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Original Article

The effects of toe direction on three-dimensional knee kinematics during closed kinetic chain exercise in patients with anterior cruciate ligament deficient knee

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ABSTRACT

Background/Objective: Closed Kinetic Chain Exercise (CKC Ex) is a safe rehabilitation method for anterior cruciate ligament deficient (ACLD) and reconstructed knees. However, CKC Ex can be risky based on abnormal toe directions. The purpose was to investigate knee kinematics during CKC Ex under three toe directions in ACLD.

Methods: Twenty patients with unilateral ACL injury participated. The subjects performed five weight-bearing-static lunge tests on each limb under three toe directions, including 0 degrees (TN), 20 degrees (TI), and -20 degrees (TO). Three-dimensional knee kinematics were calculated using three-dimensional motion analysis system and were compared among three different toe directions.

Results: Among three different toe directions, peak values of knee valgus and external rotation on ACLD side were significantly larger in TO than in TN and TI. In addition, the total excursion in the coronal plane on ACLD side was significantly larger in TO than in TN and TI. Regarding the differences between ACLD and ACLI, peak values of internal rotation angle was significantly smaller in ACLD than in ACLI.

Conclusion: From the present results, tibial rotation and knee abduction were strongly affected by toe direction. When considering a safe rehabilitation, it would be better to avoid TI and TO in CKC Ex in patients with unilateral ACL injury.

Introduction

Traditionally, closed kinetic chain (CKC) exercise has been used as safe and reliable rehabilitation method for anterior cruciate ligament deficient (ACLD) and reconstructed (ACLR) knees, as CKC exercise induces co-contraction of the agonist and antagonist muscles.[1–9] Proponents of CKC exercise believe that it is more effective than open kinetic chain (OKC) exercise to restore quadriceps femoris muscle strength, and safer than OKC as the accompanying joint compression is considered to limit anterior tibial displacement.[10] Clinically, a previous randomized controlled study investigated early (4 weeks) versus late (12 weeks) start of OKC quadriceps exercises and compared ACLR with bone-patellar tendon-bone and Hamstrings.[11] This study concluded that the Hamstrings group with an early start had more laxity after a follow-up period of 7 months than the other groups. Besides, an early start of OKC quadriceps exercises had no beneficial effect on quadriceps strength. Concerning the ACL strain, Luque-Seron JA et al suggested that the presence of the joint compressive load of CKC exercises would appear to attenuate the strain increase [12]. Therefore, CKC exercise has been used as a safe and reliable rehabilitation before and after ACL reconstruction surgery especially in the early post-operative period.[10,13,14]

On the other hand, toe direction is one of the important considerations affecting the knee kinematics in sporting activities and rehabilitation.[15–17] For example, Tran et al. investigated the effect of foot landing position on biomechanical risk factors associated with ACL injury using healthy participants with motion capture system

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during double-leg jump landing activities and indicated that toe-in landing position exacerbated biomechanical risk factors associated with ACL injury, while toe-out landing position decreased these factors.[15] Furthermore, Ishida et al. assessed the knee rotation during dynamic knee valgus while maintaining the knee flexion angle at 30°, and evaluated whether the knee rotation should be affected by three different toe directions using healthy females.[16] They concluded that the knee rotated externally during dynamic knee valgus, and the knee rotation was affected by toe direction. However, little attention has been paid to the relationship between the three-dimensional knee kinematics and toe direction during CKC exercise in patients with ACLD so far.

The purpose of the present study was to investigate knee kinematics during CKC exercise under three different toe directions, including Toe Neutral (TN), Toe-In (TI) and Toe-Out (TO) in patients with unilateral ACL injury, and to clarify toe directions would affect three-dimensional knee kinematics. It was hypothesized that tibial internal rotation would be affected by toe directions on both sides and compensatory mechanics should be observed only on ACLD side due to the rotational instability.

