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Measurements of joint moment and knee flexion angle of patients with anterior cruciate ligament deficiency during level walking and on one leg hop

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1. Introduction

There are several kinds of evaluating methods of joint function for anterior cruciate ligament (ACL) injured knees: some are based on mainly subjective assessment [11,12] and others are those combining subjective assessment, and instrumented measurements of knee stability and muscle strength recovery [8]. Functional testing including various sort of runs and hops are occasionally used for evaluating higher athletic ability of patients with ACL injuries [2,20]. More detailed analysis using floor reaction force measurements, electromyography (EMG) and three-dimensional position sensor system are undertaken to clarify motion and function that could not be analyzed only by such clinical functional assesments [1, 23]. Those systematic instrumented analyses have been used for assessing more useful training programs [9,23], evaluating usefulness of bracing [6], and clarifying gait characteristics in patients of varus leg deformity with ACL injuries [19]. Each evaluating method has its own features and limitations, and they are selected depending on usefullness, time and cost efficacy or equipments and time availability.

Gait is fundamental motion for human beings. Gait analysis has been used for analyzing the functional impairment of patients with the ACL deficiencies. Berchuck et al. reported that 75% of patients with ACL deficiency have “quadriceps avoidance gait” which has been recognized as a characteristic gait pattern of patients with ACL deficiency [4]. They showed that there were no clear differences between injured and uninjured limbs in joint moment analysis, and the joint moment of the uninjured limb was also abnormal. A “quadriceps avoidance gait” has been reaffirmed as a characteristic gait pattern using EMG [7]. In the report, the differences between the injured and uninjured limbs were also shown.

Changes of knee extension angles [16] and synovial reaction after ACL injuries [17] suggested that every patient with the same ACL injuries would differ from each other with regard to joint stiffness and fuctional condition depending on the period after injuries, even if the recovery course after the injury has a common trend. Furthermore, there are possibilities that leg function of every patient will differ

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depending on accompanying meniscal injuries and muscle strength recovery. Some 25% exception who did not show “quadriceps avoidance gait” will also suggest such individual differences in functional condition after ACL injuries.

Functional tests of higher level of athletic activities have been used for evaluating sporting abilities of patinets with ACL deficiency and after ACL reconstructions [20,24]. “One leg hop” (OLH) test is a simple, useful maneuver evaluating leg function [5,18,24] and it is included in the IKDC form as the only test for leg function [8]. Correlation between the OHL test and quadriceps strength has been reported for patients with ACL deficiency [18] and patients after ACL reconstruction [24]. Miyatsu and Andriacchi [13] analyzed the landing motion of the OLH. They found the differences of external flexion moment of the knee at landing between the injured and uninjured limbs. Kinematic and kinetic analyses of the OLH will help positioning the test as a functional testing in patients with ACL injuries and after ACL surgery.

The purposes of this study are to analyze level walking and one leg hop using rather simple and inexpensive instruments to position the tests in the functional tests for patients with ACL injuries. We measured floor reaction force, joint moments of the hip, knee and ankle and the knee joint angle on stance phase of level walking and on landing of one leg hop. The data were analyzed using the ratio of the injured to the uninjured limb. The correlation between the measured parameters and the period after injuries, muscle strength recovery and meniscal injured state were assessed to clarify the meaning of the patients’ characteristics among the patients.

2. Measurement methods

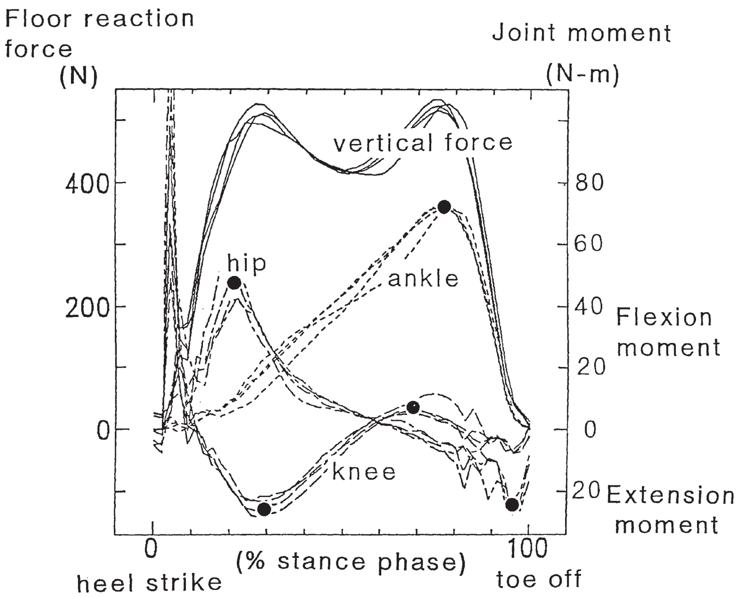
The instrumentation included a CCD-TV camera for position identification (Ohyokeisoku Lab. K.K.), a multiple component force-plate for one foot (Kistler Instrumente AG, Switzerland) and a personal computer. Light-reflecting markers were attached on the center of the greater trochanter, lateral joint space of the knee just on the lateral collateral ligament, and the lateral malleolus of the ankle. The TV camera was placed 2 m 30 cm apart from the examinee, and its accuracy was 0.15% of a view field. The patients walked on a three-meter walkway at free speed. The tests were repeated 5 times.

