



Original Article

Correlation between hip function and knee kinematics evaluated by three-dimensional motion analysis during lateral and medial side-hopping

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Abstract. [Purpose] Kinematic and kinetic characteristics of the limb during side-hopping and hip/knee interaction during this motion have not been clarified. The purposes of this study were to examine the biomechanical parameters of the knee during side hop and analyze its relationship with clinical measurements of hip function. [Subjects and Methods] Eleven male college rugby players were included. A three-dimensional motion analysis system was used to assess motion characteristics of the knee during side hop. In addition, hip range of motion and muscle strength were evaluated. Subsequently, the relationship between knee motion and the clinical parameters of the hip was analyzed. [Results] In the lateral touchdown phase, the knee was positioned in an abducted and externally rotated position, and increasing abduction moment was applied to the knee. An analysis of the interaction between knee motion and hip function showed that range of motion for hip internal rotation was significantly correlated with external rotation angle and external rotation/abduction moments of the knee during the lateral touchdown phase. [Conclusion] Range of motion for hip internal rotation should be taken into consideration for identifying the biomechanical characteristics in the side hop test results.

Key words: Side hop, Knee joint motion analysis, Hip function

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INTRODUCTION

Anterior cruciate ligament (ACL) injury is one of the most common sports injuries, which frequently occurs during jumping, landing, and cutting motions^{1, 2}). ACL reconstruction has become a standard treatment option for athletes who have functional limitations of the lower extremities for cutting and pivoting motions and wish to return to athletic activities³). In order to assess functional recovery and risk for re-injury after ACL reconstruction, the functional performance test (FPT) has been used as a performance-based measurement tool to determine the time to return to play. In addition, FPT can be an effective screening tool for ligament injury risk.

Various FPT methods have been proposed and reported in literature⁴⁻⁸). There are several types of FPT batteries including hop tests such as the single/triple hop test for distance, side hop test, and figure-of-8 hop test. Motion characteristics during these hop tests consist of jumping, landing, and cutting activities that exert impact loads on the joints of the lower limbs⁴⁻⁸).

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Previous studies on hop test results have shown that several kinematic features such as smaller knee flexion angle, larger knee valgus, and internal rotation angles are related to the risk for ACL injuries⁹⁻¹². However, three-dimensional kinematic and kinetic characteristics of the limb during side-hopping has not been clarified. Consequently, there is a lack of biomechanical evidence to support the significance of a side hop test as an FPT.

In consideration of factors affecting the motion pattern during various hopping tasks, the significance of hip function and its effect on knee kinematics and kinetics has been addressed in recent literature. In these studies, weaknesses of the hip abductor, external rotator, and extensor were depicted as risk factors inducing dynamic frontal knee motion¹³⁻¹⁵. However, no analytical data are available regarding the hip/knee interaction during side-hopping¹⁶⁻¹⁹.

This study was conducted to investigate kinematic and kinetic sequences of the knee during side hop motion using a three-dimensional motion analysis system and to examine the correlation between clinical parameters of hip function, such as range of motion (ROM) and muscle strength, on knee motion. It has been hypothesized that knee kinematic and kinetic patterns characteristic to side-hopping motion are related to ACL injuries and that hip function affects the motion pattern of the knee during side hop.

SUBJECTS AND METHODS

Twenty-one healthy, young (20–26 years) male college rugby players were initially enrolled in this study. Based on the medical history and results of physical examinations, the limbs that met the following criteria were excluded from the study: history of major musculoskeletal injuries or surgeries in the corresponding lower limb, history of acute lower limb injuries within 3 months, pain or swelling at the ankle or knee affecting the hopping motion. Consequently, 16 lower extremities (8 right and 8 left limbs) in 11 athletes were included in the study. The height of the participants ranged from 1.65 to 1.81 m and weight ranged from 69.1 to 89.5 kg. The subjects were informed of the experimental protocols, and signed informed consent forms were obtained from the study participants. The study design was approved by the Konan Women's University Research Ethics Committee before the study.

