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Original Article

Knee dynamics during take-off and landing in spike jumps performed by volleyball players with patellar tendinopathy

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Abstract. [Purpose] Patellar tendinopathy is a common sports injury. The risk factors for this injury can be categorized as intrinsic, extrinsic, and dynamic. We examined the dynamic factors in this study. [Participants and Methods] The participants were volleyball players who were assigned to a patient group (n=6) if they had medial patellar tendinopathy in the left knee or to a control group (n=7) otherwise. The participants performed spike jumps, and their ground reaction force and three-dimensional kinematic data were recorded. Knee angle and moment data were extracted at the peak extension moment of take-off and landing. [Results] The two groups showed no differences in knee angles. A tendency for abduction/external rotation moments at take-off and landing on both sides was observed in the control group, while the patient group showed adduction and internal rotation moments at take-off and adduction moment at landing in the left (injured) knee. [Conclusion] The observed knee joint moments in the left (injured) knee of the patient group may have been involved in the pathophysiological mechanism underlying the development of patellar tendinopathy.

Key words: Patellar tendinopathy, Jumper's knee, Biomechanical risk factors

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INTRODUCTION

Patellar tendinopathy (jumper's knee) is a common injury in sports that involve jumping actions. The prevalence of patellar tendinopathy varies by sport according to differences in loading characteristics on the knee joints. For example, although the overall prevalence of jumper's knee in non-elite athletes from 7 popular sports in the Netherlands was 8.5%, it was highest among volleyball players (14.4%) and lowest among soccer players (2.5%)[1)]. In Norway, the overall prevalence in elite national athletes from 9 sports was 14.2% but was much higher in volleyball (44.6%) and basketball (31.9%)[2)]. Similarly, the prevalence in elite volleyball players was 22.8% in Italy[3)]. The findings of much higher prevalence in elite and national volleyball players regardless of country suggest that the repetitive and higher load exerted on the patellar tendon during the extension of knee joints due to strong jumping actions is strongly involved in the pathophysiological mechanisms underlying the onset of the patellar tendinopathy[4–9)].

Various risk factors have been reported for the development of patellar tendinopathy. These factors fall into three categories: intrinsic, extrinsic, and dynamic[10)]. Intrinsic factors include abnormality in lower limb alignment[4, 11, 12)], male sex[13–15)], and high body mass index (BMI)[15)]. Extrinsic factors include playing floor with a hard surface[10, 16)], excessive training[11, 13, 17–19)], and heavy physical load[15)]. Several studies have also suggested the importance of dynamic biomechanical factors acting on

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*Corresponding author. Kazuhiro Obara (E-mail: kaz@pb3.so-net.ne.jp) knee joints during both take-off and landing in jump actions in the development of patellar tendinopathy[20–25]. Specifically, these studies demonstrated that the development of patellar tendinopathy is associated not only with the angles of the ankle and hip joints in addition to the knee joints but also with the increase in the load exerted on the patellar tendon. Although each study showed an excessive load exerted on the knee extension mechanism, the dynamic biomechanical factors that were common to each study have not been investigated. Therefore, we do not know which dynamic biomechanical factors are critical. This might be due to differences in the inclusion criteria of each study, including current or previous history, symptomatic or asymptomatic, and unilateral or bilateral. Furthermore, patients with patellar tendinopathy occurring in different locations were intermingled, including proximal or distal, and medial, central or lateral. Because patellar tendinopathy is localized and can develop in many locations[26, 27], we hypothesized that the dynamic biomechanical changes specific to each side are what causes patellar tendinopathy. To test this hypothesis, we examined knee joint angles and moments at take-off and landing during a spike jump action that produces a strong impact against the knee extension mechanism. In particular, we focused on patellar tendinopathy that developed in the medial region of the proximal attachment of the patellar tendon to the inferior pole of the patella of the left knee and selected volleyball players who developed this type of patellar tendinopathy. The intrinsic and extrinsic factors of the control and patient groups were matched as closely as possible. We found significant differences between the groups in knee joint moment at take-off and landing. However, no differences were observed in knee joint angles. Based on these findings, we consider the pathophysiological mechanisms that dynamically act on the knee joint and lead to the development of patellar tendinopathy.