The analysis was undergone on the sagittal plane. The positions of the hip, knee and ankle joints as well as the horizontal and vertical components of the floor reaction force were simultaneously recorded at every 16 ms. The internal moments of the hip, knee and ankle joints were calculated using a link-model. We have been reporting the internal moments of the joints since they were easier to be understood than the external moments that were measured directly [4]. The measurement error of the joint moment was less than 5 N m using the zero-moment method [14].

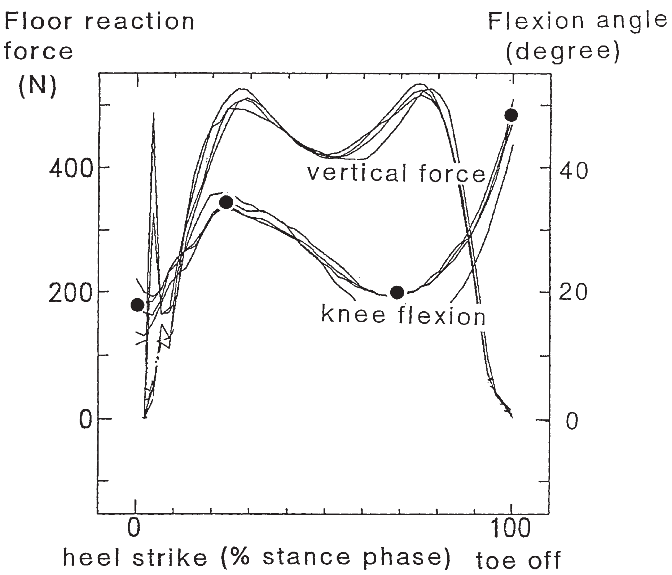
The difference between the actual joint center and the marker will affect the accuracy of the joint moment. The selection of the marker position was thought to be realistic and general position since the actual joint center is not in a single point.

2.1. Materials, methods and evaluating parameters for gait analysis

Twelve patients (4 men and 8 women) who had unilateral ACL deficiency and waited for the reconstructive surgery were selected for the gait study. They averaged 23 years old (range 15–44). They could walk on a walk way without any pain, and were observed as normal gaits. Arthroscopic examination after



(A)



(B)

Fig. 1. (A) An example of the internal moments of the hip, knee ankle joints and vertical floor reaction force in the uninjured limb at stace phase of level walking. (B) An example of the knee flexion angle and the vertical floor reaction force of the uninjured limb at stance phase of level walking.

the gait analysis revealed a complete tear of the ACL in all and meniscal injuries needed sutures or partial resection in 7 patients.

Evaluating parameters included the maximum extension and flexion internal moments of the hip, knee and ankle joints which were evaluated using the ratio of the injured to the uninjured limb (Fig. 1(A)) as well as the knee joint angle at heel-strike, maximum flexion, maximum extension and toe-off (Fig. 1(B)).

