Original Article

Side-to-side differences of three-dimensional knee kinematics during walking by normal subjects

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Abstract. [Purpose] The purpose of this study was to determine the normal range of the side-to-side difference in three dimensional knee kinematics measured by the point cluster technique (PCT). [Subjects] The subjects were twenty-one healthy normal volunteers without knee pain or an episode of injury to the legs. [Methods] The subjects were tested bilaterally at a self-selected normal walking speed and six degrees of freedom knee kinematics were measured using the PCT, and the 95% confidence intervals of the average side-to-side differences in flexion-extension (FE), adduction-abduction (AA), internal-external (IE) rotation, and anterior-posterior (AP), medial-lateral (ML), superior-inferior (SI) translation in each stage of the gait cycle were determined. [Results] The average side-to-side differences and their 95% confidence intervals in rotation/translation in each stage of the gait cycle were determined. The side-to-side differences in AA rotation and AP translation of the tibia were significantly larger in the swing phase than in the stance phase. [Conclusion] The side-to-side differences in AA rotation and AP translation were highly dependent on the stage of the gait cycle. Therefore, the normal ranges of the side-to-side differences in knee kinematics in each stage of the gait cycle, in particular AA rotation and AP translation of the tibia, is useful information for evaluating knee kinematics during walking.
Key words: Knee kinematics, Point cluster technique, Side-to-side difference

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INTRODUCTION

Abnormal knee kinematics are considered to be an important factor influencing the long-term outcomes after cruciate ligament injuries[1–3]. In order to improve long-term outcomes of treatments for the patients with cruciate ligament injuries, it is necessary to restore their knee kinematics. Therefore, it is important to precisely evaluate the kinematics of knees with cruciate ligament injuries. The motion of a knee joint with ligament injury is commonly evaluated by static methods such as the Lachman test, posterior drawer test, valgus stress test, and arthrometric measurements, e.g. KT-1000. However, patients with knee ligament deficiencies usually complain about their symptoms under dynamic conditions. Therefore, there is a possibility that the instability of the knee joint evaluated in static conditions does not reflect the functional disabilities of its ligament injury[1, 3–5].

Three-dimensional motion analysis using optical skin marker systems has been widely used as an evaluation method of body kinematics in dynamic conditions with muscular activations. This approach provides six-degrees-of-freedom motion of the kinematics of the knee during activities of daily living without restricted conditions in vivo. Andriacchi et al. developed a point cluster technique (PCT), which employs an overabundance of markers (a cluster) placed on each segment to minimize the effects of skin movement artifacts[6]. The PCT can be extended to minimize skin movement artifact by optimal weighting of the markers according to their degree of deformation. The criteria of the normal range of three-dimensional knee kinematics during walking remain uncertain. Side-to-side difference in the range of knee motion is widely used as a criterion of the normal range of knee motion[1]. To detect an abnormal knee motion during walking, it is useful to determine the normal range of the side-to-side difference in knee kinematics during walking based on the data using the PCT. To the best of our knowledge, however, no study has examined this; therefore, the purpose of the present study was to determine the normal range of the side-to-side difference in knee kinematics using PCT during walking based on three dimensional kinematics of the knee of healthy subjects.

SUBJECTS AND METHODS

The study was approved by the Research Ethics Committee of Hakodate National College of Technology and informed consent was obtained from each subject before the test. Twenty-one healthy normal volunteers without knee pain or an episode of injury to the legs were recruited for the study. The subjects were 11 males and 10 females with an average age of 27.0 (SD 7.2) years, and ranging from 21 to 47 years, and an average body mass index of 20.6 (SD 2.4) kg/m^2, ranging from 16.8 to 27.7 kg/m^2. The subjects were tested bilaterally at a self-selected normal walking speed during their walking for 8 m after the first four strides. Three sets of data with a whole gait cycle were obtained. The subjects were instructed to "Walk straight at your comfortable speed". The subjects walked barefoot on a hard surface at an average walking speed of 1.25 m/s. (SD 0.12 m/s.). The subjects took a rest before each trial until they had recovered from fatigue.