Materials and methods

Twenty patients (11 females and 9 males with a mean age of 24.4 ± 7.0 years and a mean BMI of 22.4 ± 1.9 kg/m^2), who were diagnosed as isolated unilateral ACL injury by physical examination and MRI, participated in the present study. In terms of meniscus injury, three cases had a small longitudinal tear in the posterior aspect of the lateral meniscus, and none of the patients had any meniscal symptom such as subjective pain and locking. None of the subjects had any history of major injuries or surgeries to the trunk and lower extremities except for the unilateral knee joint. A written informed consent form approved by Institutional Review Board of our university was obtained in each subject.

The measurements were performed using a motion analysis system which consisted of 8 cameras (120 frames/s; Oqus, Qualisys, Sweden) and retro-reflective markers (14 mm in diameter). The three-dimensional gait analysis was carried out by the Point Cluster Technique using 23 reflective markers placed on each segment of the lower limb and iliac crest as described by Andriacchi et al. (Fig. 1). The subjects performed five weight-bearing-static lunge tests (Static Lunge) on each limb under three toe directions, including 0° (Toe Neutral; TN), 20° (Toe In; TI), and −20° (Toe Out; TO) (Fig. 2). Toe angles were set using the same sheet for each participant, and TN was defined as 0° based on a previous study.[16] To perform the Static Lunge, the measured foot was placed in front and the unmeasured foot was placed behind the measured foot. Subject was asked to tilt the trunk by 30° and the knee flexion on measured side was set at 60° (Fig. 1). We confirmed the angles of trunk and knee flexion using a goniometer. Static Lunge was done bilaterally for anterior cruciate ligament deficient (ACLD) and intact (ACLI) knees.

Three-dimensional knee kinematics were calculated in three different toe directions. Peak values of knee flexion, valgus, and internal rotation angles were assessed. Knee valgus and internal rotation were defined as tibial abduction and rotation with respect to the femur, respectively. In addition, total excursions in each plane were evaluated at the knee joint.

The data collected for each limb were compared among three different toe directions using one-way repeated measures of ANOVA and Bonferroni correction as a post hoc test. For comparison between ACLD and ACLI, two-way ANOVA was conducted. The statistical significance level was set at P = .05. All statistical analyses were performed using SPSS® for Windows version 23 software (Microsoft, Chicago, IL).

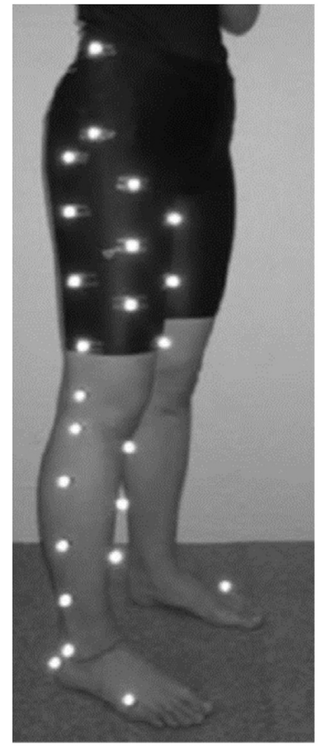

Fig. 1. The three-dimensional gait analysis was carried out by the Point Cluster Technique using 23 reflective markers placed on each segment of the lower limb and iliac crest as described by Andriacchi et al.

Results

Peak knee flexion angles were 60.2 ± 9.8°, 61.9 ± 9.6°, and 56.6 ± 6.9° in TN, TI, and TO, respectively (Table 1). There were no significant differences among groups. The target flexion angle (60°) was thus almost obtained in each toe direction. Among three different toe directions, peak values of knee valgus and external rotation angle on ACLD side were significantly larger in TO than in TN and TI (Table 1). In addition, the total excursion in the coronal plane (valgus-varus) on ACLD side was significantly larger in TO than in TN and TI (Table 2).

Peak values of internal rotation angle were significantly smaller in ACLD than in ACLI among three different toe directions (Fig. 3). Moreover, total excursion in the sagittal plane significantly decreased in ACLD than in ACLI (Fig. 4). In other parameters, no significant interaction was found between ACLD and ACLI.