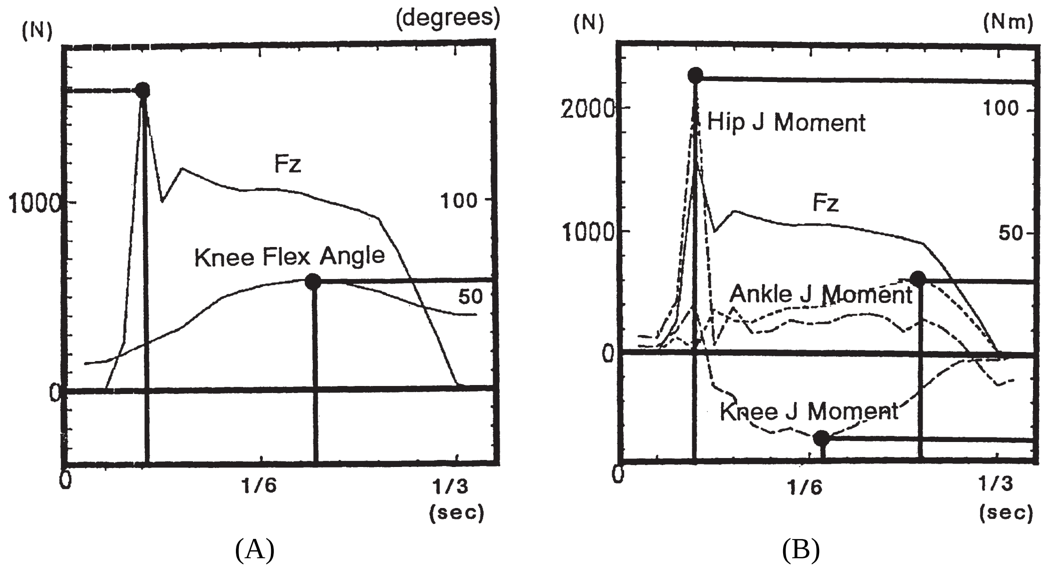


Fig. 2. The analysis included the vertical element of floor reaction force (F_z), knee flexion angle as well as duration from the beginning of landing to the peak value of the knee flexion angle (A). The analysis also included the internal joint moments of the hip, knee and ankle. Duration from the beginning of landing to the peak value of the joint moment of the joints was also evaluated (B).

2.2. Materials, methods and evaluating parameters for one leg hop

Eighteen patients (7 men and 11 women) who had unilateral ACL deficiency and waited for the reconstructive surgery were selected for the OLH study. They averaged 24 years old (range 15–44). They had no problems in daily activities and could jump on one leg without any pain. Arthroscopic examination after the tests revealed a complete tear of the ACL in all, and meniscal injuries needed sutures or partial resection in 11 patients.

They jumped two different hop distances, those were, a short distance (55 cm) and a long distance (90 cm), taking their maximum hop distance of the injured limb into consideration [15]. The short-distance hop was performed with the injured limb in 17 patients and with the uninjured limb in 15 patients. The long-distance hop was performed with the injured limb in 7 patients and with the uninjured limb in 14 patients.

Evaluating parameters included the maximum vertical floor reaction force (F_z), the maximum knee flexion angle and the time from the beginning of landing of the hop to the maximum knee flexion (Fig. 2(A)) as well as the maximum extension and flexion internal moments of the hip, knee and ankle joints and the time after the beginning of landing of the hop to the peak of each moment (Fig. 2(B)).

2.3. Evaluation methods

Each data of measurements was evaluated using a paired t-test between the injured and uninjured limbs. In the evaluation of the OLH, a paired t-test was also performed between the short- and long-distance hops. Then, each data was converted to the ratio of the injured to the uninjured limb, and analyzed between the following two groups: two groups of men and women, two groups of preoperative period being 6 months or less and greater, two groups of knee extension/flexion strength being 2 or more and less, two groups of the ratio of knee extension strength of the injured/uninjured limb being 80% or more and less (these two categories were tested using the Cybex machine), and two groups of the patients needed meniscal suture or partial resection and did not need. Mann–Whitney U-test was performed between each two groups. The significance was determined with p value being 0.05.

3. Results

3.1. Gait analyses

3.1.1. Comparison between the injured and the uninjured limb

Among the evaluations of the maximum internal moments of the three joints of the lower limb, the knee flexion moment of the injured limb was significantly less than that of the uninjured limb (Table 1).

In the evaluations of the knee flexion angles at various stance phase, the knee flexion angles of the injured limb at heel-strike and at maximum extension were significantly greater than those of the uninjured limb (Table 2).

3.1.2. Effects of difference of sex, preoperative period, knee muscle strength and meniscal injuries

The maximum knee flexion moment of the injured limb of men, 16.4 $\pm$ 10.6 (N m), was significantly greater than that of women, 7.1 $\pm$ 9.5 (N m). The maximum knee flexion moment of the uninjured limb of men, 29.0 $\pm$ 14.5 (N m), was not significantly greater than that of women, 9.1 $\pm$ 2.3 (N m).

