Influence of ankle invertor muscle fatigue on workload of the lower extremity joints during single-leg landing in the sagittal and frontal planes

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Abstract

Background: Insufficient rigidity of the foot owing to its ligaments and muscles can decrease the attenuation of the ground reaction force during landing. Therefore, dysfunction of the ankle invertors may increase the proximal joint load during landing.

Research question: What are the effects of the fatigued ankle invertors on workload in the lower extremity joints during single-leg landing?

Methods: Twenty-seven young adults (13 men and 14 women) performed landing trials in the forward and medial directions before and after exercise-induced fatigue of the ankle invertors. The exercise consisted of repeated concentric and eccentric ankle inversions until the maximum torque was below 80% of the baseline value. Negative joint workload during the landing tasks was calculated for the hip, knee, and ankle in the sagittal and frontal planes. Additionally, lower extremity work (the sum of the work of the hip, knee, and ankle) was calculated.

Results: Invertor fatiguing exercise resulted in a significant increase in negative joint work in the frontal and sagittal plane hip and the frontal plane knee during medial landing, whereas no significant change in negative joint work was observed during forward landing.

Significance: These findings suggested that ankle invertor dysfunction may induce a high load on the proximal joints and have direction-specific effects.

Keywords: ankle invertors, landing, negative joint work, fatigue

Introduction

Landing is frequently performed in sports, and the strategies of landing are focused on due to the importance of injury prevention or high performance. Contraction of antigravity muscles mainly contributes to prevent ground reaction force (GRF) from imposing large mechanical load on the body by resisting the external lower extremity joints moment caused by GRF. As GRF propagates firstly to the foot, followed by more proximal joints such as the ankle, the knee, and the hip, the foot function should affect mechanics of another joints [1–3]. Therefore, it should be important to pay attention to the kinematics, kinetics, and the structure of the foot during landing [2,4].

The foot has the different mechanical characteristic depending on whether it is in inverted or everted position. It is considered that the foot is rigid when the rearfoot is inverted, and conversely that the foot is flexible when the rearfoot is everted [5]. The foot inversion is considered to provide a rigid and effective leverage to the ankle plantarflexors and enable the ankle plantarflexors to attenuate GRF more strongly [3,6,7]. The foot posture is related to multiple components of plantar fascia, spring ligaments, tibialis posterior, and long and short plantar ligament [8–11]. A recent cadaveric study reported that tibialis posterior mitigated the navicular height from dropping, in other words, tibialis posterior resisted the foot pronation under the loaded condition [11]. Therefore, manipulating the force of ankle invertors represented by tibialis posterior would change the rigidity of the foot and the effectiveness of the foot lever for the ankle plantarflexors.

Decreased muscle strength of the invertors and the excessive pronation of the foot can inhibit attenuation of GRF considering the studies which reported high load during landing in those with flexible flatfoot, who have excessive pronation of the foot under the loaded condition and often have tibialis posterior tendon dysfunction accompanied with lowered muscle strength of the invertors, when compared to those with high arch [2] and normal structure foot [1]. It is possible that the abnormality of strength of the invertors or ligament caused the excessive foot pronation and the lowered rigidity of the foot, then the ankle plantarflexor moment was disturbed from attenuating GRF effectively. To the best of our knowledge, no studies have examined the effects of the invertors separately from other components of the ligaments, plantar fascia, and intrinsic foot muscles although the dysfunction of invertors would impose the lower extremity to high load during landing.

This study aimed to investigate the influence of a decreased strength of the ankle invertors on the lower extremity joint load during landing. An invertor fatigue exercise was conducted between the two landing trial sessions because the biomechanical changes caused by the fatigue reveal a muscle's role during the movement [18,19] and distinguish the effect of invertors from non-contractile tissues. Landing trials were conducted in both medial and forward directions because invertors can control both frontal movement of ankle and the rigidity of the foot lever to assist the plantarflexion force. We hypothesized that decreased strength of the invertors would increases sagittal plane load in the knee and hip joint.

