SHORT COMMUNICATION

Influence of increases in toe-flexor strength on sprint and jump performances

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Objectives: This study aimed to investigate the influence of increases in toe-flexor strength (TFS) through specific training on sprint and jump performances. ***Design***: This study conducted 8 weeks of training with a two-period cross-over design. ***Methods***: Eleven male sprinters performed TFS training (4 weeks, four times per week) which consisted of 6 strength exercises, and 60-m sprint, squat (SJ), countermovement (CMJ) and rebound continuous jumps (RJ), and TFS normalized to body mass were measured before and after the training period. Spatiotemporal and ground reaction force (GRF) variables during the 60-m sprint were also obtained. ***Results***: There were no significant correlations of the normalized TFS with 50-m sprint time ($r = 0.363$, $p = 0.272$), SJ ($r = 0.119$, $p = 0.728$) and CMJ heights ($r = -0.041$, $p = 0.906$), and RJ height ($r = 0.368$, $p = 0.266$), contact time ($r = -0.215$, $p = 0.526$) and index ($r = 0.380$, $p = 0.249$) at the first measurement. Through the TFS training, normalized TFS increased from 0.331 ± 0.071 kg/kg to 0.384 ± 0.086 kg/kg (16.0%) for the average of two feet. All the sprint and jump performances, as well as the spatiotemporal and GRF variables during sprinting, did not show statistically significant changes through TFS training. ***Conclusions***: These results indicate that, whereas 4 weeks of TFS training could increase normalized TFS for well-trained sprinters, the increase in normalized TFS could not be effective for improving sprint and jump performances for well-trained sprinters.

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Key words: training ■ running ■ GRF ■ foot ■ plantar flexion

INTRODUCTION

Toe-flexor muscles are the generator of metatarsophalangeal (MP) joint plantar flexion moment, and their strength is one of the important factors for healthy locomotor function and better athletic performance.[1-4] In terms of athletic performance, Yamauchi and Koyama[5] found that, in untrained males, the toe-flexor strength (TFS) was correlated with squat (SJ) and countermovement jump (CMJ) heights, as well as rebound continuous jump (RJ) index. Moreover, studies employed children showed that TFS was correlated with 50-m sprint time and vertical and horizontal jump performances.[3,6] In contrast to these findings, Yuasa et al.[7] reported that TFS was not correlated with 10- and 40-yard sprint times in male American football players. Taken together, the importance of TFS on athletic performance is not clearly evident, and there is a possibility that the TFS could not affect athletic performance for trained athletes. As the above-mentioned previous studies were cross-sectional studies, a longitudinal study would provide a more reliable understanding of the importance of TFS on athletic performance.

Unger and Wooden[8] reported that, through 6 weeks of TFS training, 15 untrained males and females increased TFS for 1.81 kg, horizontal jump distance for 10.74 cm and vertical jump height for 2.58 cm (only changed values being provided). In 15 untrained males, Goldmann et al.[9] showed that 7 weeks of TFS training improved TFS from 0.21 to 0.38 Nm/kg for the left foot and from 0.24 to 0.40 Nm/kg for the right foot, and not the CMJ but the standing long jump distance from 2.25 to 2.31 m. Moreover, in 12 untrained males, Hashimoto and Sakuraba[10] reported that 8 weeks of TFS training increased TFS from 9.3 and 9.4 kg to 14.4 and 14.2 kg for left and right feet, respectively, and improved one leg standing long jump distance (178.8 and 179 cm to 198.3 and 189.5 cm for the left and right legs, respectively), vertical jump height (54 to 55.5 cm) and 50-m sprint time (7.34 to 7.05 s). In addition, in 11 recreational runners, Day and Hahn[11] showed that 10 weeks of TFS training increased TFS (27% from approximately 2.6 N/kg), while it did not change ankle and MP joint kinematics and kinetics during running. Based on the aforementioned previous studies, whereas an increment of TFS through training could improve athletic performance for untrained persons, the influence of increases in TFS is still unknown for well-trained athletes. Sprint and jump abilities are important for many sports, and the increase in TFS is suggested for improving these performances.[12] Thus, clarifying the influence of improving TFS on sprint and jump performances in trained athletes would lead to a better understanding of the importance of TFS on athletic perfor-

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mance and would improve training programs for achieving better sports performances.

Previous studies used only sprint time as a sprint performance indicator. The running speed can be calculated as a product of step length and frequency, and these sub-components of running speed are determined by the ground reaction forces (GRFs).[13,14] Moreover, it has been shown that specific leg strength can be important for specific sprint sections, e.g., whole leg extension capability can be important for the initial acceleration, while ankle reactive strength capability can be essential for the section approaching the maximal speed.[15] Thus, investigating the underlying variables of sprinting in multiple sections of the entire sprinting could deepen our understanding of TFS on dynamic movement performance.