The knee flexion angle at heel strike of the injured limb of the group with the ratio of extension/flexion strength being 2 or more, 19.5 $\pm$ 12.9 (degrees), was significantly greater than that of the group with the ratio less than 2, 15.2 $\pm$ 7.3 (degrees). The knee flexion angle at heel-strike of the uninjured limb

Table 1
Measurements of joint moment on level walking in patients with ACL deficiency

	Injured ($n = 12$)	Uninjured ($n = 12$)	p value
Hip extension	20.8 $\pm$ 6.6 N m	19.7 $\pm$ 5.9 N m	0.2221
Flexion	35.4 $\pm$ 10.8	34.8 $\pm$ 16.5	0.8683
Knee extension	20.8 $\pm$ 6.7	18.3 $\pm$ 7.6	0.4354
Flexion	10.2 $\pm$ 10.4	15.7 $\pm$ 13.5	0.0301*
Ankle extension	0	0	
Flexion	80.6 $\pm$ 20.5	82.8 $\pm$ 20.7	0.1857

*The knee flexion moment was significantly less than that of the uninjured limb.

Table 2
Measurements of knee joint angle on stance phase of level walking in patients with ACL deficiency

	Injured ($n = 12$)	Uninjured ($n = 12$)	p value
At heel strike	17.4 $\pm$ 10.3°	12.3 $\pm$ 6.0°	0.0307*
Maximum flexion in midstance	26.4 $\pm$ 10.8	23.8 $\pm$ 8.6	0.0882
Maximum extension in midsubstance	19.1 $\pm$ 8.2	14.2 $\pm$ 6.0	0.0110*
At toe off	41.3 $\pm$ 11.2	42.0 $\pm$ 10.4	0.5289

*The knee flexion angles of the injured limb at heel-strike and at maximum extension were significantly greater than those of the injured limb.

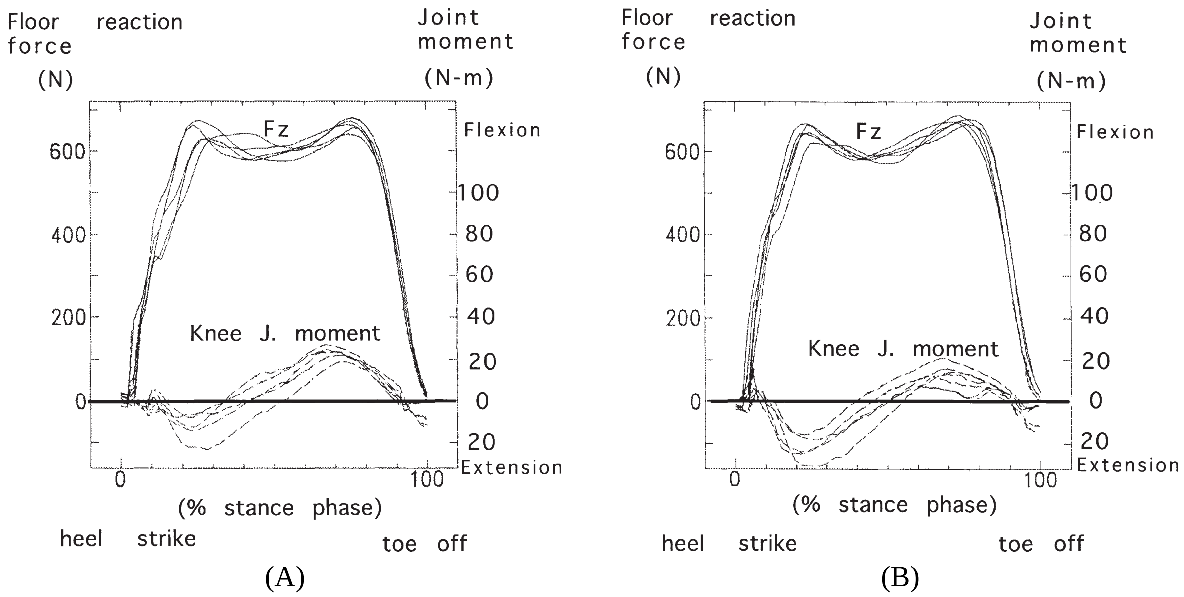


Fig. 3. An example of the "quadriceps avoidance gait" in which the internal extension knee moment of the injured limb (A) decreased to compare with that of the uninjured limb (B). Seven patients showed such a pattern.

of the group with the ratio of extension/flexion strength being 2 or more, 11.3 ± 7.2 (degrees), was not significantly different from the group with the ratio of extension/flexion strength being less than 2, 13.3 ± 5.1 (degrees).