Discussion

The results of the present study supported the hypothesis that tibial internal rotation would be affected by toe directions on both sides and compensatory mechanics should be observed only on ACLD side due to the rotational instability. It was shown that peak values of knee valgus and external rotation angles were significantly larger in TO than in TN and TI, and peak value of tibial internal rotation angle was significantly smaller in ACLD than in ACLI among three different toe directions. Ishida et al. indicated that the knee rotated externally during dynamic knee valgus and that the knee rotation was affected by toe direction.[16] In addition, they suggested that the ACL may impinge on the femoral condyle in dynamic valgus, especially in the toe-out position because of knee abduction and external rotation. Olsen et al. suggested that the mechanism of ACL injury was knee abduction combined with

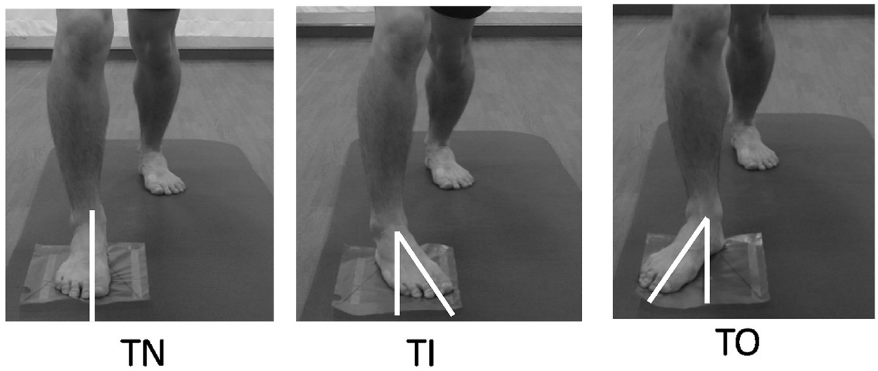

Fig. 2. Toe directions were confirmed using a same sheet for each participant, including 0° (Toe Neutral; TN), 20° (Toe In; TI), and −20° (Toe Out; TO).

Table 1
Peak knee angles of ACLD in three different toe directions (mean ± SD).

	TN	TI	TO	p Value[a]
Flexion (°)	60.2 ± 9.8	61.9 ± 9.6	56.6 ± 6.9	0.172
Valgus (°)	6.0 ± 8.6	2.1 ± 9.9*	11.0 ± 10.2**†	<0.05
Internal Rot (°)	−4.9 ± 8.8	1.4 ± 7.2*	−12.0 ± 9.7**†	<0.01

*$p < .05$ between TN and TI using post hoc Bonferroni correction.
**$p < .05$ between TN and TO using post hoc Bonferroni correction.
†$p < .05$ between TI and TO using post hoc Bonferroni correction.
[a] Values obtained using one-way repeated measures of ANOVA.

Table 2
Total excursion of ACLD during Static Lunge in three different toe directions (mean ± SD).

	TN	TI	TO	p Value[a]
Flexion (°)	52.6 ± 14.0	49.2 ± 12.6	53.3 ± 10.8	0.552
Valgus (°)	9.2 ± 5.2	6.7 ± 4.1*	13.3 ± 6.2**†	<0.01
Internal Rot (°)	7.4 ± 4.6	7.3 ± 5.4	9.5 ± 6.0	0.344

*$p < .05$ between TN and TI using post hoc Bonferroni correction.
**$p < .05$ between TN and TO using post hoc Bonferroni correction.
†$p < .05$ between TI and TO using post hoc Bonferroni correction.
[a] Values obtained using one-way repeated measures of ANOVA.

external rotation of the knee.[18] This combination causes impingement of the ACL on the femoral condyle and increases the risk of ACL injury. On the other hand, Tran et al. investigated the effects of three different toe positions on biomechanical risk factors for ACL injury in males and females during double-leg jump landing activities and concluded that toe-in landing position exacerbates biomechanical risk factors associated with ACL injury while toe-out landing position decreases these factors.[15] Koga et al. suggested that valgus loading would be a contributing factor in ACL injury mechanism and that internal tibial rotation is coupled with valgus motion.[19] In the present study, tibial internal rotation angle was significantly larger in TI, and valgus angle was notably larger in TO during static lunge both for ACLD and ACLI. Therefore, it should be noted that to avoid TO and TI would be a key factor for ACL injury and rehabilitation.