Methods

Participants

Twenty-seven healthy college students (13 men and 14 women) participated in this study. The dominant leg, which is the leg kicking a ball, were on the right side for all the participants. Participants were excluded if they had a condition affecting balance, such as vestibular disorders, lower extremity injuries, or deformities on their dominant leg, within the past 6 months. Participants with flatfoot were also excluded because the purpose of this study was to evaluate the condition related only to the invertor torque, rather than other factors such as abnormal alignments. Foot type was determined using navicular drop distance (NDD), which measures the difference in navicular tuberosity height in sitting and standing [12], and those who had an NDD of more than 10 mm were excluded. The protocol was approved by the Institutional Ethical Committee (R2650) and was conducted in accordance with the Declaration of Helsinki. Informed written consent was obtained from each participant before data collection.

Procedures

First, the participants stood with their shoulder flexed 180°, and the height of their fingertips was recorded as static reach. The maximum jump height was decided from the highest value of three countermovement jumps (Fig. 1A). A bar used in landing tasks was suspended from the ceiling at the midpoint of the maximum jump height and static reach (Fig. 1B). Subsequently, landing tasks (PRE) were performed, followed by ankle invertor torque measurement, invertor fatigue exercise, ankle invertor torque measurement again, and finally landing tasks (POST).

Landing tasks

Landing tasks were performed immediately before and after the fatigue exercise (within 20 min to complete all landing tasks). Kinematic data were collected at 250 Hz using an eight-camera motion analysis system (Vicon Motion Systems Ltd., Oxford, England) and filtered using a fourth-order low-pass Butterworth filter at 14.5 Hz [13]. Kinetic data were collected at 1,000 Hz using a force plate (Kistler Japan Co., Ltd., Tokyo, Japan) embedded in the floor and filtered using a fourth-order low-pass Butterworth filter at 100 Hz. The force plates were synchronized with the motion analysis system. In accordance with the plug-in-gait full-body marker set [14], retroreflective markers were placed on the seventh cervical spinous process, tenth thoracic spinous process, jugular notch, and xiphoid process and bilaterally on the anterolateral and posterolateral aspects of the head, acromioclavicular joints, lateral epicondyles, medial and lateral sides of the wrists, second metacarpal heads, anterior superior iliac spines, posterior superior iliac spines, lateral aspect of the shank and thigh, lateral femoral condyles, calcanei, lateral malleolus, and second metatarsal heads. Participants stood barefoot and wore tight-fitting shorts and a T-shirt during testing.

As landing is performed in various directions in sports [15], landing tasks were performed in the front and medial directions in this study. Participants were instructed to land on their dominant leg, which was the right leg in all participants. In forward landing, participants jumped with both legs, touched the suspended bar with the fingertips, and landed on their dominant leg onto the platform 70 cm ahead of the point they jumped [16] (Fig. 1B). In medial landing, participants jumped from a point 50 cm right to the platform, touched the suspended bar, and landed on the platform. They were instructed to touch the bar with their right hand and put their hands on their hips as soon as possible after landing and maintain their posture for 10 s. The following trials were excluded as failed: participants hopped after landing, the counter leg touched the floor, and their fingertips did not touch the bar. Three successful landing tasks were collected and analyzed. We confirmed the lack of a difference in maximum height of the center of mass during jump between the PRE and POST conditions. The landing tasks in different directions were performed in random order by the participants.

Negative joint work in the hip, knee, and ankle and the total of these three joints (lower extremity work) were calculated in both the sagittal and frontal planes. Furthermore, negative ankle invertor work, which is frontal ankle work excluding work due to ankle eversion moment, was calculated to explain the contribution of the ankle invertor muscles. Negative work was calculated by integrating the joint negative power. Relative joint work, which is the respective joint work standardized by the lower extremity work in percentage, was also calculated. The following variables were calculated as components of joint work: the excursion during landing, peak value of negative joint power, internal moment of extension (hip and knee) and plantar flexion (ankle), abduction (hip and knee) and inversion (ankle), angle and angular velocity of flexion (hip and knee), dorsiflexion (ankle), adduction (hip and knee), and eversion (ankle). All variables were calculated from foot strike to the minimum height of the center of mass.