There was no differences with regard to any parameters between the two groups of the preoperative period being 6 months or less and greater. Also, the group with meniscal suture or resection needed was not different from the group without any meniscal procedures.

3.1.3. Gait pattern

Seven patients showed the "quadriceps avoidance gait" in which the internal extension moment of the knee decreased (Fig. 3). Five patients indicated significant increase of knee flexion angle during the whole stance phase, two of them showed an apparent increase in knee extension moment (Fig. 4). One patient showed a different gait pattern from the typical two types.

3.2. One leg hop

3.2.1. Comparison between injured and uninjured limb

There were no significant differences of each measurements between the injured and uninjured limbs both in the short-distance hop and long-distance hop.

3.2.2. Comparison between the short-distance hop and the long-distance hop

In the injured limbs ($n = 6$), the peak value of F_z of the long-distance hop, 1216 ± 106 N, was significantly smaller than that of the short-distance hop, 1460 ± 207 N. The time from the beginning of the landing to the peak of the hip moment tended to be shorter in the long-distance hop than that in the short-distance hop. The time from the beginning of the landing to the peak of the knee moment of the long-distance hop, 0.19 ± 0.06, was significantly longer than that of the short-distance hop, 0.12 ± 0.03. The maximum flexion moment of the ankle of the long-distance hop, 64 ± 12 N m, was significantly smaller than that of the short-distance hop, 76 ± 19 N m (Fig. 5) (Table 3).