The kinematic data were collected by a three-dimensional motion analysis system using four infrared light cameras (RroRflex, Qualisys AB Inc., Gothenburg, Sweden). Ground reaction forces during the tests were also measured using two multi-component force plates (OR6, Advanced Mechanical Technology Inc., Watertown, New York). Motion and force data were collected at 120 Hz respectively. Three-dimensional motion data were processed using Qualisys Track Manager (Qualisys Track Manager 3D, Qualisys AB Inc., Gothenburg, Sweden). Force data were used to identify the time of heel strike in each gait cycle. A gait cycle was defined as the interval between heel strike to heel strike on the ipsilateral side. Light-reflective markers were placed by physical therapists well-trained in the PCT and body surface anatomy[6]. Kinematic measurements were made of 21 light-reflective markers arranged on two limb segments, creating separate cluster groups of 11 markers on the thigh and 10 markers on the shank.

The PCT employs an overabundance of markers (a cluster) placed on each segment to minimize the skin motion artifact due to segmental form change by muscle contraction and marker-oscillation[6]. The PCT is based on a cluster of points uniformly distributed on the limb segment. Each point is assigned an arbitrary mass, which can be varied at each time step. The center of mass and the inertia tensor of the cluster of points are calculated as described below. The eigenvalues and the eigenvectors of the inertia tensor are the principal moments of inertia and the principle axes of the point cluster. The eigenvectors establish a transformation between the segment and the global coordinate system. The eigenvalues are invariant to movement if the segment is behaving as a rigid body. If the eigenvalues change from their value in the rest position, then the segment where the markers are placed has deviated from rigid body movement. The individual weighting is adjusted by redistributing the weight factors at each time step to minimize the eigenvalue changes. This procedure reduces the artifact due to non-rigid body movement. Alexander et al. examined the PCT using simulation trials with systematic and random components of deformation error introduced into marker position vectors[7]. They also tested the PCT in vivo with a subject fitted with an external fixation device (Ilizarov). The average location and orientation measurement errors of the PCT were 0.6 mm (SD 0.6 mm, maximum approximately 3 mm) and 0.5 degrees (SD 0.5 degrees, maximum approximately 4 degrees) respectively[7]. Another study has also reported an accuracy of 0.79 degrees (SD 0.48 degrees) for flexion-extension, 1.79 degrees (SD 0.93 degrees) for internal-external rotation, and 0.40 degrees (SD 0.12 degrees) for abduction-adduction[8]. Intra-class correlations coefficients (1, 5) and standard errors of measurement of the PCT have been calculated using the data of a previous study and indicate substantial or almost perfect reliability[9]. In the present study, the coordinate system of the knee joint by Grood and Santay was used[10]. Six degrees of freedom knee-joint kinematics were estimated using the PCT. The position coordinate data were converted to flexion-extension (FE), abduction-adduction (AA), internal-external (IE) rotation, and the anterior-posterior (AP), medial-lateral (ML), superior-inferior (SI) translation of the tibia with respect to a gait cycle[6]. Data from three trials were averaged and the average was used for the analysis of each limb. The value of the right leg subtracted from that of the left leg was defined as the side-to-side difference in rotation/translation in each stage of the gait cycle. We then determined the average side-to-side differences and their 95% confidence intervals (CIs).

For statistical analysis, one-way analysis of variance and post-hoc Bonferroni tests were performed to compare the average side-to-side difference of each motion among 0%, 20%, 40%, 60% and 80% of the time of a gait cycle. Differences were considered statistically significant at p < 0.05 with Bonferroni adjustment for post-hoc multiple comparisons.

RESULTS

Based on the ground reaction forces of the force plates, the stance and swing phases during walking were determined. As a result, 0% to mean 61.6% (SD 1.3%) of the gait cycle was regarded as the stance phase. Therefore, 0%, 20%, 40%, 60% and 80% of the gait cycle were considered as the early stance phase, the middle stance phase, the late stance phase, the early swing phase and the late middle swing phase, respectively.

