into distance jumped in inches.

A baseline standing reach measurement on the Vertec was determined by having the subjects reach as high as possible with their respective arm while maintaining full foot contact with the Just Jump mat. The number corresponding to the highest vane the subject could ''just barely touch'' was recorded bilaterally to accommodate for any unilateral structural differences.

Subjects stood at a 90° angle to the Vertec with the test side adjacent to the apparatus. At the tester's signal, a maximal-effort, single-leg vertical jump was completed from the leg specified. Subjects were encouraged to incorporate arm swing and countermovement. The subject displaced the highest swivel vane they could using the arm on the test side. Subjects were instructed to land on the mat with both feet or the jump would be void. Subjects completed 3 jumps on each leg in alternate fashion with 30 seconds rest between jumps.

The number of the highest vane displaced was recorded and the difference between the maximum and the baseline was measured in centimeters using a metric tape measure. The computer recordings from the Just Jump apparatus were noted. Distance in inches were converted to centimeters for consistency in data analysis.

Training Protocol

Subjects completed 3 training sessions per week for 6 weeks using the Archxerciser (Elgin Exercise Equipment Corp., Lombard, IL), depicted in Figure 3. Ses-

Table 1. *t*-Test of differences between control and test legs.

	$N = 15$				
	Control leg change		Exercise leg change		Significance control vs. exercise leg
	Mean	*SD*	Mean	*SD*	
Horizontal jump*	3.67	1.53	10.74	6.46	$p < 0.05$
Vertical Just Jump*	−0.23	0.67	2.58	2.07	$p < 0.01$
Vertical Vertec*	0.62	1.71	2.85	2.41	$p < 0.01$
Toe strength†	−0.64	1.93	1.81	1.41	$p < 0.01$

* Horizontal and vertical jump are measured in cm.
† Toe strength is measured in kg.

Table 2. ICC values.

Procedure	ICC (s, k)
Horizontal jump	0.909
Vertical jump (Vertec)	0.952
Vertical jump (Just Jump)	0.909
Toe strength	0.981

Table 3. Pearson correlation coefficients.

	Control leg	Exercise leg
Vertec and Just Jump	0.879*	0.859*
Vertec and Horizontal Jump	0.851*	0.622†

* Correlation is significant at the 0.001 level.
† Correlation is significant at the 0.01 level.

sions were completed 24–72 hours apart based on individual convenience. Date and time of training sessions were recorded to monitor compliance.

A within-subjects design was utilized with each subject serving as their own control. The experimental or training foot was randomly determined by subject number such that all odd-numbered subjects trained only their right foot, all even-numbered subjects trained only their left foot. The other foot served as the control. Subjects were told not to alter their lifestyle in any way in terms of activity level or training programs (stretching or strengthening). No one was performing a unilateral lower-extremity training, such as that which might be expected in a rehabilitation program.

Data Analysis

A 2 × 4 repeated measures ANOVA was performed to analyze the change between the control leg and the exercise leg in 4 tests. The change was computed by subtracting the mean of 3 posttest measurements from the mean of 3 pretest measurements for each. Once significance was found, 4 post hoc paired sample *t*-tests ($p < 0.05$) were used to analyze the change in toe strength, vertical jump–Just Jump, vertical jump–Vertec, and horizontal jump.

Intraclass correlation coefficients (ICC) were used to determine intrarater reliability for all 4 categories. Pretraining data was collected for every third subject on the designated test day and again 24 hours later.

A Pearson product moment correlation coefficient was performed to determine the relationship between 2 testing methodologies (vertical jump–Just Jump and vertical jump–Vertec) and 2 athletic skills (horizontal jump and vertical jump–Vertec).

Results

The initial results of the ANOVA indicated that there was a significant difference between the control leg and the test leg ($p < 0.001$) across the 4 tests. The post hoc *t*-tests indicated that the exercise leg achieved a greater performance outcome than the control leg at posttest for all categories (Table 1).