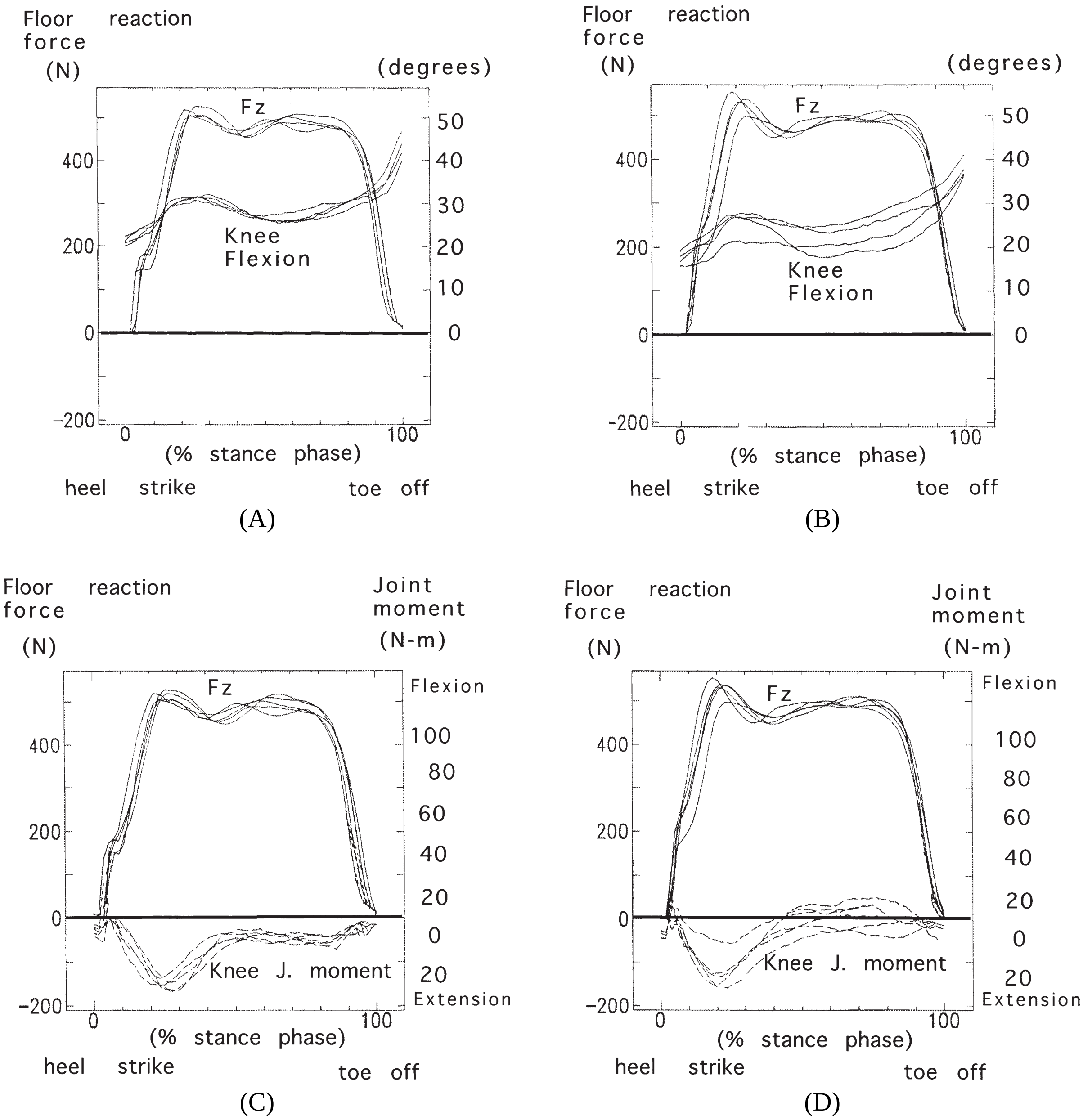


Fig. 4. An example of the "flexed knee gait" which showed significant increase in knee flexion angle of the injured limb (A) during the whole stance phase to compared with that of the uninjured limb (B). Five patients showed such a pattern. Two of them showed an apparent increase of the knee extension moment (C) compared with that of the uninjured limb (D).

In the uninjured limbs ($n = 13$), there was no difference of the peak value of F_z between the short- and long-distance hops, while the time from the beginning of landing to the maximum F_z and to the maximum knee flexion angle of the long-distance hop, 0.05 ± 0.02 and 0.19 ± 0.03, respectively, was shorter than those of the short-distance hop, 0.09 ± 0.03 and 0.21 ± 0.06, respectively. Otherwise, the tendency of the changes of the joint moment was same as those of the injured limb.