The average knee kinematics pattern of the right and left legs during a gait cycle are shown in Fig. 1. Regarding FE of the knee during walking, the average values (95% CIs) of side-to-side differences at each time frame of normal walking were 4.3 degrees (3.0 to 5.7 degrees), 4.9 degrees (3.5 to 6.3 degrees), 4.4 degrees (2.9 to 5.9 degrees), 7.4 degrees (5.2 to 9.6 degrees) and 5.4 degrees (3.4 to 7.3 degrees) at 0%, 20%, 40%, 60%, and 80% of the gait cycle, respectively (Fig. 2-A, Table 1). There were no significant differences in the side-to-side differences of FE among 0%, 20%, 40%, 60%, and 80% of the gait cycle (p=0.086). The average side-to-side differences (95%CIs) of AA were 3.8 degrees (2.6 to 5.1 degrees), 4.5 degrees (2.7 to 6.4 degrees), 3.2 degrees (2.1 to 4.3 degrees), 5.4 degrees (3.6 to 7.2 degrees) and 8.9 degrees (5.9 to 11.9 degrees) at 0%, 20%, 40%, 60%, and 80% of the gait cycle, respectively (Fig. 2-B, Table 1). The side-to-side difference of AA at 80% of the walking cycle
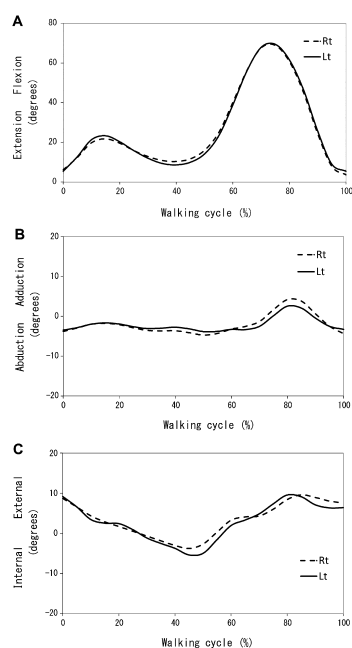
Fig. 1. The average knee kinematics pattern of the right and left legs during a gait cycle
A) flexion-extension; B) adduction-abduction; C) internal-external rotation of the tibia
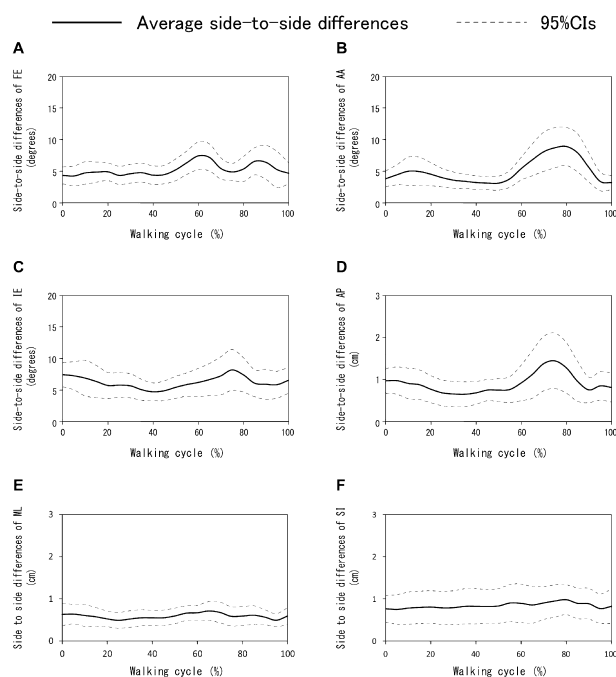

Fig. 2. The 95% confidence intervals (CIs) of side-to-side differences of the normal subjects
A) flexion-extension (FE); B) abduction-adduction (AA); C) internal-external (IE) rotation; D) anterior-posterior (AP) translation; E) medial-lateral (ML) translation; F) superior-inferior (SI) translation

Table 1. The average of side-to-side differences and their 95% confidence intervals in each stage of the gait cycle

walking cycle		0%	20%	40%	60%	80%
Rotation (degrees)	flexion-extension	4.3 (3.0–5.7)	4.9 (3.5–6.3)	4.4 (2.9–5.9)	7.4 (5.2–9.6)	5.4 (3.4–7.3)
	abduction-adduction	3.8 (2.6–5.1)	4.5 (2.7–6.4)	3.2 (2.1–4.3)	5.4 (3.6–7.2)	8.9 (5.9–11.9)[a]
	internal-external	7.4 (5.5–9.4)	5.7 (3.7–7.8)	4.7 (3.3–6.1)	6.2 (4.0–8.4)	7.4 (4.7–10.2)
Translation (mm)	anterior-posterior	9.7 (6.7–12.7)	7.7 (4.5–10.9)	6.8 (4.1–9.6)	9.2 (5.0–13.4)	12.8 (6.8–18.8)[b]
	medial-lateral	6.3 (3.7–9.0)	5.3 (3.4–7.1)	5.5 (3.7–7.3)	6.7 (4.9–8.5)	5.9 (3.7–8.1)
	superior-inferior	7.7 (4.5–10.8)	8.1 (4.2–11.9)	8.2 (4.1–12.4)	8.9 (4.4–13.5)	9.8 (9.8–18.8)