Table 2 compares the intrarater reliability for all variables investigated. Our original method to obtain this information was to retest every third subject. However, on completion of data collection, 5 subjects meeting this criteria were not sufficient to evaluate test-retest reliability. Alternately, the first and second measurements were used for each subject since each subject had a measurement taken 3 times. The sample therefore included 30 pairs of measurements. The difference between this method vs. the previous method is that the measurements were taken 3 times in a row, not 24 hours later. By using all 15 subjects, the power for each test is above 0.95. This method reduces the possibility of high ICCs by chance. These results are similar to a study by Greenberger et al. (11) who determined ICC values ranged from 0.92 to 0.96 for the 1-legged hop for distance, indicating a high degree of reliability.

A significant correlation was found when comparing 2 different methods of quantifying vertical-jump performance and 2 different athletic skills (Table 3).

Discussion

This study supported the hypothesis that metatarsophalangeal muscle flexor strength can be improved through a specific strengthening program. Such training also results in improved performance in functional activities such as horizontal and vertical jumping. This initial study by design was broad in its scope in terms of age, athletic background, and ability. It provides a groundwork for future investigations looking at more specific populations. A future study to specifically examine the training effect for elite jumpers would be enlightening. Hudson (13) felt that skilled jumpers were capable of making greater improvements in jump performance. Certainly, for the elite jumper even small improvements can have profound implications in a competitive setting.

The experimental construct utilized a single-legged vs. a double-legged jumping task in order to use a within-subjects design. Each subject provided both control and experimental data. By avoiding the need to precisely match subjects in control and experimental groups for all potential variables (age, level of athletic ability and experience, activity level during training period, etc.), the variable of toe flexor strengthening was isolated. Single-legged testing is commonly performed in a rehabilitation setting to assess functional ability (strength and stability) of an involved leg (20). Single-legged hop tests for distance have been found to be valid and reliable measurements (11, 18, 23).

The vertical-jump testing component highlighted some shortcomings of both devices. When using the Vertec device, one must first establish baseline data and control for unilateral upper-extremity or trunk restrictions by using 2 different baseline measurements, if indicated. The highest vane displaced must be visually noted and the difference between baseline and maximal displacement calculated or manually measured. The vanes must be physically returned to the ''start'' position. All of this amounts to a more time-consuming process. The Just Jump permits quicker data collection since immediate visualization of jump height occurs on the computer screen, and the next trial can be run as soon as the screen is cleared via a button. An inconsistency arises with the Vertec if the subject hits the apparatus with their hand either before or after reaching the apex of the jump, resulting in data that is inaccurately low or high. Inaccurate data may also be obtained with the Just Jump if subjects incorrectly position their hips and knees in a tuck position, causing a false reading that is too high.

There were several intrinsic shortcomings to this study. The methods required that subjects complete 1 practice trial followed by 3 test trials. One practice trial may have not been enough to stabilize the learning effect, although the literature is not clear what an optimal number of practice trials should be. Bolgla and Keskula (4) found that a marked learning effect occurred during single-legged hop testing. Some researchers have suggested implementing unlimited practice time until repeatable measures are achieved.

Although this study established that adaptations occurred with training, the contribution of muscular vs. neural factors can only be speculative. Future studies would need to study muscle fiber hypertrophy, differences in type I and type II fiber cross-sectional areas, histochemical changes of the muscle, and differences in maximal nerve conduction velocity.

Practical Applications

Improvement in jumping ability is a primary training goal for many athletes. With specifically designed training programs, even top-caliber athletes can demonstrate improvements of 10–25% (6). Most training methods employed today emphasize the larger, primary muscle groups involved in athletic skills. The stabilizing and accessory muscles are often neglected. In high-level competition, where even the smallest improvements are important, a comprehensive training program including all contributing musculature should be utilized. In this study, the training of the smaller agonistic flexor muscles of the foot resulted in significant ($p < 0.05$) improvement of vertical and horizontal jump performance.

This study established a correlation between the use of the Just Jump computerized system, which records air time, and the Vertec, which consists of a vertical pole with moveable indicators. Depending on instrument availability and familiarity, the clinician or coach can effectively use either apparatus. The tester should also not feel constrained to assess training effects by only the vertical or horizontal jump. Based on this study, the relative difference in performance would be the same using either device—Just Jump or Vertec—and a vertical or horizontal jump. However, they cannot be used interchangeably for the same subject.

Note: Caroline Unger, MSPT, CSCS, is now with Genesis-Southern Ocean Center in Manahawkin, NJ 08008.

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