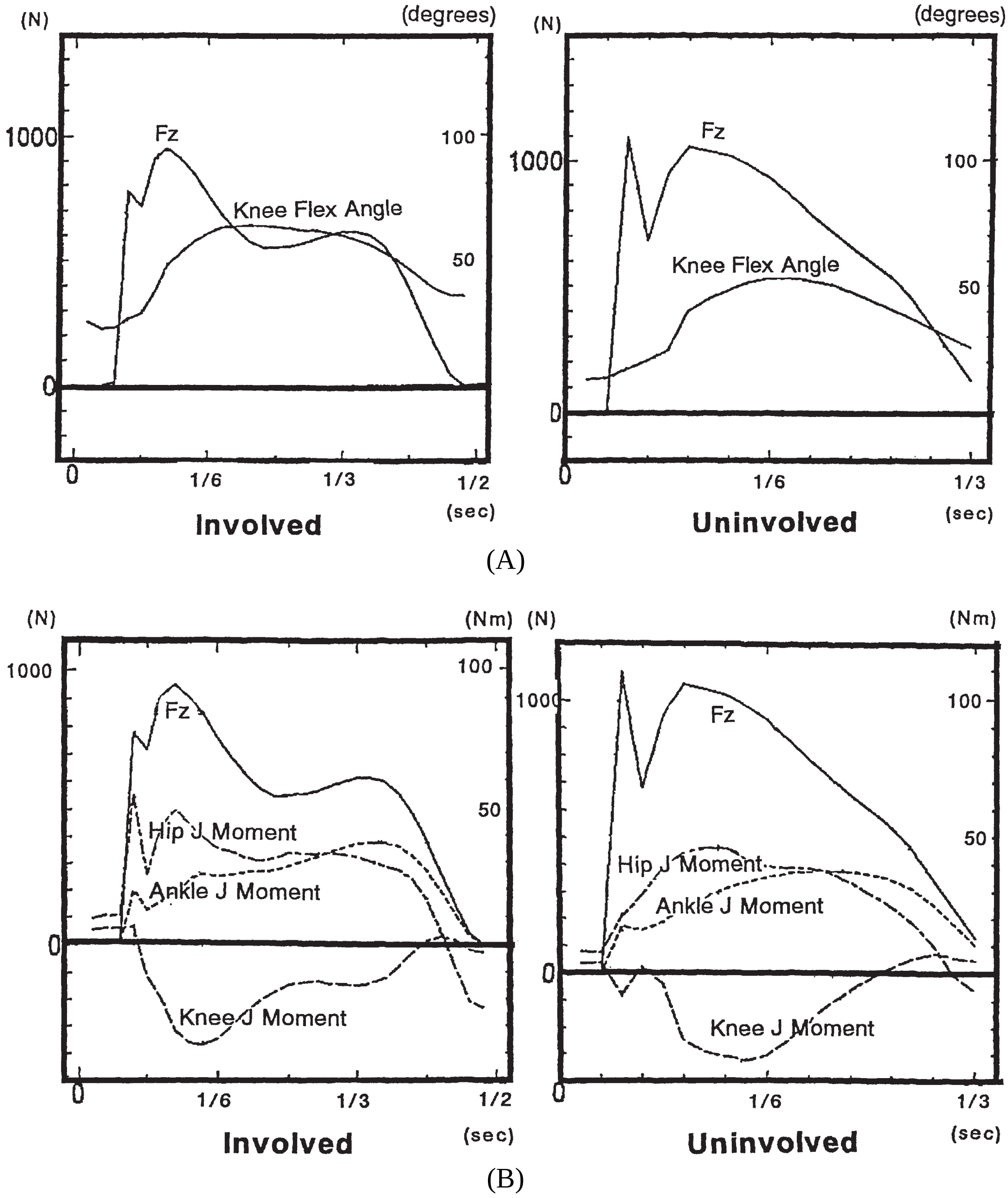


Fig. 5. An example of a case. Ninety centimeters one leg hop of 44-year old female 3 months after injury. The involved leg showed 12% reduction of F_z and 2.9 times elongation of the duration from the beginning of landing to the peak. Maximum knee flexion angle and the duration to the maximum knee flexion were increased by 20% (A). The hip flexion moment was increased and the knee extension moment was decreased in this case (B).

3.2.3. Effects of difference of sex, preoperative period, knee muscle strength and meniscal injuries

Data was analyzed using the ratio of the injured to the uninjured limb to evaluate the effects of sex, preoperative period, knee muscle strength and meniscal injuries. Men showed significantly smaller amount of maximum knee flexion angle at landing in the injured limb, 50 ± 10 degrees, than that of women,

Table 3
Measurements of short- and long-distance hops in the injured limbs (paired; n = 6)

	Short-distance hop	Long-distance hop	p-value
Maximum F_z (N)	1460 ± 207	1216 ± 106	0.0508
Time to peal F_z (s)	0.10 ± 0.05	0.06 ± 0.02	0.1486
Max knee flex angle (degrees)	49 ± 9	53 ± 10	0.3730
Time to max knee flex angle (s)	0.20 ± 0.02	0.20 ± 0.05	0.8649
Max hip extension moment (N m)	88 ± 38	81 ± 22	0.6576
Time to max hip moment (s)	0.12 ± 0.11	0.06 ± 0.04	0.0688
Max knee flexion moment (N m)	37 ± 13	47 ± 12	0.2153
Time to max knee moment (s)	0.19 ± 0.06	0.12 ± 0.03	0.0377*
Max ankle flexion moment (N m)	76 ± 19	64 ± 12	0.0363*
Time to max ankle moment (s)	0.21 ± 0.05	0.18 ± 0.05	0.1990

*The paired t-test revealed significant differences between the short- and long-distance hops ($p < 0.05$).

Table 4
Measurements of short- and long-distance hop in the uninjured limbs (paired; n = 13)

	Short-distance hop	Long-distance hop	p-value
Peak F_z (N)	1396 ± 183	1256 ± 172	0.1011
Time to peak F_z (s)	0.09 ± 0.03	0.05 ± 0.02	0.0090*
Max knee flex angle (degrees)	57 ± 7	56 ± 6	0.9514
Time to max knee flex angle (s)	0.21 ± 0.06	0.19 ± 0.03	0.0604
Max hip extension moment (N m)	89 ± 36	94 ± 23	0.4619
Time to max hip moment (s)	0.06 ± 0.04	0.06 ± 0.04	0.9481
Max knee flexion moment (N m)	49 ± 13	50 ± 12	0.7153
Time to max knee moment (s)	0.14 ± 0.02	0.12 ± 0.02	0.0020*
Max ankle flexion moment (N m)	62 ± 14	52 ± 17	0.0167*
Time to max ankle moment (s)	0.14 ± 0.09	0.18 ± 0.08	0.1132

*The paired t-test revealed significant differences between the short- and long-distance hops ($p < 0.05$).