(Mean, 95% CI)
a: post-hoc Bonferroni tests (vs. 0%: p<0.001, vs. 20%: p<0.001, vs. 40%: p<0.001, vs. 60%: p<0.001)
b: post-hoc Bonferroni test (vs. 40% p<0.001)

was significantly greater than those at 0%, 20%, 40% and 60% of the gait cycle (vs. 0%: p<0.001, vs. 20%: p<0.001, vs. 40%: p<0.001, vs. 60%: p<0.001). The average side-to-side differences (95%CIs) of IE rotation were 7.4 degrees (5.5 to 9.4 degrees), 5.7 degrees (3.7 to 7.8 degrees), 4.7 degrees (3.3 to 6.1 degrees), 6.2 degrees (4.0 to 8.4 degrees) and 7.4 degrees (4.7 to 10.2 degrees) at 0%, 20%, 40%, 60%, and 80% of the gait cycle, respectively (Fig. 2-C, Table 1). There were no significant differences in the side-to-side differences of IE rotation among 0%, 20%, 40%, 60%, and 80% of the gait cycle (p=0.332). At 0%, 20%, 40%, 60%, and 80% of the gait cycle, the average values (95% CIs) of side-to-side differences of AP translation were 9.7 mm (6.7 to 12.7 mm), 7.7 mm (4.5 to 10.9 mm), 6.8 mm (4.1 to 9.6 mm), 9.2 mm (5.0 to 13.4 mm) and 12.8 mm (6.8

to 18.8 mm), respectively (Fig. 2-D, Table 1). The side-to-side difference of AP translation at 80% of the gait cycle was significantly greater than that at 40% of the gait cycle (p=0.001). The average side-to-side differences (95%CIs) of ML translation were 6.3 mm (3.7 to 9.0 mm), 5.3 mm (3.4 to 7.1 mm), 5.5 mm (3.7 to 7.3 mm), 6.7 mm (4.9 to 8.5 mm) and 5.9 mm (3.7 to 8.1 mm), respectively (Fig. 2-E, Table 1). There were no significant differences in the side-to-side differences of ML translation among 0%, 20%, 40%, 60%, and 80% of the walking cycle (p=0.875). Similarly the average side-to-side differences (95%CIs) of SI translation were 7.7 mm (4.5 to 10.8 mm), 8.1 mm (4.2 to 11.9 mm), 8.2 mm (4.1 to 12.4 mm), 8.9 mm (4.4 to 13.5 mm) and 9.8 mm (9.8 to 18.8 mm), respectively (Fig. 2-F, Table 1). There were no significant differences in the side-to-side differences of

SL translation among 0%, 20%, 40%, 60%, and 80% of the walking cycle (p=0.947).

For clinical application, the knee kinematics of a case with the posterior cruciate ligament injury (PCL) were also evaluated. A 37 year-old male suffered a knee injury while playing rugby football. The case showed grade-3 positive in the posterior drawer test, and posteromedial rotatory instability[11]. The MRI images indicated a PCL injury. At two months after injury, evaluation of 3-D kinematics during walking was performed using the same procedures described above. Based on the side-to-side differences of kinematic data during each stage of gait, the tibia of the injured leg was shifted posteriorly in AP translation during 20% to 60% walking cycle, and shifted internally in IE rotation during 0% to 60% gait cycle (Fig. 3).

DISCUSSION

The present study investigated the side-to-side differences in kinematics of the knee joint during walking by healthy subjects. The side-to-side differences in adduction-abduction rotation and anterior-posterior translation of the tibia were found to be highly dependent on the stage of gait, and they were significantly larger in the swing phase than in the stance phase. Therefore, our findings suggest that it is important to know the normal ranges of the side-to-side differences in knee kinematics in each stage of the gait cycle, in particular those of adduction-abduction and anterior-posterior translation of the knee, in order to evaluate the knee kinematics of subjects during walking. The reason why the side-to-side differences of adduction-abduction rotation and anterior-posterior translation of the tibia during walking are larger in the swing phase than in the stance phase remain unknown. One possible reason is mechanical restraint of the motion of the tibia during walking. The leg is not subject to weight bearing in the swing phase, and the tibia can move with less mechanical restraint in the swing phase than in the stance phase. Without weight bearing, the knee is relaxed and the joint kinematics are likely to be influenced by ligament balance, rather than joint morphology.