In terms of compensatory mechanics, peak value of tibial internal rotation angle was significantly smaller in ACLD than in ACLI among three different toe directions, and largest tibial external rotation angle was observed in TO with ACLD. Moreover, total excursion of knee flexion angle was significantly smaller in ACLD than in ACLI among three different toe directions. Generally, in gait analysis, stiffening strategy and pivot shift avoidance are well

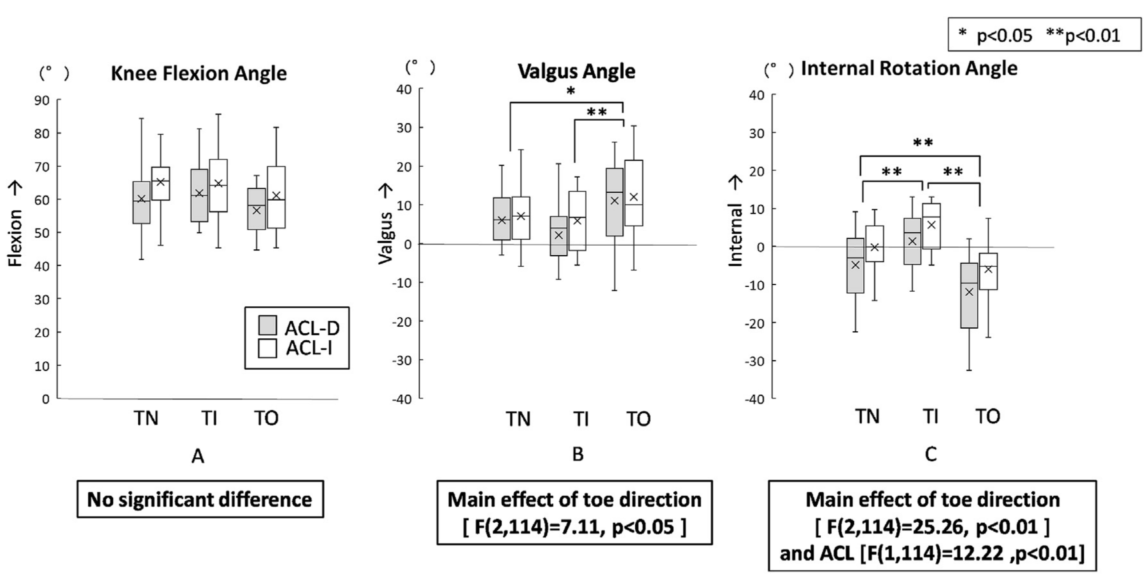

Fig. 3. Comparison of peak values of knee flexion, valgus, and internal rotation angles during Static Lunge in three different toe directions between ACLD and ACLI.