Fatigue protocol

The fatigue exercise and measurement of peak torque were performed using Biodex System 4 (Biodex Medical Systems Inc., Shirley, NY, USA). Participants were seated with the seatback tilt at 70°, knee flexed from 30° to 45° [17], and the pelvis and trunk were fixed with belts. The dominant foot was fixed to the footplate with the ankle plantar flexed at 10°. A proximal shank on the dominant side was placed on a limb pad and fixed to it, and the hip was restricted from abducting with a Velcro band at the thigh. The range of ankle motion in the fatigue protocol was set from 0° to 25° eversion. We confirmed that all participants were able to move the ankle without resistance through the excursion before the start of the exercise. Fatigue exercises and peak torque measurements were performed in this setting. The maximum voluntary isokinetic contraction of the ankle invertor was performed three times at 5°/s in concentric and eccentric contractions, respectively. Peak torque and work were calculated. Peak torque (Nm) was used to check approximate fatigue, and work (J) was used for analysis because a decrease in work reflects invertor fatigue across the full range of motion.

Fatigue is defined as a reduction in the capacity of a muscle to generate force[18], [19]. In this study, fatigue of the invertor was defined as a reduction in the isokinetic concentric work of the invertor by over 20% because previous study reported that subtalar inversion and foot adduction strength was lowered by 20 to 30% in patients of posterior tibialis tendon dysfunction compared to the controls [20]. In the fatigue exercise, six sets of 50 concentric and eccentric isotonic contractions at 60% of the concentric peak torque and 90% of the eccentric peak torque were performed. One-minute rest was given after every set. If peak torque did not decrease by 20% from baseline after six sets, participants performed additional two sets of fatigue exercises followed by remeasurement of peak torque. Even if additional fatigue exercise was insufficient to induce 20% fatigue, no further fatigue exercise was performed. Analysis was conducted only for those who experienced weakness of isokinetic invertor work by over 20% after fatigue exercise.

Data analysis

After the Shapiro–Wilk test for normality of distribution, paired t-tests or Wilcoxon's signed-rank test was conducted for the difference in landing kinetic and kinematic variables before and after fatigue and for the difference in frontal ankle kinetic and kinematic variables between forward and medial landing. Benjamini–Hochberg correction was applied to 16 variables (negative joint work in the ankle, knee, hip, and the sum thereof in the frontal and sagittal planes) to control for type I errors caused by multiple comparisons [21] because they are the main outcomes that directly represent the joint workload (α = 0.05). The effect size is reported in *r*.

Results

Fatigue

Five participants were excluded from the analysis because the data of invertor torque measurement was missing in one and there was insufficient reduction in invertor work in four participants. As a result, 22 participants (9 women and 13 men) were analyzed. They had a mean height, mass, age, and NDD of 165.0 ± 8.7 cm, 57.45 ± 9.7 kg, 23.6 ± 1.6 years, and 5.91 ± 1.20 mm, respectively. Isokinetic invertor work after fatigue was 70.58 ± 8.11% of the baseline value.

Landing

Negative joint work and relative joint work are shown in Figures 2 (forward landing) and 3 (medial landing).In forward landing, no significant difference was found at any joints post-fatigue (Fig. 2A-1, 2A-2). Relative joint work in forward landing showed increased sagittal hip work following fatigue exercise (Fig. 2B-1). No significant difference was found in the frontal plane (Fig. 2B-2). In contrast, in medial landing, significant increases were found in negative joint work in sagittal and frontal lower extremity joint ($p < 0.01$), sagittal and frontal hip, and frontal knee joint work (Fig. 3A-1, 3A-2). Furthermore, sagittal relative joint work increased in the hip and decreased in the ankle (Fig. 3B-1). Frontal relative joint work was not significant (Fig. 3B-2). Invertor relative joint work at PRE was

3.62 ± 3.72% at the forward landing and 17.43 ± 8.43% at anterior landing.

Variables that consisted of joint work were calculated at medial landing because the change of the work at medial landing was larger than that of forward landing (Table 1). As a result, in sagittal hip at medial landing, significant increases were shown at peak negative joint power, peak extension moment, peak flexion angle velocity, and peak flexion angle. In the frontal plane, a significant increase was observed in the frontal hip excursion, maximum knee adduction velocity, peak ankle eversion, peak eversion angle velocity, and ankle frontal excursion.

In a comparison of frontal ankle kinetic and kinematic variables between forward and medial landing (PRE), invertor work and inversion moment in medial landing were significantly higher than those in forward landing (Table 2).

