J. Phys. Ther. Sci. 28: 2241–2244, 2016

The Journal of Physical Therapy Science

Original Article

Correlation between toe flexor strength and ankle dorsiflexion ROM during the countermovement jump

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Abstract. [Purpose] This study assessed the relationships between peak toe flexor muscle strength, ankle dorsiflexion range of motion, and countermovement jump height. [Subjects and Methods] Eighteen healthy volunteers participated in the study. Each participant completed tests for peak toe flexor muscle strength, ankle dorsiflexion range of motion, and countermovement jump height. [Results] The results showed (1) a moderate correlation between ankle dorsiflexion range of motion and countermovement jump height and (2) a high correlation between peak first toe flexor muscle strength and countermovement jump height. Peak first toe flexor muscle strength and ankle dorsiflexion range of motion are the main contributors to countermovement jump performance. [Conclusion] These findings indicate that the measurement of peak first toe flexor muscle strength and ankle dorsiflexion range of motion may be useful in clinical practice for improving jump performance in athletes training for sports such as volleyball and basketball.

Key words: Ankle dorsiflexion, Countermovement jump, Toe strength

(This article was submitted Feb. 18, 2016, and was accepted May 7, 2016)

INTRODUCTION

The countermovement jump (CMJ) is an explosive movement that is essential in many sports, including basketball and volleyball[1]. CMJ height, which is determined by measuring the jump height starting from an erect position followed by a downward movement before starting to push off, is an important criterion in athletic evaluation. Athletes spend much time and effort in various training activities to improve their athletic performance[2]. Many researchers have reported the performance characteristics of the CMJ and have discussed multiple issues related to achieving better CMJ height[3–5].

Ugrinowitsch et al.[6] reported that better CMJ height was the result of an increased vertical shift in the body's center of mass. To improve CMJ performance, ankle flexibility[4], muscle strength[3, 7, 8], initial jumping posture (squat depth)[5], and take-off velocity during vertical jump[1] are required. Robertson and Fleming[9] investigated the contributions of the extensors in the lower limb and found that the greatest contributor to jump performance was the hip (40%) followed by the ankle

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Table 1. Mean (± SD) of peak toe flexor muscle strengths by participants (n=18)

	First toe	Second toe	Third toe	Fourth toe	Fifth toe
Peak TFM strength	13.1 ± 3.9	3.1 ± 1.0	2.8 ± 0.8	3.1 ± 1.0	4.2 ± 1.3

Values are presented as the mean ± SD.
TFM: toe flexor muscle

(35.8%) and the knee (24.2%). Furthermore, another study suggested that ankle joint flexibility contributes significantly to increasing CMJ height[4]. During a vertical jump, the contribution of the ankle joint depends on the torque produced by the plantar flexors as well as the ankle dorsiflexion range of motion (DF ROM)[10].

Toe flexor muscles (TFM), which support the longitudinal arch of the foot against the reaction of the floor on the forefoot, also affect athletic performance[11]. Previous studies reported that TFM strengthening may have a positive effect on athletic performance[7, 12]. In addition, TFM strength may affect the use of the metatarsophalangeal joint (MPJ) before take-off during the CMJ[10]. To date, no studies on the effects of TFM strength on CMJ height have been conducted.

Therefore, this study investigated the correlations between peak TFM strength, DF ROM, and CMJ height. The results of this study may help identify the factors for improving CMJ height in training athletes.

SUBJECTS AND METHODS

Eighteen healthy volunteers (age: 23.3 ± 2.5 years, body weight: 71.9 ± 11.2 kg, height: 174.6 ± 3.8 cm, DF ROM: 19.6 ± 3.9°, CMJ height: 46.3 ± 10.3 cm) participated in this study. All participants were free of injuries, especially in the ankle joints, feet, and MPJ. The exclusion criteria were (1) any cardiovascular, respiratory, abdominal, neurological, musculoskeletal, or other chronic disease and (2) any symptoms that could affect the musculoskeletal system. The study procedure was approved by the Yonsei University Wonju Campus Human Studies Committee (approval number: 1041849-201508-BM-018-03); all participants provided written informed consent before enrollment.

Peak TFM strength, DF ROM, and CMJ height were used as the variables in this cross-sectional study. Each participant's body weight and height were determined at the beginning of the test protocol. Prior to gathering data, participants performed a warm-up that consisted of 5 minutes of walking up and down the stairs. They then attempted 2-legged jumps 6 times to become familiar with the CMJ. Three CMJs were performed by each participant, and the mean value (mean CMJ height) was used for analysis.