58 ± 9 degrees. In the uninjured limbs, there was no significant difference of maximum knee flexion angle at landing between men and women, 57 ± 8 and 54 ± 7 degrees, respectively.

Patients who needed meniscal procedures showed significantly greater amount of maximum knee flexion angle at landing in the injured limb, 57 ± 9 degrees, than that of patients who did not need any meniscal procedures, 50 ± 9 degrees. In the uninjured limbs, there was no significant difference of maximum knee flexion angle at landing between those with and without meniscal procedures, 54 ± 7 and 54 ± 7 degrees, respectively.

Patients who had poor recovery of the knee extension strength with less than 80% of the uninjured limb showed shorter time from the beginning of landing to the peak of the ankle flexion moment in the injured limb, 0.144 ± 0.071 s, than those who had better recovery of the knee extensor, 0.170 ± 0.088 s. In the uninjured limbs, there was no significant difference of time from the beginning of landing to the peak of the ankle flexion moment between patients with poor recovery and better recovery of the knee extension strength, 0.128 ± 0.054 and 0.186 ± 0.150 s, respectively.

There was no clear differences of any evaluating parameters at landing of one leg hop with respect to preoperative time.

4. Discussion

4.1. Level walking

Berchuck et al. [4] reported that patients with ACL deficiency showed abnormal pattern of level walking in the uninjured limb as well as in the injured when the data was analyzed using the value of joint moments normalized by height and body weight, while there was no clear differences between the injured and uninjured limbs. To the contrary, the results of this study indicated that there were significant differences of evaluating parameters on level walking between the injured and the uninjured limb in patients with ACL deficiency. The reasons of the differences between two studies will be in that the patients of their study were dominant in men; our study did not normalize joint moments using height and body weight; and in our study preoperative exercises may not be so sufficient that muscle strength recovery and abnormal gait pattern were not corrected at the testing.

The study indicated two patterns of level walking characterized in patients with ACL deficiency, that is, “knee flexed gait” in which a patient kept significantly greater flexion of the injured knee than the uninjured on walking as well as “quadriceps avoidance gait”. About the “knee flexed gait”, Andriacchi [3] suggested insufficient preopeative exercises in those patients from his experience. However, as the majority of the patients who showed such abnormality was women in this study, their findings were partly due to the differences of sex.

The abnormal gait pattern indicated in the study will risk the knee joint function in long-term: “quadriceps avoidance gait” will decrease quadriceps strength, and “knee flexed gait” will accelerate knee flexion contracture. Those abnormality will cause patellofemoral disorders in long term even if a patient does not feel uncomfortable in the daily livings. Preoperative abnormality of gait may cause harmful effects on the knees after ACL reconstruction. In that sense, preoperative gait analysis will be useful measurements.

For future studies, effects of preoperative abnormality of gait on recovery course after ACL surgery should be assessed. It should be clarified by means of gait analysis whether the differences of graft materials affect the postoperative results or not, although it was reported that patients with the ACL reconstruction using central one-third of patellar tendon become normal gait pattern at one year after surgery [22].

4.2. One leg hop

The study suggested that the control mechanism of the lower limb preventing knee instability in patients with ACL deficiency is not the same for each patient but several factors will exist and be combined when they hop and land on one leg.

Common changes both in the injured and uninjured limbs when the hop distance became longer may be interpreted as inevitable factors that patients cannot control. Those common changes were as follows; the time from the beginning at landing to maximum internal moment of the knee flexion became significantly shorter, and the maximum value of the ankle flexion moment significantly decreased. People will control higher impact by quicker knee joint reaction, however, control mechanism of the ankle will decrease when the hop distance becomes longer.

On the other hand, different changes of the injured limb from the uninjured limb will be interpreted as control mechanism characterized in the limb with ACL deficiency when the hop distance becomes longer. About F_z, the uninjured limb showed a significant shortening of the time after the beginning of landing to the peak of F_z, while the injured limb showed significant decrease of F_z value when the hop distance became longer. The patient seemed to land softly with ACL deficient limb so that he or she will not increase the peak value of F_z. The fact shown in the uninjured limb that the patient reached maximum knee flexion quicker was thought to increase unstable feeling to the injured limb. The patients landed more slowly with the hip being extended quicker and the knee being flexed for longer time to control unstable feeling of the injured knee.

For future studies, pre- and postoperative study will make the mechanism of one leg hop in the ACL injured knee more clearly. When a patient shows poor recovery of the one leg hop test, the analysis of one leg hop test may make the reasons more clear.

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