Discussion

This study investigated the changes in workload during forward and medial single-leg landings due to approximately 30% decrease in ankle invertor work. In medial landing, the decreased strength of the ankle invertors induced increased negative lower extremity joint work in both the sagittal plane and the frontal plane. On the other hand in forward landing, no significant difference was found in absolute joint work, which was contrary to our hypothesis. To the best of our knowledge, this is the first study to investigate the effect of the fatigue-induced decrease of the ankle invertor strength on lower extremity joint work during forward and medial single-leg landings.

Participants performed the fatigue protocol until the maximum concentric work of inversion fell below 80% of the baseline value. A previous study, which investigated the effects of hip abductor muscle fatigue on landing, reported that more than 20% decrease of maximum muscle strength affected kinematics and muscle activity of the ankle [22]. The decrease of inversion strength by 20-30% is also clinically realistic degree of muscle weakness in patients [20]. The fatigue exercise in the present study resulted in the invertor work decline to 70.58 ± 8.11% of its baseline level. The kinematic change would be caused by the decline of the invertor strength in this study.

In medial landing, the fatigue of ankle invertors caused increased absolute lower extremity work in the sagittal and frontal planes. The fatigue relevant change in ankle joint during medial landing was the increase in ankle eversion excursion and ankle eversion velocity (Table1), implying the lowered rigidity of the foot. These kinematic changes in the ankle frontal plane could have affected the changes in lower extremity joint load. One possible mechanism is that the decreased rigidity of the foot could not serve effective lever for ankle plantarflexors. This dysfunction could have induced large force to propagate to the knee and the hip and thereby increased the frontal plane knee work and the frontal and sagittal plane hip work. Precise analysis on these variables composing the increased work can supply additional implications. Increased sagittal hip work can be explained by the increase in peak extension power, extension moment, flexion angle velocity, flexion angle, and sagittal excursion

(Table 1). A previous study reported that those with flat feet showed a larger hip flexion angle accompanied by an increased GRF during double-leg landing than those with normal feet [1], which supports this study in that ankle weakness in the frontal plane increased the sagittal hip strategy. Increased hip excursion and the peak knee adduction velocity were observed in the frontal plane. A previous study reported that hip abductor fatigue, in other words, relative overload in the frontal hip, increased the hip adduction angle and knee adduction velocity during running [23]. Therefore, changes in the knee and hip in the frontal plane in this study might have been caused by the increased frontal hip work.

Contrary to our expectations, only the increase in relative hip work in the sagittal plane was found in forward landing (Fig.2 B-1). We had expected that absolute lower extremity work would increase because the inversion fatigue would make the foot lever flexible and inhibit the ankle plantarflexors from attenuating GRF considering the high load during forward landing and drop landing in flatfoot, which has also flexible foot lever [1,2]. However, the absolute work changes were not seen in forward landing. It may have been caused by following reason. One is that the internal ankle inversion work (i.e. external ankle eversion work) was lower in forward landing compared to in medial landing (Table2); therefore the strength of the ankle invertor might not affect the attenuation of GFR during forward landing. The other factor was that the participants in this study had the normal noncontractile tissue. When individuals with flatfoot perform forward landing, the degenerated foot ligaments and plantar fascia maybe impair the foot rigidity, which probably can induce the high load during landing[1,2]. The present participants who have the normal noncontractile tissue might have maintained their landing mechanics using the normal noncontractile tissues regardless of their inversion strength.

The limitation of this study is that we could not evaluate the accurate foot stiffness because we used the model which recognized the foot as a single segment without evaluating respective bony movement of rearfoot, midfoot, and forefoot. We should more precisely evaluate the mechanism of the inversion fatigue-relevant change in lower extremity workload using multi-segment foot model [4,24]. Another limitation is that we did not correct variables other than the main outcomes. Therefore, sub-outcomes should be used for the supplemental interpretation of the main outcomes because of the risk of type I errors.

In conclusion, the fatigue exercise decreased ankle inversion strength by 30% from baseline. A medial landing after fatigue increased the ankle eversion excursion and velocity. It is possible that the foot became flexible and could not supply the effective lever for the ankle plantarflexors and consequently increased the hip work in the sagittal and frontal planes and the knee work in the frontal plane during medial landing. As high load in lower extremity joints may lead to injuries, therapists should assess the muscle strength of ankle invertors especially in those engaging in multi-directional sports.

Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure Legends

Fig. 1. A. Measurement of the maximum vertical jump height. B. Forward landing (B-1) and medial landing (B-2). Participants jumped with both legs, touched the bar at the height of 50% of the maximum vertical jump height with the fingertips of their right hand, and landed on their right leg.

Fig. 2. Negative joint work (J/kg) and relative joint work (%) in forward landing before and after invertor fatigue. A. Negative joint work in the sagittal plane (J/kg) (A-1) and negative joint work in the frontal plane (J/kg) (A-2). B. Relative joint work in the sagittal plane (%) (B-1) and relative joint work in the frontal plane (%) (B-2). Sum: sum of negative joint work in the hip, knee, and ankle. Inv: negative work in the frontal ankle, which is explained by the internal ankle inversion moment. The asterisk (*) indicates significant difference between PRE and POST.

Fig. 3. Negative joint work (J/kg) and relative joint work (%) in medial landing before and after invertor fatigue. A. Negative joint work in the sagittal plane (J/kg) (A-1) and negative joint work in the frontal plane (J/kg) (A-2). B. Relative joint work in the sagittal plane (%) (B-1) and relative joint work in the frontal plane (%) (B-2). Sum: sum of negative joint work in the hip, knee, and ankle. Inv: negative work in the frontal ankle, which is explained by the internal ankle inversion moment. The asterisk (*) indicates significant difference between PRE and POST.