Peak TFM strength was measured using a digital dynamometer (MSC-200, AMETEC Inc, Largo, FL, USA). For a stable measurement setting, the digital dynamometer was attached to a wooden frame consisting of a platform, a vertical board, and a footboard[13, 14]. Each participant was instructed to sit comfortably with his or her back supported by a chair backrest and to place the foot to be tested on the footboard. The hip, knee, and ankle joints were positioned at 90° during the test. The toe to be measured was inserted into a leather cuff that was placed on the plantar side of the proximal phalanx, and the participant was instructed to pull the cuff downward as hard as possible for 5 seconds. Each of the 5 toes (phalanges) was measured 3 times in the same way. For familiarization with the testing procedure, participants were allowed to practice before measurement. For analysis, the highest value of 3 TFM strength measurements in each toe was used. A 3-minute rest period was provided between the strength measurements of each toe to minimize muscle fatigue. A blinded tester with experience working with a digital dynamometer read and recorded the strength value for each TFM on the digital display to eliminate experimental bias (Table 1).

The maximal DF ROM of the dominant leg was measured with a universal goniometer in 1° increments with the participant lying prone with 90° knee flexion. One lever of the goniometer was positioned on the proximal fibular head, while the pivot was placed on the lateral malleolus. The measuring arm was positioned on the fifth metatarsal bone, and its position was used to determine the passive DF ROM[15]. This measurement was repeated 3 times.

For the CMJ trials, the feet were placed parallel on the ground as the starting position. Participants were instructed to perform 3 maximal CMJs with the use of both arms, trying to cover the longest possible vertical distance. After each CMJ attempt, a 3-minute rest was given. The highest successful CMJ height among the 3 attempts of each participant was chosen for jump height analysis[7]. Two-dimensional (2D) kinematics measurement was obtained during the procedure with regular sampling at 25 Hz. A camera (Canon 500D, Tokyo, Japan) was mounted on a tripod, which was placed 5 m away from the participants, to record movements in the sagittal plane. This study used the sacral marker method for CMJ height measurement. A marker was placed on the sacrum at the approximate center of mass (COM), and the camera lens was focused on each participant's sacral marker in the standing position[16]. CMJ height was calculated as the maximum vertical displacement of COM during CMJ. Video sequences were digitized and examined using VirtualDub software (Avery Lee, version 1.5.10, Cambridge, MA, USA; http://www.virtualdub.org/). The images were then analyzed using the ImageJ computer program (National Institutes of Health, Bethesda, Maryland USA; http://rsb.info.nih.gov/nih-image) for height comparison.

The data were analyzed using PASW version 18.0 (Chicago, IL, USA) for Windows. Pearson correlation coefficients (r) were used to determine the strength and directionality of the relationships among the variables (peak TFM strength, DF ROM,

Table 2. Correlation coefficients between peak TFM strength, DF ROM, and CMJ height

	First TFM	Second TFM	Third TFM	Fourth TFM	Fifth TFM	DF ROM	CMJ height
First TFM strength	1.0						
Second TFM strength	0.16	1.0					
Third TFM strength	−0.082	0.701**	1.0				
Fourth TFM strength	0.228	0.503*	0.790**	1.0			
Fifth TFM strength	0.208	0.625**	0.623**	0.585*	1.0		
DF ROM	0.710**	0.219	−0.186	−0.007	−0.029	1.0	
CMJ height	0.765**	0.021	−0.233	−0.102	0.063	0.642**	1.0

*p<0.05; **p<0.001.
CMJ: Countermovement jump, DF ROM: ankle dorsiflexion range of motion, TFM: toe flexor muscle

and CMJ height). Mukaka[17] suggested threshold values of 0.0–0.3, 0.3–0.5, 0.5–0.7, 0.7–0.9, and 0.9–1.0 for negligible, low, moderate, high, and very high correlation coefficients, respectively. In addition, the coefficient of determination (r^2) was used to account for the variation among the variables. In all analyses, $p<0.05$ was taken to indicate statistical significance.

RESULTS

Table 2 shows the Pearson's correlation coefficients between peak TFM strength, DF ROM, and CMJ height in the participants. CMJ height showed a moderate correlation with DF ROM ($r=0.642$, $r^2=41.3\%$, $p<0.001$) and a high correlation with peak first TFM strength ($r=0.765$, $r^2=58.5\%$, $p<0.001$). The relationships between CMJ height and peak TFM strength of the other toes were negligible ($r=0.021$ to -0.233, $p>0.05$).

