Landing Posture in Elite Female Athletes During a Drop Vertical Jump Before and After a High-Intensity Ergometer Fatigue Protocol

A Study of 20 Japanese Women's Soccer League Players

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Background: Even elite athletes, who usually show stable postural control, sometimes cannot control their posture after high-load training. This instability may contribute to anterior cruciate ligament injury.

Purpose/Hypothesis: The purpose of this study was to evaluate the landing posture of elite female soccer players before and after a novel high-intensity fatigue-inducing exercise protocol. We hypothesized that the landing posture will change before versus after the fatigue protocol.

Study Design: Descriptive laboratory study.

Method: The study participants were 20 female elite soccer players. All athletes performed 3 drop vertical jumps (DVJs), pedaled an ergometer 8 times with full force for 10 seconds each (fatigue protocol), and then repeated the 3 DVJs. We measured and compared the athletes' blood lactate levels before and after the fatigue protocol, as well as the hip flexion, knee flexion, and ankle dorsiflexion angles and final landing posture during the DJVs.

Results: Blood lactate levels increased significantly pre- to postprotocol (from 2.7 ± 1.9 to 15.0 ± 3.6 mmol/L; $P < .001$), while there were decreases in hip flexion angle (from 35.0° ± 11.2° to 22.4° ± 8.8°; $P < .001$) and ankle dorsiflexion angle (from 26.4° ± 3.9° to 20.0° ± 3.7°; $P < .001$). The number of athletes who could not maintain a stable DVJ final landing posture increased from 10% before the fatigue protocol to 70% after.

Conclusion: The elite female athletes in our study showed significant decreases in hip flexion and ankle dorsiflexion angles in the DVJ landing after a fatigue-inducing protocol. Most elite athletes were unable to maintain a stable posture on the DVJ landing after the fatigue protocol.

Clinical Relevance: This study advances our understanding of how elite athletes land in a fatigued state.

Keywords: anterior cruciate ligament injury; fatigue protocol; postural control

Although various effective surgical procedures and rehabilitations in recent years have allowed many athletes to return to sports,[29] anterior cruciate ligament (ACL) injury is one of the most severe injuries for athletes in terms of requiring long absence from sports, early osteoarthritis,[3] and difficulties returning to preinjury performance.[7,8,25,29] Prevention of ACL injury is critical, and in the past 2 decades, several prevention protocols focusing on neuromuscular training have resulted in successful implementations and favorable effects.[30,41] However, a large number of athletes still experience ACL injuries.[15]

There are increasingly more studies evaluating postural changes before and after fatigue and the influence of fatigue on ACL injury. Some studies have reported on the joint angle placing athletes at high risk of ACL injury after fatigue; others have reported an increase in lower extremity trauma later in the game.[16,17,35,40] Neuromuscular fatigue has also been proposed to be another risk factor for noncontact ACL injuries because muscles contribute to joint stability.[5,13,26,43] McCall et al[27] confirmed fatigue and

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muscle imbalance to be injury risk factors for professional football players. Jumping is considered a fundamental movement for sports such as soccer.[33] However, it includes the risk of injury because of the loading placed on the joints during the landing motions.[1] Among studies that evaluated the landing posture of athletes after fatigue intensity, some used a set number of repetitions or a set time in which certain tasks were performed for inducing fatigue.[28,32] Those methods did not consider the different fatigue tolerance levels of participants. The most commonly used fatigue level assessment method was the rate of perceived exertion or volitional exhaustion.[9,14,26,43] In addition, all of these methods were subjective evaluations. Only a few studies were based on objective evaluations that used the rate of muscle weakness or the rate of decline in task performance.[21,26,39]

To push an athlete to a highly fatigued state, it is necessary to consider each one's tolerance for fatigue and anaerobic capacity. We developed a unique fatigue-inducing protocol by applying interval training to a full-strength pedaling test, which is usually used in post–ACL surgery rehabilitation and training. We used blood lactate levels to evaluate whether the fatigue protocol appropriately induced fatigue in athletes.

The purpose of this study was to investigate how the posture of elite athletes changes during jump landings before and after fatigue loading. As ACL injuries occur more frequently in female than male athletes,[2] we tested this protocol on players in the Japanese Women's Soccer League. We hypothesized that the effects of high-intensity loading on the landing posture of these athletes will change before versus after the fatigue protocol.