The purpose of this study was to investigate the influence of increases in TFS through specific training on sprint performance and its sub-components, as well as jump performances. Because a previous cross-sectional study showed a possibility that the TFS could not relate to athletic performance for trained athletes, we hypothesized that the increment of TFS would not influence athletic performance for trained athletes. The findings would provide an understanding of the importance of TFS on athletic performance (sprinting and jumping) and be useful for practitioners for decision making of their training direction.

MATERIALS & METHODS

Experimental protocols

This study conducted 8 weeks of training with a two-period cross-over design. Half of the participants performed TFS training in addition to their regular training program during the first four weeks (training period), and they performed their regular training program only during the second four weeks (control period). The training period of 4 weeks was decided as it is enough for improving TFS,[9] and it did not affect participants' regular training for their competition schedules. The rest of the participants performed their regular training program only first, then their regular training program and TFS training. The TFS training was performed four times per week for four weeks. Due to the small number of available participants and for avoiding the effect of the period, the crossover design was adopted in this study.

Participants

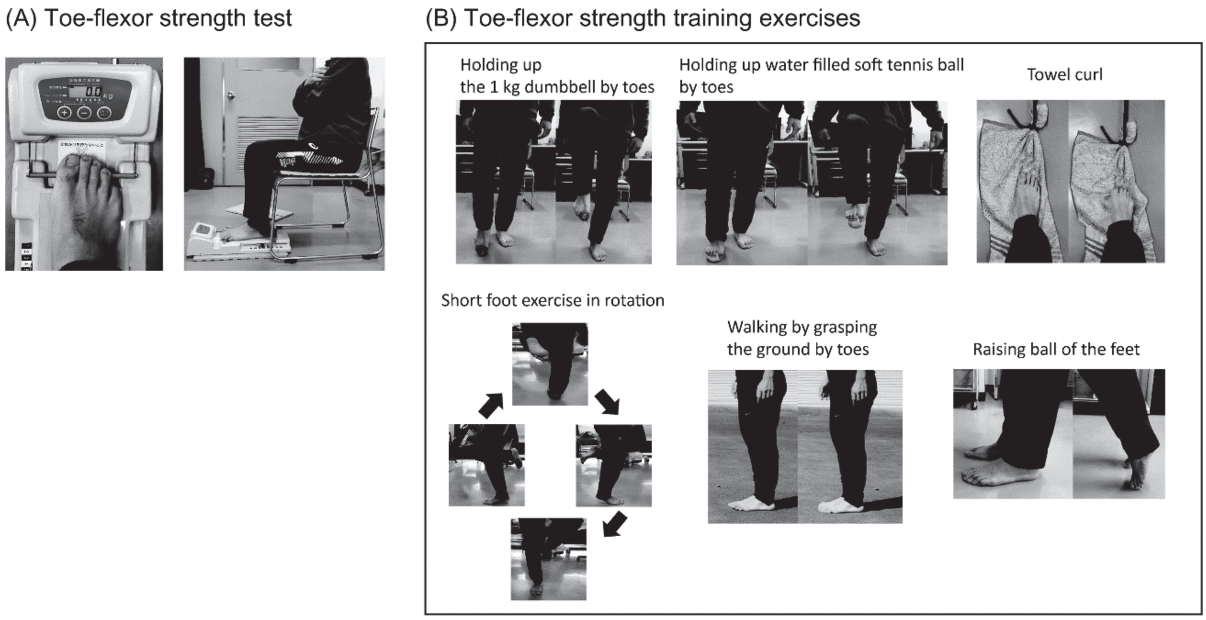
Eleven male sprinters (mean ± SD: age, 19.4 ± 1.2 y; stature, 1.71 ± 0.06 m; body mass, 65.0 ± 4.3 kg; personal best 100-m time, 11.19 ± 0.48 s) from a university athletic club were recruited for this study. The aim, risks of involvement, and experimental conditions of the study were explained before the experiment, and written informed consent was obtained from the participants. The experimental procedures were conducted with approval from the research ethics committee of the institute.