DISCUSSION

The results of this study indicate that CMJ height is correlated with peak first TFM strength and DF ROM in healthy subjects.

Several previous studies investigated multiple issues related to CMJ and reported a proximal-to-distal sequence of muscle activation—hip extensors, followed by knee extensors and finally ankle plantar flexors[3, 18]—and a proximal-to-distal transfer of energy during jumping[10, 19]. Papaiakovou[4] reported that the ankle should be a key joint in transmitting the energy generated by the proximal part (hip extensor, knee extensor, and ankle plantar flexor) to the ground during CMJ execution. However, the MPJ is smaller than the other joints in the leg, but the MPJ force amounts to about 86% body weight during push-off in the gait cycle[20]. The TFM around the MPJ may have a profound effect on forefoot loading and force transmission[21], and improvements of TFM strength training may have a significant effect on athletic performance enhancement[7, 12].

The results of this study indicate a high correlation between peak first TFM strength and CMJ height ($r=0.765$, $r^2=58.5\%$, $p<0.001$). Cohen[22] reported that the coefficient of determination could be used to more fully interpret the r value. Thus, 58.5% of the total variation in peak first TFM strength can be explained by variation in CMJ height. Nihal et al.[23] reported that dancers had greater hallux muscle strength than non-dancers (7 ± 4N vs. 6 ± 4N, respectively; $p<0.049$). In addition, the first TFM strength was twice the second TFM strength (9 ± 4N vs. 4 ± 1N, respectively; $p<0.001$). Furthermore, Tanaka et al.[24] demonstrated that the TFM are important contributors to sustaining dynamic balance; in particular, the TFM of the hallux was greater than the sum of the others combined. TFM strength may influence MPJ stiffness before take-off during CMJ performance. Stefanyshyn and Nigg[10] reported that increasing MPJ stiffness would decrease the energy lost at the MPJ, which would correspond to a positive effect on jump height. This finding may indicate a lack in the peak first TFM strength leading to a large amount of energy loss and, therefore, would not adequately transmit energy via the lower limb extensors before take-off during a CMJ. Thus, the results of this study suggest that the peak first TFM strength is an important factor not only in stabilization of the forefoot but also in the transmission of energy generated from the lower limb extensors to the ground, as well as in improving athletic performance; it is a major contributor in performing a higher CMJ.

DF ROM during a full squat before take-off was reported to affect CMJ height[25]. In this study, CMJ height showed a moderate positive correlation with DF ROM ($r=0.642$, $r^2=41.3\%$, $p<0.001$), consistent with the results of a previous study[4]. Individuals with a greater DF ROM were reported to have the ability to place their heels in contact with the ground during a full squat, which causes the ankle plantar flexor muscles to achieve sufficient force-generating capacity for a deeper squat position before take-off[4]. It has been shown that an active muscle, when lengthened, may sustain high forces and stretch the tendon sufficiently so that it can store elastic energy for the late concentric phase when the muscle activity starts to decay[26]. However, studies have shown that people lacking DF ROM raised their heels off the ground, had greater horizontal shift rather than vertical shift of COM, and achieved a low jump height[25, 26]. Thus, DF ROM is thought to be a second contributor to achieving sufficient force-generating capacity and proper vertical shift of COM during CMJ performance. Maintaining proper DF ROM has a significant impact on performing a higher CMJ.

This study has several limitations. First, the participants performed the experiment barefoot, but they wear shoes for actual athletic activities. Second, other related muscles that may contribute to the CMJ, including the ankle plantar flexors, knee extensors, and hip extensors, were not investigated. Third, this study did not investigate kinetic data during the CMJ. Therefore, the results of this study are difficult to generalize. However, this study is the first to examine the relationship between peak TFM strength and CMJ height. Further study is needed to investigate the correlation between peak TFM strength and ankle plantar flexors. Second, further research will need to examine whether improvement in peak TFM strength and DF ROM can have a clinically useful impact on CMJ performance.

This study was performed to investigate the correlations between DF ROM, peak TFM strength, and CMJ height. The results of this study indicate that the peak first TFM strength and DF ROM are the main contributors to CMJ performance. Measuring the strength of peak first TFM, ankle plantar flexors, knee extensors, and hip extensors in the lower limb and DF ROM may be useful in clinical practice for improving jump performance in athletes such as volleyball and basketball players.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial and administrative support provided by the "Brain Korea 21 Project" sponsored by the Korean Research Foundation.

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