METHODS

Study Participants

A total of 20 healthy female elite soccer field players, all of whom belonged to the same soccer team of the Japanese top league, were recruited to participate in this study during the 2017 soccer season (mean ± SD; age, 23.15 ± 3.03 years; body height, 160.31 ± 4.57 cm; body mass, 53.6 ± 4.53 kg) (Table 1). None of the participants had a history of cardiovascular, respiratory, or neurologic issues or dysfunction of the lower extremity. The study was approved by the ethics committee of our institution, and all players provided informed consent.

TABLE 1
Participant Characteristics[a]

No.	Age, y	Body Height, cm	Body Mass, kg	BMI, kg/m^2
1	23	164.9	50.3	18.5
2	21	159.3	53.8	21.2
3	21	159.5	51.7	20.3
4	19	158.4	53.4	21.3
5	20	160.5	57.9	22.5
6	22	153.2	46.8	19.9
7	22	161.9	62.1	23.7
8	22	160.0	52.1	20.4
9	20	153.5	52.3	22.2
10	29	156.2	45.9	18.8
11	28	164.1	63.4	23.5
12	28	165.9	53.7	19.5
13	27	164.3	54.4	20.2
14	24	155.8	48.6	20.0
15	25	156.8	49.4	20.1
16	25	170.9	57.4	19.7
17	24	156.6	57.5	23.4
18	23	159.1	52.6	20.8
19	20	159.4	55.6	21.9
20	20	166.0	54.2	19.7

[a]BMI, body mass index.

Experimental Procedure

Pedaling Test. The fatigue-inducing exercise protocol consisted of pedaling on an ergometer (Power Max V2; Konami Sports). As a pretest, each participant performed 10 seconds of full-power pedaling at 1% body weight to warm up, followed by a 2-minute rest interval, followed by 10 seconds of full-power pedaling at 2.5%, 5%, and 10% of body weight, in that order, with a 2-minute interval between tests. We calculated the maximum anaerobic power (MAnP) for each athlete by obtaining a regression line from the peak power and peak revolutions per minute at the 3 levels of load obtained in the measurements, based on the formula of Nakamura et al.[31,44] Nakamura et al found that the regression coefficients of 2 regression equations obtained from measurements at 8 loads and 3 loads in an anaerobic exercise test with an ergometer were almost identical, with no statistically significant difference in MAnP values.

After the pretest, each player rested for ≥30 minutes. The fatigue-inducing exercise consisted of pedaling 8 times on the ergometer at MAnP for 10 seconds each, with an interval of 30 seconds between times. We called this the ergometer fatigue protocol (EFP).

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Ethical approval for this study was obtained from the Kyoto Interdisciplinary Institute of Community Medicine (ERB-18-03).

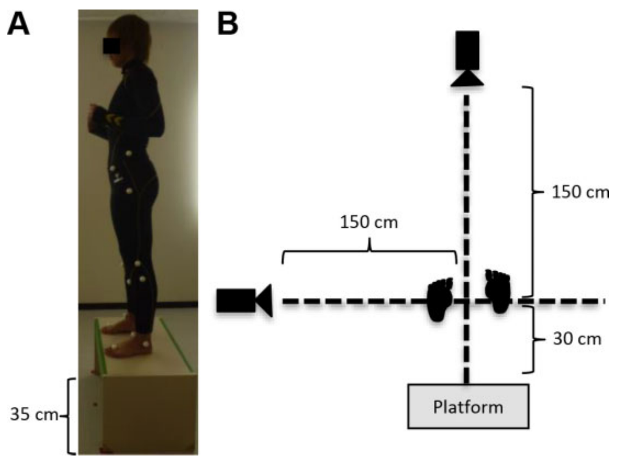

Figure 1. Setup of marker positions, platform, and video cameras for drop vertical jump task. (A) Five markers were attached to the body surface: left anterior-superior iliac spine, lateral thigh, lateral femoral epicondyle, fibular head, and lateral malleolus. (B) Two video cameras were installed with high-speed shooting (120 frames/s). Each was positioned 1.5 m from the landing point: 1 ahead of the athlete and 1 to the left side.

Drop Vertical Jump Task. The drop vertical jump (DVJ) task was described and demonstrated to each athlete. Each DVJ consisted of a leap from a 35-cm platform to the ground 30 cm ahead (first landing), then a vertical jump with maximum power and landing (final landing). Each participant was not allowed to practice each task, and no instructions regarding jumping techniques were given to avoid coaching effects on the natural performances of these tasks. Five markers were attached to the body surface—at the left anterior-superior iliac spine, lateral thigh, lateral femoral epicondyle, fibular head, and lateral malleolus—and 2 video cameras were installed: one 1.5 m ahead of the participant and the other 1.5 m to the left side (Figure 1).