Three-dimensional analysis of knee motion during side hop and measurements of hip ROM and muscle strength were conducted for each subject. A cross-sectional study design was used to analyze the relationship between the values obtained from the tests.

In the first session, a three-dimensional motion analysis of the knee during side hop movement was performed using a MAC3D automatic digitizing motion analysis system equipped with eight cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) and two force plates (AMTI Japan Ltd.).

For assessment of the side hopping motion, the IOR (Istituto Orthopedico Rizzoli) full-body model was applied for definition of bilateral upper- and lower-body segments including the CODA model for the pelvis²⁰⁻²³. Eighty-four spherical reflective markers (diameter: 12 mm) were attached to the subjects' skin directly on the anatomical bony landmarks of the upper and lower body using double-sided adhesive tape. The locations of the markers were as follows:

- 1) Head segment (4 markers).
- 2) Spinous process of the 7th cervical vertebrae, second thoracic vertebrae and 7th thoracic vertebrae level (midpoint between the inferior angles of the most caudal points of the two scapulae), incisura jugularis, xiphoid process, and the 1st, 3rd, and 5th lumbar vertebrae for the neck and thoracic segment.
- 3) Acromion, deltoid tuberosity, lateral epicondyle of the humerus, dorsal aspect of the forearm, styloid processes of the ulna and radius and head of the third metacarpus for the bilateral upper-extremity segments.
- 4) Anterior superior and posterior superior iliac spines for the pelvis segment.
- 5) The greater trochanter, the lateral and medial femoral epicondyles with 4 cluster markers attached to the lateral aspect of the thigh for the bilateral thigh segments.
- 6) The head of the fibula, the tibial tuberosity, the lateral and medial malleoli with 4 cluster markers attached to the lateral aspect of the leg for the bilateral shank segments.
- 7) Proximal posterior surface of the calcaneus and distal attachment of the Achilles tendon on the calcaneus, the sustentaculum tali, the peroneal tubercle, the tuberosity navicular, the 1st, 2nd and 5th metatarsal heads, proximal distal phalanx, bases of the 1st and 2nd metatarsals, styloid process of the 5th metatarsal for the bilateral foot segments.

A series of subject calibration trials in anatomical standing posture was performed to determine anatomical landmarks and lower limb joint coordinate systems²⁴.

For the side hop movement, the subjects were instructed to first stand on two force plates with both feet parallel and 30 cm apart and then asked to stand on one leg with the other leg maintained in a flexed knee position at approximately 60°, with the arms abducted widely for body balance control. Side-hopping started with this posture and was performed as accurately and quickly as possible on the two force plates placed between interval line tape-markers with 30 cm apart in accordance with previous investigations⁸. The subjects performed several trials of the side hop for both legs until they could successfully perform 10 repetitions for each leg. Trials were excluded if the entire foot did not contact the force plates or if any markers were lost during side-hopping.

The motions of the reflective markers were tracked with 8 synchronized cameras at 200 Hz, and the force plates were time synchronized and sampled at a rate of 1,000 Hz. Missing data in the marker trajectories were interpolated using the

EvaRT 5.04 software (Motion Analysis Corporation, Santa Rosa, CA, USA). The raw three-dimensional coordinate data were filtered using a zero-lag fourth-order low-pass Butterworth filter with a cut-off frequency of 6 Hz using with Visual 3D v5.02 software (C-Motion, Inc., USA).

The joint angles and moments were calculated using the Euler angle method for flexion/extension, abduction/adduction, and internal/external rotation sequences according to the recommendations of the International Society of Biomechanics²⁵⁻²⁷.

The side hop movement was divided into two phases: contact phase and jumping phase. Contact phase was defined as the duration from when the vertical ground reaction force exceeded 10 N to when it decreased to less than 10N before toe-off. The side hop represents repetition of jumping and landing motions in two opposite (lateral-to-medial and medial-to-lateral) directions, and kinematic and kinetic features of the lower extremity at the touchdown phase are thought to be different between the lateral and medial touchdown phases (Fig. 1). Therefore, motion analysis was separately performed for the two contact phases: the lateral touchdown phase (LTDP) and the medial touchdown phase (MTDP).