PARTICIPANTS AND METHODS

Participants were volleyball players who belonged to competitive high school and university volleyball teams in Hokkaido, Japan. The participants, who were all skilled spikers, were assigned to a control group (n=7) or a patient group (n=6). They had no histories of surgery, trauma, effusion, or instability in the knee joints. They were considered right-hand dominant as well as right-leg dominant on the basis of their preferred kicking leg, and they preferred a right–left, step-close take-off technique when performing the spike jump. Both groups were matched by age, weight, height, leg length, BMI, training time, and years of exposure (Table 1). The participants in the control group (5 males and 2 females) were healthy, with no history of knee pain or injury in the lower limbs. The participants in the patient group (5 males and 1 female) underwent an examination by a skilled orthopedist specializing in sports medicine and were assigned to the patient group based on the following criteria: (1) tenderness localized at the medial section of the proximal attachment of the patellar tendon to the inferior pole of the patella of the only left knee; (2) stage 1 tendinopathy (pain after practice or after a game), according to the symptoms described by Blazina et al.[4] and modified by Roels et al.[28]; (3) no history of knee pain during exercise. Written informed consent was obtained from each participant before data collection, and parental/guardian consent was obtained for minors. This study was approved by the Asahikawa Medical University Research Ethics Committee (16085).

Three-dimensional data of reflective markers (14-mm diameter spheres) placed on the participants' bodies were collected at a sample rate of 60 Hz using a 5-camera motion analysis system (VICON370; Oxford Metrics Ltd., Oxford, UK). Ground reaction force data were recorded at 1,050 Hz using two AMTI force platforms (LG6-4-1; Advanced Mechanical Technology, Inc, Watertown, MA, USA) embedded in the floor.

All participants wore their own shoes for volleyball and followed a warm-up and stretching routine. The reflective markers were tightly placed bilaterally on the following anatomical landmarks: the acromia, greater trochanters, lateral and medial femoral epicondyles, lateral and medial malleoli, and first and fifth metatarsal heads. Each participant completed a standing static calibration, followed by a series of spike jump trials. They took 3 or 4 approach steps prior to take-off and performed the spike jump with maximum effort, simulating a game-speed spike. Each participant performed three spike jump trials. After the trials, the participants were allowed sufficient time to cool down. During the course of the study, no participant developed another injury or exacerbated their patella tendinopathy.

Table 1. Characteristics of participants in the control and patient groups

	Control group (n=7)	Patient group (n=6)
	Male=5 Female=2	Male=5 Female=1
Age, years	20.3 (3.2)	18.5 (1.9)
Weight, kg	64.7 (5.4)	63.9 (8.1)
Height, cm	172.9 (6.7)	173.3 (6.6)
Leg length, cm	93.6 (3.1)	93.1 (7.6)
BMI, kg/m^2	21.8 (1.7)	21.2 (1.8)
Training time, hours/week	15.9 (4.0)	15.5 (2.3)
Exposure, years	7.9 (1.9)	6.7 (1.4)

Mean (standard deviation). BMI: body mass index.

Both the three-dimensional data of the reflective markers and the ground reaction force data were filtered using a fourth-order zero-lag Butterworth low-pass filter of 20 Hz29), which was synchronized at 60 Hz using Workstation software (Oxford Metrics Ltd.). Kinematic and kinetic calculations were performed using the processing software BodyBuilder (Oxford Metrics Ltd.). Reflective markers were used to construct anatomical coordinate systems for the trunk, thigh, shank, and foot segments. Knee joint angles were calculated using Cardan angles (a process that is equivalent to resolving about a joint coordinate system)30), and the knee joint angles during the spike jump were derived from the static position.

Knee joint moments were expressed as net internal moments and normalized by body mass (kg), gravity (9.81 m/s^2), and leg length (m)31).