Figures

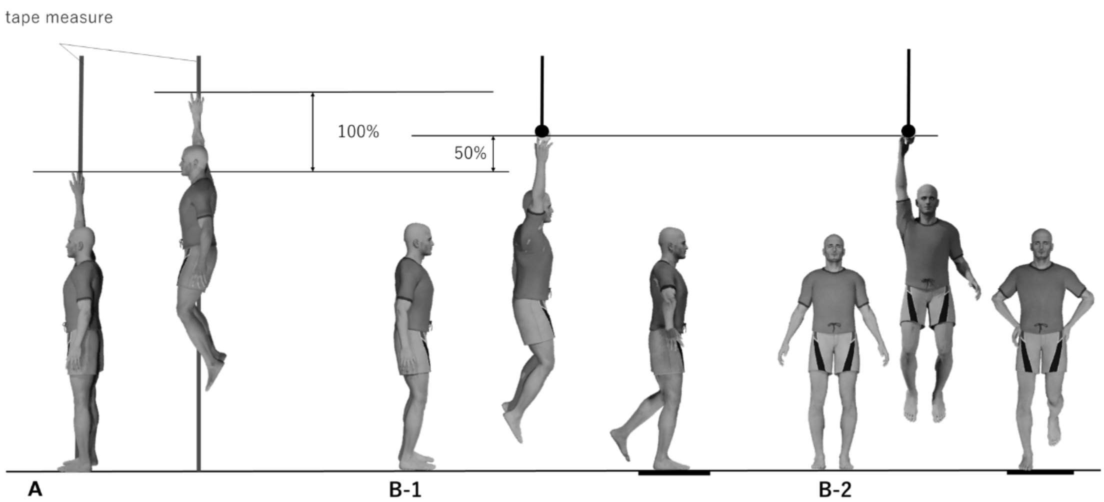

Fig.1

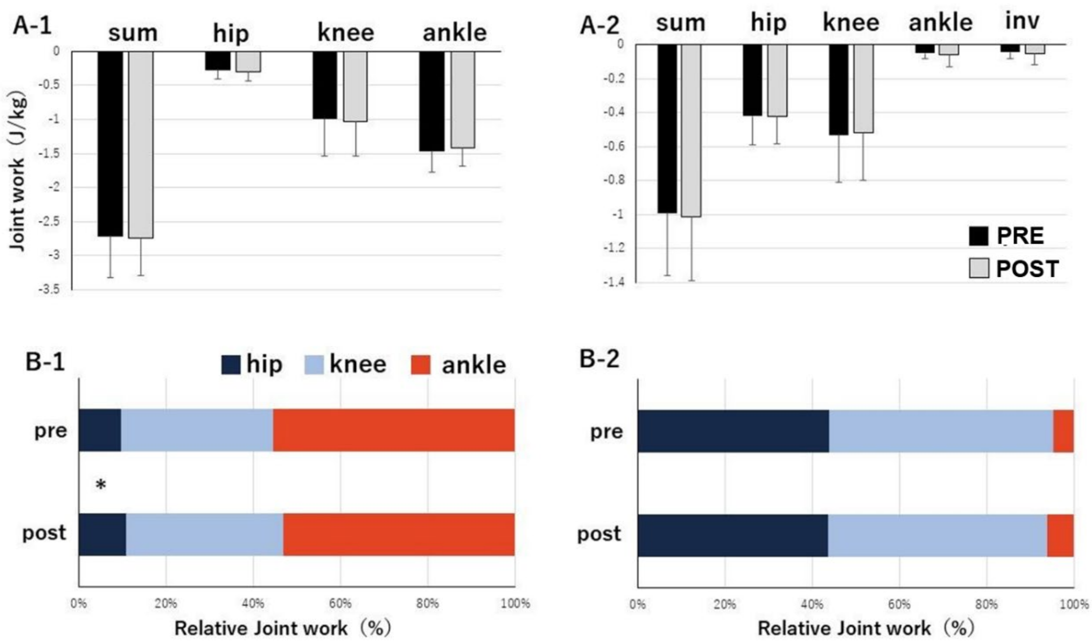

Fig.2

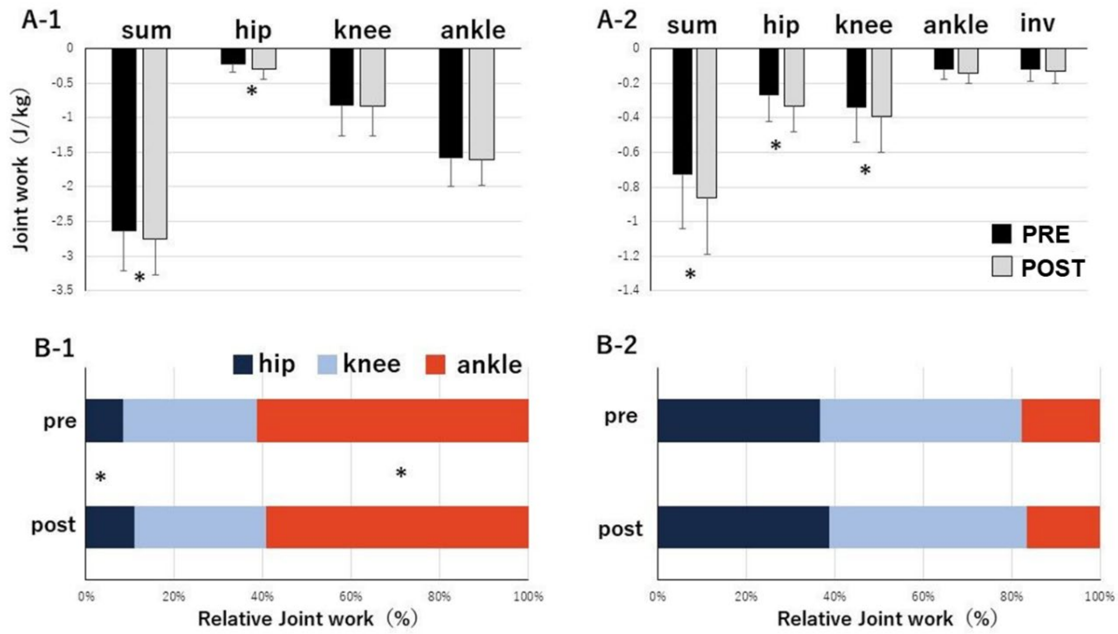
A-1
sum
hip
knee
ankle
Joint work（J/kg）
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
*
*
A-2
sum
hip
knee
ankle
inv
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
*
*
*
PRE
POST
B-1
hip
knee
ankle
pre
post
*
*
0%
20%
40%
60%
80%
100%
Relative Joint work（%）
B-2
pre
post
0%
20%
40%
60%
80%
100%
Relative Joint work（%）

Fig.3

Tables

Table 1. Mean (SD), P value, and effect size (r) for kinematics and kinetics variables during medial landing.