Measurement of Blood Lactate Level. As an objective indicator of fatigue, the blood lactate level of each athlete was measured with a meter (Lactate-Pro LT-1730; Arcray). Levels were measured by collecting capillary blood samples from the participant's fingers. The cutoff threshold for fatigue was considered a blood lactate concentration of 4 mmol/L.[20,42]

Experiment. After height and weight measurement, each player underwent the pedaling pretest, then rested for ≥ 30 minutes. We measured the blood lactate level at rest. Next, each participant performed 3 DVJs, followed by the EFP. We measured the blood lactate level within 3 minutes after the EFP. Finally, each performed 3 DVJs within 5 minutes after performing the EFP (Figure 2).

Evaluation

Images from the videos were captured with QuickTime Player (Apple). Images were played back frame by frame, and the first point (FP) at which the entire plantar surface was grounded was selected. We used ImageJ (National Institutes of Health) for image analysis. Hip flexion, knee flexion, and ankle dorsiflexion angles of FP were measured during the first landing (Figure 3). All joint angles were measured twice by an examiner (A.K.) and once by another examiner (K.H.) in a blinded manner using computer software to assess intra- and interobserver reliability. We also observed the movement after initial contact during the final landing, and 2 examiners (A.K., S.Y.) classified the movements into 4 groups:

Success: able to maintain balance while landing without moving foot position
Moved forward: able to maintain balance in a standing position after moving the foot ground position forward
Moved backward: able to maintain balance in a standing position after moving the foot ground position backward
Fell backward: falls backward without maintaining the standing position after landing

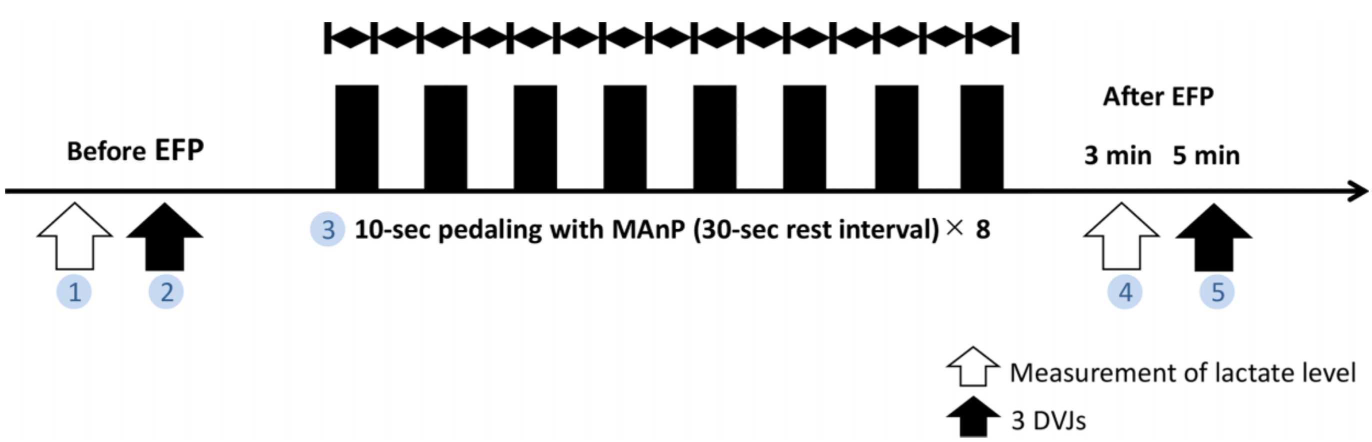

Figure 2. Experimental procedure. Measurement of lactate level before the EFP (*1*). Performance of 3 DVJs (*2*). Performance of the EFP: pedaling at MAnP 8 times for 10 seconds each, with a 30-second rest between times (*3*). (*4*) Blood lactate level measured within 3 minutes after the EFP (*4*). Performance of 3 DVJs within 5 minutes after the EFP (*5*). DVJ, drop vertical jump; EFP, ergometer fatigue protocol; MAnP, maximum anaerobic power.