We compared the mean values and standard deviations (SD) of knee joint angles and moments in the sagittal (flexion–extension), coronal (abduction–adduction), and axial (external–internal) planes between the control and patient groups at the moment when the extension moment reached its peak during take-off and landing. The data were analyzed using Mann–Whitney U-test to determine whether there were any significant differences ($p<0.05$). Statistical analyses were conducted using the software package BellCurve for Excel (Social Survey Research Information Co., Ltd., Tokyo, Japan).

For each participant, we further elucidated the direction of the ground reaction force vector in relation to the position of the knee joint at the moment when the extension moment reached its peak during take-off and landing by using the Workstation software (Fig. 1).

RESULTS

The periods during which extension moment reached its peak during take-off and landing were defined as peak take-off and peak landing, respectively. Table 2 shows the mean values and SDs of the knee joint angles at peak take-off and peak landing in the control and patient groups. There were no significant differences in the knee joint angles of both sides between the two groups. In both groups, the right knee joint tended to align with flexion, adduction, and internal rotation at peak take-off and landing, whereas the left knee joint tended to align with flexion, abduction, and internal rotation at peak take-off, and with flexion, adduction, and internal rotation at peak landing.

In contrast to the angles, knee joint moments acting on the injured side of the patient group differed from those of the control group, particularly the abduction-adduction and external-internal rotation moments. The results are shown in Table 3, including the mean values and SDs of the knee joint moments at peak take-off and landing in the control and patient groups.

At peak take-off, the knee joint moments in the right knee in both groups were in the direction of extension, abduction, and external rotation, and there were no differences between the two groups. In the control group, the left knee joint moments were in the direction of extension, abduction, and external rotation, whereas in the patient group, they were in the direction of extension, adduction, and internal rotation; significant differences were observed in the abduction–adduction and external–internal rotation moments.

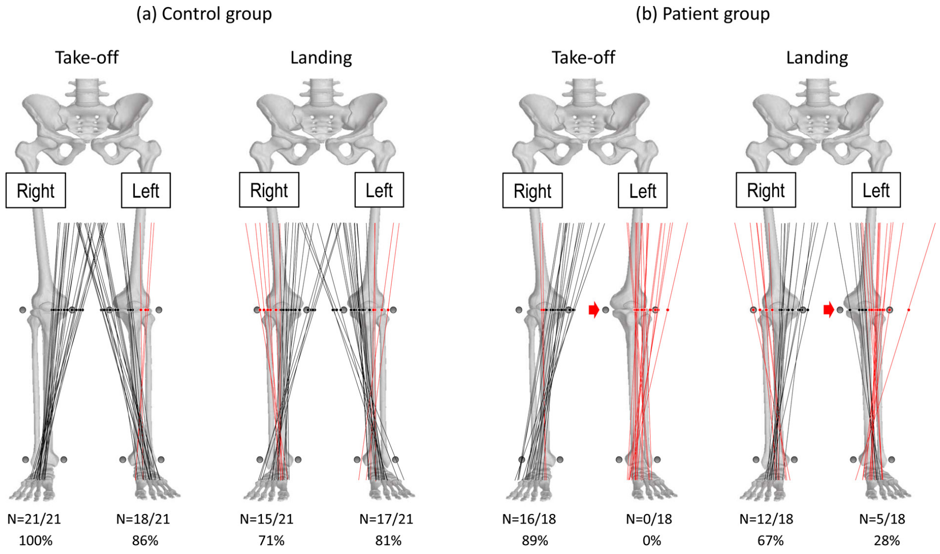

Fig. 1. Direction of ground reaction force vectors in relation to the position of the knee joints.
In (a) and (b), the direction of ground reaction force vectors generated when the extension moment reached its maximum at take-off (left sides) and landing (right sides) are shown together with overlapping frontal view of the lower body, including the pelvis and bilateral legs. Underneath each drawing, the number and percentage of the vectors that passed the medial side of the knee joints are shown together with the total numbers of vectors.