Measurement and data processing

After self-selected warm-up, participants performed two 60-m sprints with 10 minutes interval. The GRF during sprinting from the start to the 50-m mark was recorded using a long force platform system which consisted of 54 force platforms (TF-90100, TF-3055, TF-32120, Tec Gihan, Uji, Japan; 1000 Hz).[16,17,18] Participants who wore spiked shoes sprinted from the starting blocks. A start signal was provided using an electric starting gun which initiated the recording of GRF. Sprint times at every 10-m to the 50-m mark were computed using time-distance data which was calculated by double integration of mass-specific anteroposterior GRF signal. The influence of air resistance was taken into account in accordance with a previous study.[18] Step-to-step spatiotemporal and GRF variables from the start to the 50.5-m mark were calculated in accordance with previous studies.[16,17] All the GRF variables were divided by body mass. Average values for all the variables during the entire sprinting were calculated using all steps except for the block clearance. The fastest trial for each participant, determined by the average running speed for the entire sprint, was used for further analyses.

Approximately 10 minutes after the second sprint, TFS and vertical jump tests were performed in a randomized order with resting for 3 minutes between tests. The jump tests were performed in accordance with a previous study.[15] All jump tests were performed without arm swing action. Two trials were performed for SJ and CMJ, and the best trial based on the jump height was used for the statistical analysis. For RJ, the jump with the highest index (explained below), excluding the last jump, was chosen for statistical analysis. The researchers checked whether the jumps were performed correctly by visual assessment. If a participant performed a jump incorrectly, he was required to perform it again. A contact mat system was used to measure jump heights and contact times (Multi Jump Tester; DKH Co., Tokyo, Japan). The contact mat system detected the ON and OFF signals during foot contact on the ground and the flight of the body in milliseconds. The jump height was calculated using Bosco's theory.[19] The SJ and CMJ were measured only for height. The RJ was measured for jump height, contact time, and jump index; i.e., the ratio of the jump height (m) divided by the contact time (s).[15]

The TFS was measured as maximal isometric toe grip strength using a specific measurement device (T.K.K.3364, Takei Scientific Instruments, Niigata) (Fig. 1A).[1,5,20] The measurement was performed in a seated position with hip, knee and ankle angles being 90 degrees (Fig. 1A).[20] The seat height was adjusted according to the participant's leg length. The ankle of the measuring foot was fixed on the device using a Velcro strap. The participants were instructed to grasp the grip bar of the measurement device by toe as strongly as possible through gradual increases in the strength in 3 s and then to keep the strength for 3 s. The participant's arms were crossed in front of the chest, and body movement other than measuring toe was not allowed during the measurement. The maximal value shown on the monitor of the device was recorded. The measurement was performed twice for each of the left and right feet, and the average of greater values from the right and left feet was used for further analysis. Moreover, average TFS was divided by body mass as normalized average TFS.



(C) Toe-flexor strength training program

Training exercise	1st week	2nd week	3rd week	4th week
Holding up the 1 kg dumbbell by toes	3 × 10	3 × 20	3 × 30	3 × 30
Holding up water filled soft tennis ball by toes	3 × 10	3 × 20	3 × 30	3 × 30
Towel curl	3 × 10	3 × 20	3 × 30	3 × 30
Short foot exercise in rotation	5 rotations	6 rotations	7 rotations	7 rotations
Walking by grasping the ground by toes	2 × 2 m	4 × 2 m	6 × 2 m	6 × 2 m
Raising ball of the feet	3 × 10	3 × 20	3 × 30	3 × 30

Figure 1 Experimental set-up, training exercises and training programs for toe-flexor strength. (A) Toe-flexor strength measurement device and measurement position. (B) Toe-flexor strength training exercises. (C) Toe-flexor strength training program.

Toe-flexor strength training

Participants in the training period performed 30 minutes of training for four days per week for 4 weeks. The training was instructed by an experimenter during the exercise session. The TFS training consisted of 6 strength exercises as depicted in Figure 1B. The TFS training programs are summarized in a table (Fig. 1C). For "holding up the 1 kg dumbbell by toes", the participant pinched the 1 kg dumbbell with the first and second toes and repeatedly raised the thigh with holding the dumbbell until the thigh being parallel to the ground. For the "holding up water-filled soft tennis ball by toes", the participant grasped the water-filled soft tennis ball with the all toes and repeatedly raised the thigh with holding the water-filled soft tennis ball until the thigh was parallel to the ground. For the "towel curl", the participant repeatedly grasped the towel by all toes.[12] For the "short foot exercise in rotation", the participant made his foot short and rotated centering around the toes and MP joint.[12] For "walking by grasping the ground by toes", the participant moved forward by grasping the ground by toes. For "raising ball of the feet", the participant repeatedly stood on tiptoes without the balls touching the ground.