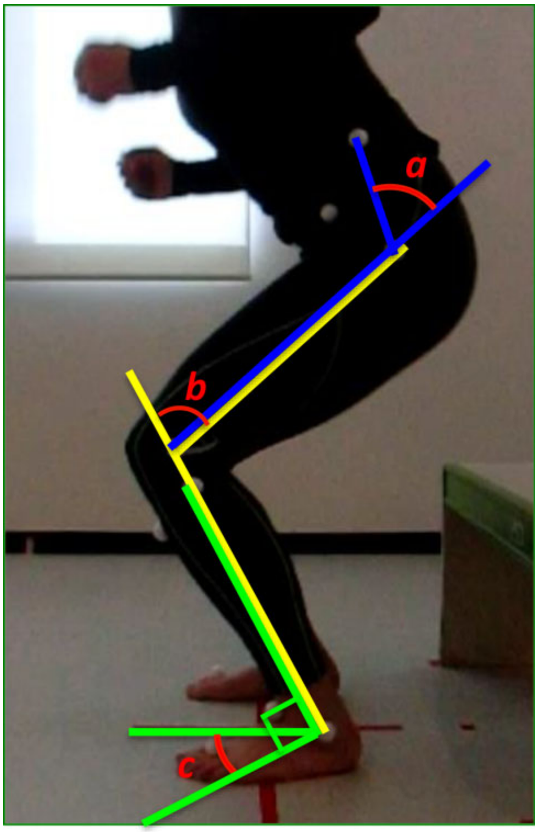

Figure 3. Angle measurements as shown on the first landing during a drop vertical jump: *a*, hip flexion angle; *b*, knee flexion angle; *c*, ankle dorsiflexion angle.

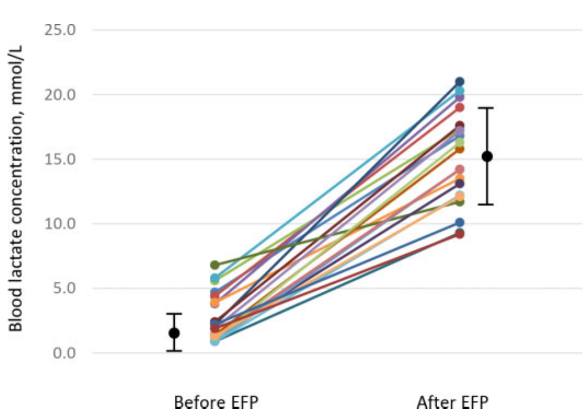

Figure 4. Changes in blood lactate level. Colored lines, individual participants; black dot, overall mean; error bars, SD. EFP, ergometer fatigue protocol.

We defined the successful landing as "stable posture" and the other 3 movements as "unstable posture."

Statistical Analysis

All statistical analyses were conducted in SPSS (Version 21; SPSS Inc), and the alpha level was set at .05. Cohen effects sizes were calculated for variables to compare them before versus after the EFP. Intra- and interobserver reliability was measured by the intraclass correlation coefficient.

Results were analyzed using StatView 5.0 (Abacus Concepts). The Wilcoxon signed-rank test was used to compare DVJ joint angles on the first landing before versus after the EFP, and the Fisher exact test was used to compare the postures on the final landing (stable vs unstable) before versus after the EFP. $P \leq .05$ was considered significant.

A post hoc power analysis was performed using G*Power 3.[12] For a total sample size of 20 and type I error (α) of .05, the study was expected to provide a power ($1 - \beta$) of 0.81 for detecting an effect size (ω) of 0.6.

TABLE 2
Change in Joint Angle Before and After the EFP[a]

	Before EFP	After EFP	P^b	Effect Size
Angle, deg				
Hip flexion	35.0 ± 11.2	22.4 ± 8.8	**<.001**	–0.56
Knee flexion	50.0 ± 5.9	49.1 ± 6.1	.91	–0.02
Ankle dorsiflexion	26.4 ± 3.9	20.0 ± 3.7	**<.001**	–0.65

[a]Data are presented as the mean ± SD of 3 drop vertical jumps measured at the first landing. EFP, ergometer fatigue protocol.
[b]Bold *P* values indicate statistically significant difference before vs after the EFP ($P \leq .05$).

RESULTS

Blood Lactate Concentration

The blood lactate concentrations of all participants after the EFP were beyond 4 mmol/L, indicating fatigue. The blood lactate concentration increased significantly from pre-EFP (2.7 ± 1.9 mmol/L) to post-EFP (15.0 ± 3.6 mmol/L [$P < .001$]; effect size, –0.86) (Figure 4).