Table 2. Knee joint angles in spike jump movements

			Control group	Patient group
Take-off				
	Right	Flex	75.8° (20.0°)	82.4° (12.0°)
		Abd	−5.48° (5.37°)	−5.76° (6.60°)
		ER	−12.9° (8.80°)	−10.5° (9.55°)
	Left	Flex	75.4° (11.7°)	73.9° (11.1°)
		Abd	2.64° (6.92°)	5.30° (9.65°)
		ER	−8.99° (7.34°)	−8.40° (11.7°)
Landing				
	Right	Flex	64.2° (16.9°)	67.3° (12.7°)
		Abd	−3.11° (6.53°)	−4.61° (8.18°)
		ER	−8.05° (7.05°)	−5.74° (15.0°)
	Left	Flex	65.4° (13.9°)	68.0° (10.8°)
		Abd	−0.51° (6.44°)	−4.94° (9.69°)
		ER	−2.26° (8.45°)	−2.85° (11.8°)

Mean (standard deviation). Flex: flexion; Abd: abduction; ER: external rotation.

Table 3. Knee joint moments in spike jump movements

			Control group	Patient group
Take-off				
	Right	Ext	2.79×10^{-1} (4.41×10^{-2})	2.29×10^{-1} (4.74×10^{-2})
		Abd	5.05×10^{-2} (3.40×10^{-2})	2.96×10^{-2} (3.22×10^{-2})
		ER	3.00×10^{-2} (1.70×10^{-2})	3.86×10^{-2} (1.87×10^{-2})
	Left	Ext	2.50×10^{-1} (4.70×10^{-2})	2.67×10^{-1} (1.76×10^{-2})
		Abd**	4.14×10^{-2} (4.58×10^{-2})	-7.42×10^{-2} (4.41×10^{-2})
		ER*	1.07×10^{-2} (1.01×10^{-2})	-8.57×10^{-3} (1.73×10^{-2})
Landing				
	Right	Ext*	2.36×10^{-1} (5.72×10^{-2})	1.71×10^{-1} (2.56×10^{-2})
		Abd	1.89×10^{-2} (4.70×10^{-2})	-1.18×10^{-2} (2.83×10^{-2})
		ER	5.50×10^{-3} (1.46×10^{-2})	1.06×10^{-2} (1.74×10^{-2})
	Left	Ext	2.48×10^{-1} (2.98×10^{-2})	2.13×10^{-1} (7.40×10^{-2})
		Abd*	4.57×10^{-2} (4.53×10^{-2})	-2.49×10^{-2} (6.66×10^{-2})
		ER	1.09×10^{-2} (1.66×10^{-2})	4.56×10^{-3} (2.06×10^{-2})

Knee joint moments were normalized to body mass (kg), gravity (9.81 m/s^2), and leg length (m).
Mean (standard deviation).
Ext: extension; Abd: abduction; ER: external rotation.
*$p<0.05$; **$p<0.01$.

At peak landing, the knee joint moments in both knees were in the direction of extension, abduction, and external rotation in the control group, whereas in the patient group, they were in the direction of extension, adduction, and external rotation. In the right knee at peak landing, the extension moment was higher in the control group than in the patient group, and the difference was significant. Although the direction of the abduction–adduction moment differed between the two groups in the right knee at peak landing, the difference was not significant. In the left knee at peak landing, there were no significant differences in the extension and external rotation moments, but there was a significant difference in the abduction–adduction moment as in peak take-off.

Figure 1 shows the ground reaction force vectors generated in both legs of each participant for all trials are shown in the frontal view of the standardized leg skeleton diagram. The vectors arising from the floor were aligned at the height of the middle of the thigh. Vectors in black and red are those passing through the medial and lateral sides of the knee joint, respectively.