Statistical analyses

Descriptive data were presented by means and standard deviations (SDs). To examine the reliability and the magnitude of measurement error of TFS strength value, 95% limits of agreement (LoA) and minimal detectable change (MDC) were calculated using two values obtained at the first measurement session.[21,22] The MDC was calculated using the following equation.

$$\mathrm{MDC} = \mathrm{SEM} \times 1.96 \times \sqrt{2}$$

Where SEM was the standard error of measurement calculated using the following equation.

$$\mathrm{SEM} = \mathrm{SD} \times \sqrt{1 - \mathrm{ICC}(1,1)}$$

Where SD was the standard deviation of all TFS values, and ICC(1,1) was the intra-class correlation coefficient between two trial values. In order to clarify the possibility of detraining effect for the first trained group, paired t-test was used to examine the changes in the normalized TFS during the control period for each group separately and unpaired t-test was used to examine the difference in changes in TFS during the control period between two groups. To examine the relationship of the normalized TFS with jump and sprint performances, a correlation coefficient was computed using the data at the first measurement session. Changes in TFS, jump and sprint performances were examined using statistics specific to the two-period crossover design.[23] The significance level was set at $P < 0.05$. All the statistical analyses were performed using JMP 12 statistical software (SAS Institute Japan Ltd, Tokyo, Japan).

RESULTS

The LoA of TFS between two trial values at the first measurement session was −2.80 to 2.86 kg. Moreover, the MDC of TFS was 1.13 kg. Regarding the possibility of detraining effect, there were no significant changes in the normalized TFS during the control period for each group ($p = 0.321$ and 0.576 for the first-trained and second-trained groups) and no significant difference in changes in the normalized TFS values during the control period between the two groups ($p = 0.663$). Moreover, there were no significant correlations of the normalized TFS with 50-m sprint time ($r = 0.363$, $p = 0.272$), SJ ($r = 0.119$, $p = 0.728$) and CMJ heights ($r = -0.041$, $p = 0.906$), and RJ height ($r = 0.368$, $p = 0.266$), contact time ($r = -0.215$, $p = 0.526$) and index ($r = 0.380$, $p = 0.249$) at the first measurement session. Through the TFS training, TFS and its normalized value increased for 16.1% and 16.0% (Table 1). All the jump and sprint performances did not show statistically significant changes through TFS training (Table 1).

DISCUSSION

This study first investigated the influence of improved TFS on sprint and jump performances in well-trained sprinters. Although this study did not include a washout period between two training or control sessions, there were no significant changes between pre- and post-tests for each group during the control period and no significant difference in changes in values during the control period between two groups, suggesting that the current protocol can be accepted to examine the effect of TFS training. The main findings of the current study were that 4 weeks of TFS training could increase TFS, but the jump performances and sprint performance and underlying components of sprinting did not change in accompanied with the increased TFS.

Taking into account the magnitudes of the LoA and MDC, increments of TFS (16.1%) and normalized TFS (16.0%) on average of two feet indicate that a training period of 4 weeks is enough for strengthening toe-flexors even for well-trained athletes. In previous studies, the magnitudes of the increases in TFS through TFS training were 81% and 67% for the left and right feet, respectively[9] and 55% and 51% for the left and right feet, respectively[10]. These magnitudes are substantially greater than the magnitudes in the current study, but the participants in the previous studies were untrained males, who

Table 1 Changes in toe-flexor strength, jump and sprint spatiotemporal and ground reaction force variables during toe-flexor strength training and control periods.