Sagittal	Pre	Post	p	ES
Peak power （Nm/sec・kg）				
Hip	-9.62 (6.23)	-11.39 (7.32)	.02*	.47
Knee	-17.66 (7.81)	-17.93 (8.29)	.78	.06
Ankle	-26.31 (5.65)	-26.11 (5.23)	.79	.06
Internal peak moment （Nm/kg）				
Hip Extension	2.45 (0.80)	2.79 (0.94)	.01*	.52
Knee Extension	2.22 (0.73)	2.25 (0.67)	.79	.06
Ankle Plantarflexion	2.67 (0.56)	2.71 (0.53)	.46	.16
Peak angle velocity(°/sec)				
Hip Flexion	352 (85)	377 (79)	.01*	.54
Knee Flexion	511 (87)	530 (106)	.19	.28
Ankle Dorsiflexion	985 (103)	999 (123)	.41	.18
Peak angle（°）				
Hip Flexion	34.8 (11.1)	38.7 (9.7)	< .01*	.59
Knee Flexion	46.8 (12.6)	48.9 (11.6)	< .01*	.58
Ankle Dorsiflexion	35.7 (5.0)	36.5 (4.6)	< .01*	.21
Excursion（°）				

Hip	21.0 (9.2)	23.4 (10.1)	.02*	.49
Knee	41.2 (10.8)	42.6 (10.3)	.20	.28
Ankle	59.8 (6.6)	61.5 (8.1)	.05*	.42

Frontal

	Pre	Post	p	ES
Peak power （Nm/sec・kg）				
Hip	-6.94 (4.11)	-7.84 (3.56)	.09	.36
Knee	-8.18 (4.38)	-9.22 (4.47)	.06	.39
Ankle	-3.3 (2.24)	-3.65 (1.97)	.15	.31
Internal peak moment （Nm/kg）				
Hip Abduction	2.55 (0.59)	2.72 (0.68)	.07	.39
Knee Abduction	1.51 (0.56)	1.56 (0.56)	.51	.15
Ankle Inversion	0.48 (0.19)	0.51 (0.20)	.19	.28
Peak angle velocity(°/sec)				
Hip Adduction	220 (115)	234 (87)	.31	.22
Knee Adduction	443 (121)	501 (156)	.02*	.50
Ankle Eversion	552 (129)	627 (152)	< .01*	.71
Peak angle（°）				
Hip Adduction	6.6 (5.5)	8.25 (6.7)	.06	.39
Knee Adduction	20.9 (10.9)	21.0 (10.6)	.69	.09

Ankle Eversion	23.0 (13.2)	25.0 (13.0)	.69	.42
Excursion（°）				
Hip	11.1 (5.4)	12.8 (4.2)	.03*	.47
Knee	19.6 (7.7)	20.8 (6.9)	.09	.36
Ankle	26.0 (7.0)	29.1 (7.4)	< .01*	.63

The asterisk (*) indicates significance at $p < 0.05$. All variables were analyzed during foot contact to the minimum height of the center of mass.

Table 2. Mean (SD), P value, and effect size (r) for the ankle kinetic and kinematic values in the frontal plane during forward and medial landing (Pre).

	Forward	Medial	p	ES
Frontal work （J/kg）	-0.05 (0.03)	-0.12 (0.06)	< .01*	.84
Invertor work （J/kg）	-0.04(0.04)	-0.12 (0.07)	< .01*	.87
Inversion moment (Nm/kg）	0.17 (0.13)	0.48 (0.19)	< .01*	.92
Peak eversion angle（°）	23.6 (12.7)	23.0 (13.2)	.32	.22
Peak eversion velocity（°/sec）	554 (145)	552 (132)	.91	.03
Excursion（°）	26.1 (7.5)	26.0 (7.0)	.94	.02

The asterisk (*) indicates significance at $p < 0.05$. Ankle frontal work, invertor work, peak inversion moment, peak eversion velocity, peak eversion angle, ankle frontal excursion. All variables were analyzed during foot contact to the minimum height of the center of mass.