In the 7 control group participants, the ground reaction force vectors of the right and left legs at peak take-off passed through the medial side of the knee joint with probabilities of 100% (n=21/21) and 85.7% (n=18/21), respectively (the left panel in Fig. 1a). At peak landing (the right panel in Fig. 1a), the majority of the vectors similarly passed through the medial side of each knee joint (right: 15/21=71.4%, left: 17/21=81.0%).

In the 6 patient group participants (Fig. 1b), the ground reaction force vectors of the right (healthy) legs at peak take-off passed through the medial side of the knee joint (16/18=88.9%). However, the vectors of the left (tendinopathic) legs did not pass through the medial side (0/18=0%) but went through the lateral side of the knee joint instead. At peak landing, although two-thirds of the vectors of the right (healthy) leg passed through the medial side (12/18=66.7%), only just under 30% (5/18=27.8%) of the vectors of the left (tendinopathic) leg passed through the medial side of the knee joint.

DISCUSSION

In this study, with the aim of identifying dynamic factors, we attempted to match intrinsic and extrinsic factors between the control and patient groups to the extent possible. Accordingly, we selected participants in the patient group who had tenderness localized at the inferior pole of the medial section of the left patellar tendon. Furthermore, because participants with a previous or current history of knee joint pain might acquire movements adapted to the pain, we selected patellar tendinopathy patients with no history of knee pain during activity. However, a limitation of this study is its small sample size. Only 7 control participants and 6 patient participants satisfied the selection criteria, so we cannot disregard the possibility of sampling bias. Thus, the results may not be sufficient to offer a solid conclusion, and further examination may be necessary to verify the present findings in terms of the common dynamic characteristics of the medial type of patellar tendinopathy.

The novel findings of this study are summarized as follows. First, there were no significant differences in knee joint angles at either peak take-off or peak landing between the control and patient groups. Second, specific joint moments were observed in the knee joints with patellar tendinopathy in the patient group. The control group exhibited abduction and external rotation joint moments at both peak take-off and landing. Although the uninjured (right) side of the knee in both groups exhibited abduction and external rotation moments, knee joints with tendinopathy (left) showed adduction and internal rotation joint moments at peak take-off. Third, the direction of ground reaction force vectors at peak take-off differed between the control and patient groups. The vectors of the control group passed mostly through the medial side of the knee joints. However, in the patient group, the vectors passed through the lateral side of the knee joint in the tendinopathic (left) leg but through the medial side in the healthy (right) leg (Fig. 1).

There are many reports concerning the mechanisms of patellar tendinopathy based on kinetic analysis. For example, Richards et al. employed logistic regression analysis to evaluate the data of kinetic studies in an attempt to predict the occurrence of patellar tendinopathy20). They concluded that the probability of patellar tendinopathy was greatest when high impact forces and a high rate of force development in the knee extensor mechanism were combined with substantial tibial external moments and deep knee flexion. Conflicting results were also reported in which patients with patellar tendinopathy showed a reduced load-reducing effect not only on the knee joint but also on the ankle joint during jumping21, 22). Meanwhile, Edwards et al. suggested that risk factors in the development of patellar tendon abnormality and, in turn, patellar tendinopathy did not include the magnitude of the patellar tendon load but rather the different patterns of that load that were produced by altered recruitments of muscle contractions acting on hip, knee, and ankle joints23). Sorenson et al. found it hard to conclude whether the observed dynamics in patellar tendinopathy patients were the cause of the injury or instead an adaptation to the injury24). The findings of the above kinematic studies are possibly involved in the pathophysiology of patellar tendinopathy. However, it remains unclear whether there is a common mechanism underlying the development of patellar tendonitis or whether patellar tendinopathy develops through various different mechanisms. One reason for this finding may be that the injured sites in participants with patellar tendinopathy in each study differed and that the pre-existing group and the unaffected group were mixed.