	Training period			Control period			Training effect
	Pre-training	Post-training	Difference	Pre-training	Post-training	Difference	(p value)
TFS average [kg]	21.5±4.8	25.1±5.6	3.6±2.4	23.3±5.5	23.2±4.9	−0.1±1.3	0.003
Normalized TFS average [kg/kg]	0.331±0.071	0.384±0.086	0.053±0.042	0.355±0.074	0.337±0.095	−0.018±0.077	0.031
SJ height [m]	0.448±0.042	0.456±0.052	0.008±0.024	0.446±0.057	0.464±0.047	0.018±0.018	0.267
CMJ height [m]	0.481±0.039	0.477±0.042	−0.004±0.017	0.471±0.047	0.493±0.047	0.022±0.021	0.082
RJ height [m]	0.410±0.048	0.411±0.047	<0.001±0.039	0.414±0.048	0.404±0.047	−0.010±0.041	0.731
RJ contact time [s]	0.155±0.011	0.152±0.013	−0.003±0.013	0.154±0.013	0.156±0.012	0.001±0.009	0.190
RJ index [m/s]	2.67±0.41	2.72±0.34	0.05±0.30	2.70±0.37	2.61±0.35	−0.09±0.28	0.296
10-m time [s]	1.86±0.07	1.88±0.09	0.02±0.05	1.88±0.08	1.88±0.08	<0.01±0.04	0.834
20-m time [s]	3.06±0.11	3.08±0.13	0.02±0.05	3.08±0.12	3.07±0.11	<0.01±0.03	0.805
30-m time [s]	4.16±0.15	4.17±0.17	0.02±0.07	4.17±0.16	4.16±0.15	−0.01±0.04	0.846
40-m time [s]	5.22±0.18	5.23±0.21	0.02±0.08	5.23±0.20	5.22±0.18	−0.01±0.05	0.897
50-m time [s]	6.27±0.22	6.29±0.25	0.02±0.10	6.28±0.23	6.27±0.21	−0.01±0.06	0.903
Average velocity [m/s]	8.38±0.29	8.40±0.33	0.02±0.14	8.40±0.30	8.41±0.27	0.01±0.10	0.627
Average step length [m]	1.81±0.07	1.79±0.07	−0.02±0.04	1.80±0.07	1.80±0.07	0.01±0.03	0.244
Average step frequency [Hz]	4.64±0.28	4.68±0.24	0.05±0.10	4.68±0.24	4.66±0.27	−0.01±0.10	0.164
Average support time [s]	0.111±0.009	0.110±0.009	−0.001±0.003	0.110±0.008	0.110±0.009	<0.001±0.003	0.171
Average flight time [s]	0.106±0.008	0.104±0.009	−0.001±0.004	0.105±0.009	0.105±0.009	<0.001±0.003	0.433
Average braking mean force [N/kg]	−0.128±0.020	−0.127±0.017	<0.001±0.007	−0.127±0.017	−0.126±0.018	0.001±0.005	0.873
Average propulsive mean force [N/kg]	0.411±0.019	0.411±0.021	<0.001±0.010	0.410±0.022	0.411±0.021	0.002±0.007	0.961
Average anteroposterior mean force [N/kg]	0.283±0.013	0.284±0.018	0.001±0.012	0.283±0.018	0.286±0.014	0.003±0.008	0.965
Average vertical mean force [N/kg]	2.08±0.12	2.06±0.10	−0.02±0.05	2.06±0.09	2.07±0.12	<0.01±0.05	0.300

TFS, toe-flexor strength; SJ, squat jump; CMJ, countermovement jump; RJ, rebound continuous jump.
Training effect indicates the treatment result of crossover design statistical analysis.
The bold font indicates significant training effect.
The average values indicate averages for all steps during 50-m sprint.

had great trainability, and this fact can explain the contradiction in addition to the difference in training period (4 weeks in this study versus 7 and 8 weeks in the previous studies). In recreational runners, Day and Hahn[11] reported the magnitude of increase in TFS as 27% with 10 weeks of TFS training (only the right foot being tested). This magnitude is still greater than the value in this study, but the trainability of the participants in the current study seems to be lower than the participants in the previous study as the participants in this study were well-trained sprinters. Moreover, Day and Hahn[11] showed the magnitude of increase in TFS as 16% at 5 weeks. Although the contents of the training exercises are not equal, the magnitude of the increase in TFS in the previous study is comparable to the value in this study. Thus, the TFS training in this study could increase enough magnitude of TFS.

In this study, all the athletic performances including sprinting and jumping, as well as underlying components, did not change accompanied by increased TFS, suggesting that 16% increment of TFS might not affect athletic performance. The fact that there were no significant correlations of the normalized TFS with sprint and jump performances at the first measurement session supports the aforementioned finding. Because all the 10-m section times during sprinting did not change, the possibility of sprint-section-specific changes is also not supported. Previously, some studies showed improvements in athletic performance such as horizontal jump distance, vertical jump height and 50-m sprint time.[8,9,10] However, the participants of these previous studies were untrained males and females. In contrast to these previous studies, a study by Day and Hahn[11] which employed recreational runners demonstrated that the improved TFS did not change ankle and MP joint kinematics and kinetics during running, supporting the current findings of unchanged sprint and jump performances. Compared to the other major leg joints (hip, knee and ankle), produced MP joint moment through TFS is small during sprinting,[24] indicating that the changes in TFS are possibly less effective for athletic performance.

In conclusion, whereas 4 weeks of TFS training could increase TFS for well-trained sprinters, the increase in TFS could not be effective for improving sprint and jump performances for well-trained sprinters. These findings could be useful when planning a training program for trained athletes.

CONFLICT OF INTEREST STATEMENT

The authors do not have any conflict of interest to declare.

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