In the second session for clinical evaluation, first, ROM measurement was performed for the hip. An inclinometer, Angle Finder Level inclinometer plastic device (Mitsutomo Manufacturing. Co. Ltd., Japan), was used. ROM measurements for extension in supine position and internal/external rotation (IR/ER) in prone position were performed using this device^{28, 29}. Each measurement was performed three times and the maximum value of the three measurements was adopted. When the tests were performed using the inclinometer in previous study, it was assured that the intra-class correlation coefficients ranged from 0.94 to 0.99. The examination was performed by one examiner for all subjects in this study.

In addition, muscle strength measurements were performed for the hip. The BIODEX System 3 (Biodex Medical Systems, Inc. NY, USA) was used for isokinetic strength measurement of the hip extensor. The test was performed twice in three repetitions with maximum voluntary effort at 60°/sec, and the peak torque was estimated. Hip external rotator strength was evaluated using a hand-held dynamometer (HHD), microFET2 (HOGGAN Scientific, LLC, UT, USA), for static force of hip external rotation with hip abducted in the half-squat posture. Use of the HHD has been shown to provide excellent intra-class correlation coefficients for measurement of maximal isometric strength of hip muscles^{19, 30}. The participants were told to stabilize themselves by crossing their arms in front of their chest. Strength measurement was performed while the subject was holding a half-squat posture with neutral position of the knee and hip in coronal and horizontal planes. The force pad of the HHD was placed on the lateral epicondyle of the femur, and the examiner manually applied resistance to the subject's motion. The subject being tested exerted a submaximal voluntary contraction, and the examiner confirmed whether the action was appropriately conducted by the subject as instructed. Following this confirmation, the subject exerted a 5-second maximum isometric contraction against the HHD. The test was performed twice for each leg. Between the 2 test trials, a rest period of one minute was introduced. The highest force value during the two consecutive measurements for each leg was used for data analysis.

For data analysis of the kinematic and kinetic parameters of the knee, angle and moment values for internal/external rotation and adduction/abduction were calculated, in which internal rotation and adduction were denoted as positive. The phases of interest for data analysis were the LTDP and MTDP. Therefore, each individual's data were time-normalized in each phase and averaged across their limbs. The parameters adopted for the analysis were the highest angle and moment values during each phase. The moment values were normalized by body weight and height. Analytical parameters derived from clinical measurement of the hip were internal/external rotation and extension angles for ROM, and the weight-adjusted extensor torque and external rotator force values for strength.

Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 20.0 for Windows (IBM, Chicago, IL, USA). The paired t-test was used for the comparison of joint angle and moment of the knee between LTDP and MTDP. Pearson correlation coefficients were calculated to assess the relationship between kinematic/kinetic variables of the knee and the clinical parameters of the hip. For all statistical analyses, the significance level was set at <0.05.

RESULTS

In the motion analysis of the knee during side hop, kinematic and kinetic sequences during the touchdown phase showed distinctly different features between the LTDP and MTDP. During LTDP, the knee was aligned in an abducted and externally rotated position throughout the period of contact. Regarding the moment, the kinetic sequence in this phase started with small adduction moment followed by increasing abduction moment until the mid-phase and subsequent return to small adduction moment in the late phase. Internal/external rotational moment was minimal throughout the period (Fig. 2).

During MTDP, the knee was initially aligned in an abducted and externally rotated position. By the mid-phase, a gradual increase in abduction and a decrease in external rotation were observed. Subsequently, the knee position returned to the initial condition. Sequential change in moment during MTDP exhibited the reverse pattern compared to that in LTDP. In the initial phase, the knee underwent small abduction moment at landing. Subsequently, adduction moment applied to the knee was gradually increased until the mid-phase followed by subsequent return to abduction moment in the late phase. The internal/external rotation moments were smaller compared to the adduction/abduction moments, while a small increase in external rotation moment was observed in the mid-phase (Fig. 3).