Edwards et al. pointed out the possibility that the knee joint angles with greater abduction and internal rotation might be one of the mechanisms by which the load on the medial and midsection of the proximal part of the patellar tendon increased23). Similarly, in the present study, the angles of the left knee joints at peak take-off exhibited abduction and internal rotation in both the control and patient groups. Therefore, changes in joint angle alone are unlikely to be a cause of patellar tendinopathy. As for the pathophysiological basis of patellar tendinopathy, we propose the possibility that the direction of knee joint moments acting on the injured side in the patient group differed from that in the control group. Specifically, during the period when extension moments reach their maximum (e.g., peak take-off), the knee joints of the control group had abduction and external rotation moments (Fig. 2a), whereas the knee joints of the patient group exhibited adduction and internal rotation moments (Fig. 2b). Such abnormal alterations of knee joint moments may increase the excessive load, or tension, to the medial section of the patellar tendon when the extension moment is largely increased. Furthermore, because the adduction moments were also generated at peak landing in the patient group, the altered and abnormal load possibly acted on the medial section of the patellar tendon during this period. Consequently, repetitive jumping movements that generate such an abnormal and excessive load in the medial section of the patellar tendon may cause the development of patellar tendinopathy.

The observation of the direction of ground reaction force vectors obtained using Workstation software can be more useful because the vectors of the damaged side passed through the lateral side of the knee joint at take-off without exception. Although the question of whether players who have the same kinetic characteristics will develop patellar tendinopathy

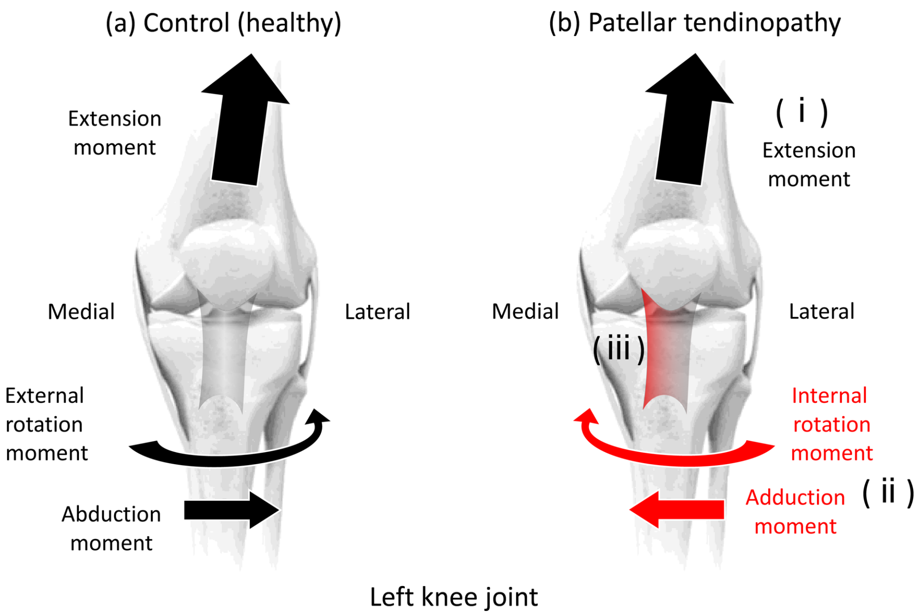

Fig. 2. Possible pathophysiological mechanisms of patellar tendinopathy in our patients.
(a) In the control group, the abduction and external rotation moments are generated when the maximum extension moment is acting on the left knee joint at peak take-off.
(b) In the patellar tendinopathy patient, a strong extension moment at peak take-off leads to a strong contraction of knee extensor muscles (i), which increases the tension of the patellar tendon. Here, the adduction moment together with the internal rotation moment (ii) may excessively increase the load acting on the medial section of the patellar tendon (iii), resulting in damage to the medial part of the patellar tendon.

remains, correcting the jumping motion form may be necessary to prevent players from developing patellar tendinopathy. Accordingly, elimination of the dynamic pathophysiological factors described in this study, in addition to intrinsic and extrinsic factors, may play a role in preventing patellar tendinopathy in athletes who frequently engage in jumping motions.

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Conflicts of interest

There are no conflicts of interest to disclose.

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