Joint Angles on DVJ Before and After the EFP

The correlation coefficients for the intra- and interobserver reliability were >0.85 (range, 0.87-0.92) and >0.80 (range, 0.82-0.92), respectively, indicating excellent agreement for both. Table 2 shows the joint angle measurements. Hip flexion and ankle dorsiflexion were significantly lower after the EFP (hip, 22.4° ± 8.8°; ankle, 20.0° ± 3.7°) than before the EFP (hip, 35.0° ± 11.2° [$P < .001$]; ankle, 26.4° ± 3.9° [$P < .001$]). There were no significant differences in knee flexion (Figure 5).

Posture on the Final DJV Landing

Before the EFP, there were 18 players with stable posture and 2 with unstable posture (2 moved backward) on the final DVJ landing; after the EFP, 6 players had a stable posture and 14 had an unstable posture (1 moved forward, 10 moved backward, 3 fell backward). These posture evaluations were the same by both examiners. The percentage of athletes with stable posture was 90% before the EFP

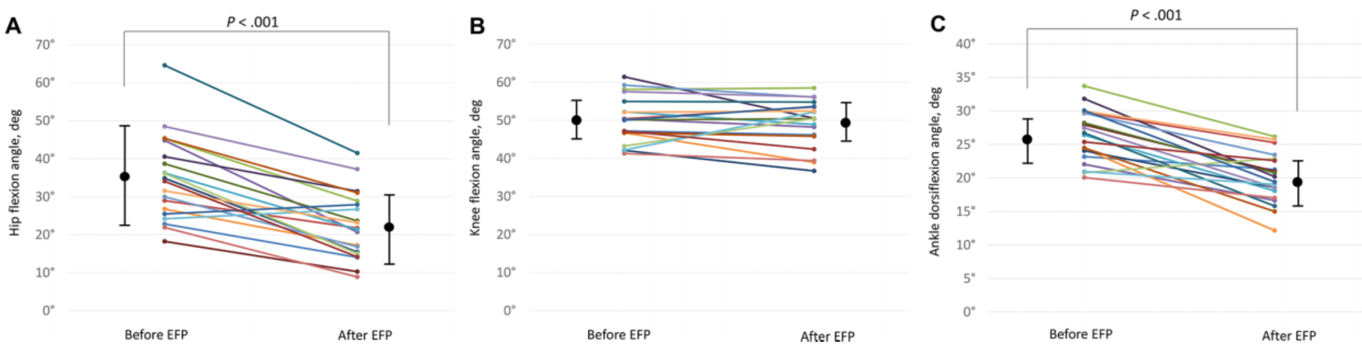

Figure 5. Changes in (A) hip flexion, (B) knee flexion, and (C) ankle dorsiflexion angles before vs after the ergometer fatigue protocol (EFP). Colored lines, individual participants; black dot, overall mean; error bars, SD.

TABLE 3
Landing Postural Changes Before and After the EFP for Each Athlete[a]

No.	Before EFP	After EFP
1	Success	Moved backward
2	Success	Fell backward
3	Success	Fell backward
4	Success	Success
5	Success	Success
6	Success	Moved forward
7	Success	Success
8	Success	Moved backward
9	Moved backward	Moved backward
10	Moved backward	Moved backward
11	Success	Moved backward
12	Success	Moved backward
13	Success	Moved backward
14	Success	Moved backward
15	Success	Moved backward
16	Success	Success
17	Success	Moved backward
18	Success	Success
19	Success	Fell backward
20	Success	Success

[a]Success was considered a stable posture, and the other 3 movements were considered unstable postures. EFP, ergometer fatigue protocol.

but significantly decreased to 30% after the EFP (odds ratio, 0.05 [95% CI, 0.05-0.32]; $P < .001$) (Table 3).

DISCUSSION

The main finding of this study was that hip flexion and ankle dorsiflexion angles at FP were significantly less after fatigue-induced exercise as compared with baseline values; however, knee flexion angles did not change. More athletes moved backward after the initial contact on the final landing as compared with baseline.