On comparing kinematic parameters of the knee between LTDP and MTDP, LTDP was characterized by a significantly larger abduction angle than MTDP, while a significantly larger external rotation angle was observed for MTDP compared to

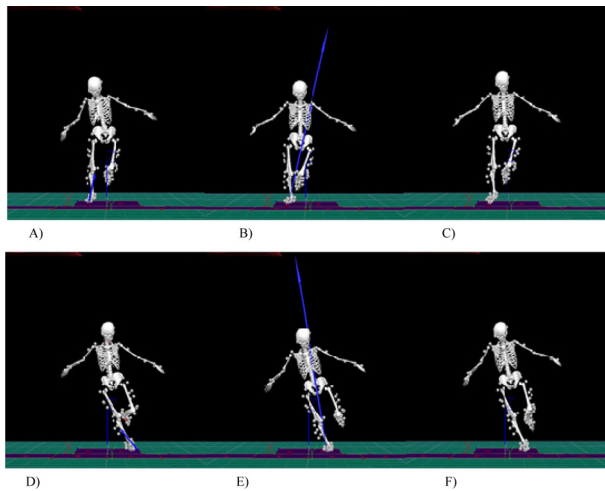


Fig. 1. Illustration of side hop motion during the touchdown phase for the right leg

Top: Lateral touch-down phase for the right leg (LTDP)
 A) → B): Illustration shows kinematic sequence at touching down with the right foot on a force-plate toward the right.
 B) → C): Illustration shows kinematic sequence until the moment of taking off with the right foot toward the left.
 Bottom: Medial touch-down phase for the right leg (MTDP)
 D) → E): Illustration shows kinematic sequence at touching down with the right foot on the other force-plate toward the left.
 E) → F): Illustration shows kinematic sequence until the moment of taking off with the right foot toward the right.

Table 1. Comparison of knee joint angle and moment of external/internal rotation and abduction/adduction between LTDP and MTDP during side hop

	LTDP	MTDP	
Angle (deg)			
Min ER	3.3 ± 6.7	6.2 ± 6.9	**
Max ER	6.3 ± 6.5	11.7 ± 5.7	**
Min ABD	5.0 ± 3.4	0.1 ± 2.2	**
Max ABD	9.5 ± 4.0	7.2 ± 4.1	**
Moment (×10 ²)* ¹			
Max IR	0.8 ± 0.7	0.0 ± 0.2	**
Max ER	1.2 ± 1.0	1.5 ± 0.3	
Max ADD	2.7 ± 0.6	3.3 ± 3.1	
Max ABD	5.5 ± 2.5	4.1 ± 1.0	*

*¹The value was calculated as moment (Nm) divided by weight (N) and height (m)*p<0.05, **p<0.01. IR: Internal rotation; ER: external rotation; ADD: Adduction; ABD: Abduction; LTDP: lateral touchdown phase; MTDP: medial touchdown phase

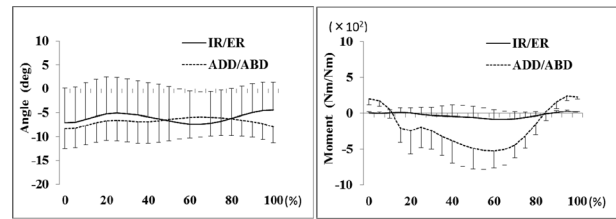


Fig. 2. Mean time sequence data of knee internal (+)/external (-) rotation and adduction (+)/abduction (-) angles and moments during LTDP from initial contact (0%) to toe-off (100%)

IR: internal rotation; ER: external rotation; ADD: adduction; ABD: abduction

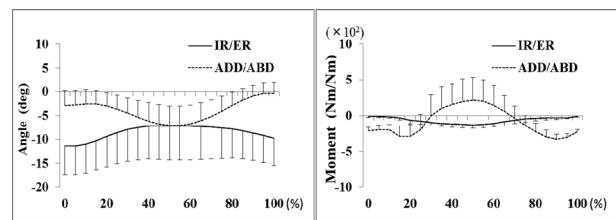


Fig. 3. Mean time sequence data of knee internal (+)/external (-) rotation and adduction (+)/abduction (-) angles and moments during MTDP from initial contact (0%) to toe-off (100%)