The knee kinematics during walking of a PCL injury case are also presented. For this case, an abnormal side-to-side difference in internal rotation of the tibia during walking as well as an abnormal side-to-side difference in posterior

translation of the tibia were found. Li et al. reported that PCL deficiency significantly increases posterior translation of the tibia during knee flexion under a weight-bearing condition using a dual-orthogonal fluoroscopic system[12]. However, there was no significant difference in internal-external rotation between PCL-injury and normal knees throughout the range of flexion. In our present study, the case might have had associated injuries of posteromedial structures of the knee. Previous cadaver studies have shown that additional injuries of posteromedial structures significantly increase internal rotation of the tibia as well as posterior translation of the tibia in PCL deficient knees[13–15].

Regarding clinical relevance, our findings indicate that the evaluation of the side-to-side difference of knee-joint kinematics provides useful information for clinical practice. However, caution is required in the clinical application of the evaluation of the side-to-side difference of knee-joint kinematics during walking because, there is a possibility that the contralateral leg would functionally adapt to the condition after trauma or disease. Some investigators have reported that the contralateral leg as well as the injured leg functionally adapt to the condition after the injury of the ACL and show the so-called quadriceps-avoidance gait[16–19]. Therefore, the evaluation of the side-to-side difference of knee joint kinematics may underestimate the knee kinematics of an injured leg.

Three-dimensional motion analysis based on skin marker systems has been reported. While this approach can measure in vivo kinematics of the knee in a dynamic condition, namely in a more physiological condition, it has been reported to have low accuracy due to skin movement artifacts[20, 21]. The recently described PCT employs an over-abundance of markers (a cluster) placed on each segment to minimize the effects of skin movement artifact[6]. The PCT can be extended to minimize skin movement artifacts by optimal weighting of the markers according to their degree of deformation[6]. Furthermore PCT permits direct in vivo measurement of the complete six-degrees-of-freedom motion of the kinematics of the knee during activities of daily living. PCT has, therefore, recently attracted attention, since the data of three dimensional kinematics of the knee during activities of daily living including walking are considered to reflect function of the knee joint.

Walking speed, surface condition, and shoes presumably influence the results of gait analysis. In addition it is important to recognize there is variability in normal gait. The knee kinematics measured in this study during walking and gait speed were similar to those reported by other investigators[22–26].

The present study had a few limitations. First, since the point cluster technique is based on skin makers, the accuracy of the relative positions of the femur with respect to the tibia depends on the marker attachment technique of the examiner. Second, the sample size of the present study, 21, was not large enough to determine the normal range of the side-to-side-difference of the knee kinematics during walking. Third, the effect of age or gender differences was not investigated in the present study. However, no significant differences have been reported between age groups and gender in previous knee kinematics studies[27–29], suggesting
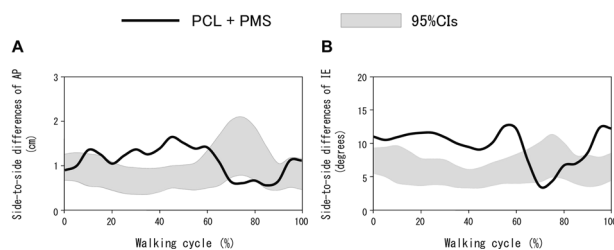

Fig. 3 The side-to-side difference of the femur relative to the tibia in the case with PCL and PMS injuries with the 95% confidence intervals (CIs) of the normal subjects
A) anterior-posterior (AP) translation; B) internal-external (IE) rotation

their effects in this study would have been small. Despite the above-noted limitations, the mean side-to-side differences and their 95% CIs as objective criteria of normal knee kinematics are useful information for the functional evaluation of subjects with disorders of the knee joint.

In conclusion, the knee kinematics of healthy subjects during walking were measured using the PCT, and the normal range of side-to-side differences in knee kinematics were determined for five stages of the gait cycle. The side-to-side differences in AA rotation and AP translation were highly dependent on the stage of gait; therefore, the normal ranges of the side-to-side differences in knee kinematics of each stage of gait, in particular AA rotation and AP translation of the tibia, are useful information for the evaluation of the normal and pathological knee kinematics during walking.

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