Using different fatigue protocols and measurements, previous studies on changes in postural stability, joint angles, and other parameters in healthy athletes have reported variable outcomes.[3,4,37,45] Despite several systematic reviews about the relationship between fatigue protocol and ACL injury, whether fatigue increases the risk of ACL injury remains controversial.[3,4] Bourne et al[6] argued that changes in movement associated with fatigue are changes that avoid ACL injury. As such, more research is needed to assess athletes' responses before and after exercise with fatigue to better understand the clinical impact of fatigue on ACL injury. It is also warranted to develop protocols that can evaluate different types of athletes under such conditions as those on the field, in general gymnasiums, or in rehabilitation rooms.[19]

We used a unique fatigue protocol that consists of individual intensity for each athlete. Fatigue loads were applied on participants with their personal load strengths measured before the protocol. Barber-Westin and Noyes[3] stated that it is necessary to consider potential interparticipant variability in cardiovascular and muscular endurance to not confound biomechanical findings, because each athlete has unique parameters, including complex intrinsic factors. Additionally, the method used in this study to assess fatigue is considered appropriate. As studies about fatigue and decision making indicated that a short bout of exercise at a high intensity results in a decrement in cognitive processing (eg, longer reaction times) whereas exercise at a moderate intensity does not,[11,36] we had to make a severe fatigue condition. In this study, we confirmed that the blood lactate concentration—an objective index for evaluating level of fatigue—was above the standard 4 mmol/L in all participants after loading[20] and significantly increased from baseline to post-EFP. Direct measurement of blood lactate is a more accurate measure of fatigue than the method based on lactate threshold heart rate.[18,34] This suggests that our protocol is an appropriate protocol that can push players to exhaustion, not only consciously but objectively.

In the present study, although players were not provided any guidance to perform the DVJ safely, 90% succeeded in a stable landing. The target team was a group of top athletes with the ability to perform the stable landing motion without any load. We believe that most elite athletes who have knowledge of safe landing postures can maintain them and avoid risky postures in games, because of the favorable result of introducing some prevention protocols.[30]

Nevertheless, the success rate in landing in a stable posture significantly decreased from 90% before the EFP to 30% after the EFP, suggesting that even elite athletes who have the ability to keep a stable landing posture could not do so after a fatigue-inducing exercise protocol.

Hip flexion and ankle dorsiflexion angles significantly decreased after the participants experienced a high-intensity load, but knee flexion angle did not significantly change. Considering that some previous studies with high-risk groups of ACL injury reported that decreased knee flexion angle caused unstable landing movements with a higher risk of ACL injuries and falls,[10,22,38] the result of our study might suggest that athletes under a fatigue condition encounter a landing posture that is different from the high-risk landing posture of ACL injuries made by high-risk athletes. During the first landing in the DVJ (ie, heel-ground contact just before a vertical jump), the ankle dorsiflexion and hip flexion angles were reduced. This suggests that whatever the knee joint flexion angle was, the center of gravity shifted backward in the sagittal section, indicating that a backward balance tilt had already occurred at the first landing. Furthermore, in the current study, all but 1 of the unstable landing postures identified in the final landing assessment was a backward shift.

The present study provides knowledge that in a highly fatigued state, the ankle dorsiflexion and hip flexion angles may be smaller than before fatigue when subsequent jumping movements are required. Because the reaction time after ground contact to detect danger is at least 150 to 200 ms whereas an ACL injury occurs only 40 ms after ground contact,[23,24] emphasis has been placed on strengthening athletes in terms of feedforward strategies rather than feedback strategies. Therefore, knowledge of joint angle during landing that can occur at high fatigue levels may be important information for athlete education for injury prevention. Ideally, sports physicians and therapists with commonly equipped rehabilitation rooms will use this fatigue protocol to evaluate postural changes before and after fatigue in athletes of varying activity levels and provide feedback to them, and we hope that this study will provide new insights for future research.

Limitations

This study is not without limitations. First, we used 2-dimensional evaluation from only the left side. Future research needs to analyze postures in more detail by using devices capable of 3-dimensional evaluation. Nevertheless, 2-dimensional evaluation is a useful method for smaller-scale facilities or fields with a small number of staff members evaluating the posture change of athletes. Second, this study was unable to offer specific suggestions, such as indicating the muscles that athletes should strengthen to perform landing movements under fatigue as well as before fatigue. The reason is that no tests were conducted in this study to identify the muscles that are active during landing movements. A more detailed approach to this consideration is needed in the future.

CONCLUSION

The elite female athletes in our study showed significant decreases in hip flexion and ankle dorsiflexion angles in the DVJ landing after a fatigue-inducing protocol. Most elite athletes were unable to maintain a stable posture on the DVJ landing after the fatigue protocol.

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