IR: internal rotation; ER: external rotation; ADD: adduction; ABD: abduction

Table 2. Clinical measurements for hip range of motion and strength (n=16 limbs)

Hip range of motion		
Extension (deg)	11.4 ± 3.3	(5.0–17.0)
Internal rotation (deg)* ¹	32.5 ± 12.8	(5.0–50.0)
External rotation (deg)* ¹	42.3 ± 10.3	(25.0–60.0)
Muscle strength		
Hip extension (Nm/kg)* ²	4.8 ± 1.2	(2.8–7.2)
Hip external rotation (%)* ³	27.9 ± 9.3	(13.9–40.9)

Minimum and maximum values are shown in parentheses. *¹Significant difference between internal and external rotation at p-value less than 0.05. *²The value was calculated as torque (Nm/kg) divided by weight (kg). *³The value was calculated as force (%) divided by weight (kg).

LTDP (Table 1). Regarding the moment values, internal rotation moment and abduction moment in LTDP were significantly larger than those in MTDP (Table 1). Moreover, manifestations of maximal abduction moment in LTDP and maximal adduction moment in MTDP in the mid-phase represented a distinct contrast between the two phases (Figs. 2 and 3).

In this study population, the ROM values were relatively small for hip extension and internal rotation (Table 2). The measured external rotation angle was significantly larger than the internal rotation angle. Muscle strength measurement showed substantial variability despite the fairly uniform subject demographics (male rugby football players in their twenties).

Table 3. Pearson correlation coefficients between clinical measurements of hip and kinematic/kinetic data of the knee joint during lateral touch-down phase

	Knee joint angle				Knee joint moment			
	Min ER	Max ER	Min ABD	Max ABD	Max IR	Max ER	Max ADD	Max ABD
Hip range of motion								
Extension (deg)	0.06	0.12	0.35	0.34	0.26	0.23	0.06	-0.01
Internal rotation (deg)	0.47	0.51*	-0.08	0.09	0.15	0.52*	0.03	0.53*
External rotation (deg)	-0.02	-0.02	-0.04	0.10	-0.21	-0.23	0.04	-0.03
Muscle strength								
Hip extension (Nm/kg)* ¹	0.04	0.00	0.09	0.19	-0.04	-0.07	0.14	-0.07
Hip external rotation (%) ^{*2}	0.00	0.00	-0.36	-0.39	0.41	0.49	0.18	0.42

*¹The value was calculated as torque (Nm/kg) divided by weight (kg). *²The value was calculated as force (%) divided by weight (kg). *p<0.05. IR: Internal rotation; ER: external rotation; ADD: Adduction; ABD: Abduction

Table 4. Pearson correlation coefficients between clinical measurements of hip and kinematic/kinetic data of the knee joint during medial touch-down phase

	Knee joint angle				Knee joint moment			
	Min ER	Max ER	Min ABD	Max ABD	Max IR	Max ER	Max ADD	Max ABD
Hip range of motion								
Extension (deg)	-0.07	0.00	0.28	0.46	0.32	-0.04	0.14	-0.20
Internal rotation (deg)	0.35	0.43	0.09	0.05	-0.03	0.10	0.00	0.39
External rotation (deg)	-0.05	-0.11	-0.08	0.02	0.18	0.32	-0.08	-0.45
Muscle strength								
Hip extension (Nm/kg)* ¹	-0.14	-0.15	0.06	0.38	0.18	0.48	0.01	-0.22
Hip external rotation (%) ^{*2}	0.10	0.17	-0.34	-0.45	-0.13	-0.20	0.48	0.45

*¹The value was calculated as torque (Nm/kg) divided by weight (kg). *²The value was calculated as force (%) divided by weight (kg). IR: Internal rotation; ER: external rotation; ADD: Adduction; ABD: Abduction

The relationship between the kinematic and kinetic variables of the knee during LTDP and the clinical parameters of the hip is presented in Table 3. A statistically significant correlation was demonstrated between the internal rotation ROM of the hip and the maximal external rotation angle of the knee during this phase. Regarding the moment, maximal external rotation and maximal abduction moments during LTDP significantly correlated with internal rotation ROM of the hip. Relevant analysis for the parameters during MTDP showed no significant correlation between the kinematic/kinetic results of the knee and the clinical parameters of the hip (Table 4).

DISCUSSION

In the first part of this study, a three-dimensional motion analysis of the knee during side-hopping motion was performed to investigate how the knee is positioned and loaded. Consequently, significant differences in kinematic and kinetic parameters were noted between motions during LTDP and MTDP. During LTDP, a significantly larger abduction angle was observed, which corresponded to primary knee kinematics at the time of non-contact ACL injury¹¹⁻¹³. Indeed, dynamic knee valgus observed in the frontal plane during common athletic screening tasks is regarded as a motion pattern associated with a high risk for knee injuries³¹. In contrast, the load applied to the knee during MTDP was generally smaller than that applied during LTDP, and kinematically the knee was characterized by a larger external rotation angle in positioning.

In the analysis of hip/knee interaction, internal rotation ROM of the hip was shown to influence knee kinematics and kinetics during LTDP in side hop motion. Side hop motion involves complex trunk and limb motions, and thus the evaluation should include motion components other than the knee. A preliminary study showed that quadriceps and hamstrings strength had little correlation with side hop performance³². Previous relevant studies reported a negative correlation between extensor and abductor strengths of the hip and valgus angle of the knee during various tasks^{16-18, 33}. The present study has shown that hip ROM can be a factor that influences knee motion during side hop.

The hop test has been used for assessment of patients following ACL reconstruction to evaluate postoperative functional recovery and the risk for reinjures. Patients who undergo ACL reconstruction exhibit varying degrees of functional limitations⁴. During postoperative rehabilitation, accomplishment of an effective training protocol based on accurate evaluation of

functional recovery is essential to enable uneventful return to sports activity. Hewett et al. proposed that strength training with correction of faulty movement biomechanics and balance training are the most effective methods for preventing ACL injuries³⁴). Various modes and types of tasks were used for evaluation of functional performance. The single-leg squatting test has been tested for efficacy and reliability in evaluation of hip function^{35,36}). The hop test can be regarded as a dynamic single-leg squatting test, although a small body of work is available in lending support to the test performance. To date, 4 types of hop tests have been reported in literature: single-leg, cross-over, triple, and 6 m timed hop tests^{4, 37}). Previous studies on these tests have correlated the test results with knee function measured with only a self-reported questionnaire³⁷). However, those studies did not include motion analysis. Since there is a paucity of data available in literature regarding motion characteristics during side hopping, the results of this study can provide valuable information that can help understand three-dimensional knee motion and hip/knee interaction during side hop motion. Based on the results of this study, it is proposed that internal rotation ROM of the hip should be included as a factor for evaluation in hop test results. For subjects with increased internal rotation ROM of the hip, exercises that strengthen the hip external rotator and abductor may effectively reduce the risk for ACL injury or re-injury after ACL reconstruction.

There were several limitations in this study. First, the sample size was small, and the obtained results are not robust enough to draw definitive conclusion. Moreover, inclusion of the results obtained from either bilateral or unilateral limbs among the subjects may result in an uneven data distribution and bias in data acquisition. Second, the subject population was limited to male rugby players whereas previous studies have shown gender differences in dynamic knee joint motion during various functional performance tests^{5, 8–10, 17, 18}). Third, this study did not include the assessment of hip adduction/abduction ROM, which would also be potential factors related to the knee valgus motion. In future studies, the assessment of hip adduction/abduction ROM should be included in the evaluation of the hip to clarify the relationship of hip function and knee kinematics/kinetics during the hop test.

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