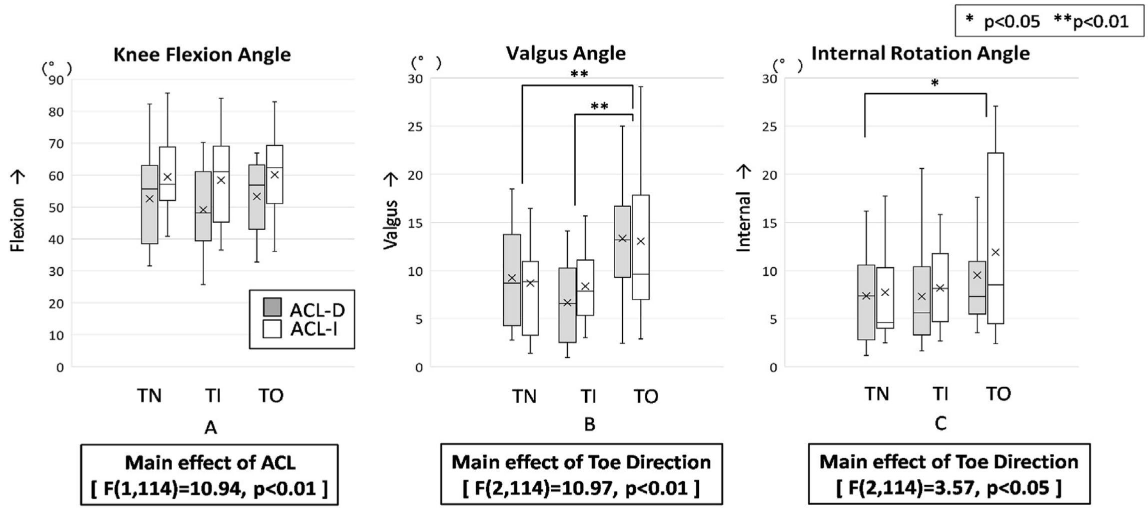

Fig. 4. Comparison of total excursion in each plane during Static Lunge in three different toe directions between ACLD and ACLI.

known.[20,21] In the present study, total excursion of knee flexion was significantly smaller as stiffening knee, and peak internal rotation of the tibia was also smaller as pivot shift avoidance. Similarly, Takeda et al. indicated that less valgus and more external tibial rotation were observed for ACLD especially in high demand motions such as jogging and jogging to a 90-degree side cutting, compared to ACLI. Although the Static Lunge is typical CKC exercise and not a high demand motion, compensatory mechanics were obvious for ACLD in the present investigation as the peak value of tibial internal rotation angle was significantly smaller in ACLD with three toe directions.

Several limitations should be noted in the present study. First, muscle strength including Quadriceps or Hamstrings was not evaluated. Thus, the influence of the muscle weakness was not known in ACLD. Second, as only the Static Lunge was included in the present study, other movements have been unknown. Lastly, biomechanics during CKC exercise after ACL reconstruction was not assessed. Therefore, it was impossible to clarify whether compensatory mechanics could be improved or not after the surgery. Nonetheless, the present results provide valuable information regarding the safe knee kinematics for ACLD during CKC exercise.

In conclusion, the results of the present study showed that tibial rotation and knee abduction were strongly affected by toe direction even in CKC exercise. Although patients could maintain the safe position during CKC exercise, compensatory movement was observed in ACLD based on toe directions. It would be better to avoid not only TI but TO even in CKC exercise.

Conflicts of interest

The authors have no conflicts of interest relevant to this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.asmart.2019.07.002.

References

1. Abbas C, Daher J. Pilot study: post-operative rehabilitation pathway changes and implementation of functional closed kinetic chain exercise in total hip and total knee replacement patient. *J Bodyw Mov Ther*. 2017;21:823–829.
2. Felicio LR, Saad MC, Liporaci RF, Baffa Ado P, dos Santos AC, Bevilaqua-Grossi D. Correlation between trochlear groove depth and patellar position during open and closed kinetic chain exercises in subjects with anterior knee pain. *J Appl Biomech*. 2012;28:335–342.
3. Adouni M, Shirazi-Adl A. Knee joint biomechanics in closed-kinetic-chain exercises. *Comput Methods Biomech Biomed Eng*. 2009;12:661–670.
4. Stensdotter AK, Dalen T, Holmgren C, Hager-Ross C. Knee angle and force vector-dependent variations in open and closed kinetic chain for M. popliteus activation. *J Orthop Res*. 2008;26:217–224.
5. Enocson AG, Berg HE, Vargas R, Jenner G, Tesch PA. Signal intensity of MR-images of thigh muscles following acute open- and closed chain kinetic knee extensor exercise - index of muscle use. *Eur J Appl Physiol*. 2005;94:357–363.
6. Perry MC, Morrissey MC, King JB, Morrissey D, Earnshaw P. Effects of closed versus open kinetic chain knee extensor resistance training on knee laxity and leg function in patients during the 8- to 14-week post-operative period after anterior cruciate ligament reconstruction. *Knee Surg Sport Traumatol Arthrosc*. 2005;13:357–369.
7. Kvist J, Gillquist J. Sagittal plane knee translation and electromyographic activity during closed and open kinetic chain exercises in anterior cruciate ligament-deficient patients and control subjects. *Am J Sports Med*. 2001;29:72–82.
8. Morrissey MC, Hudson ZL, Drechsler WI, Coutts FJ, Knight PR, King JB. Effects of open versus closed kinetic chain training on knee laxity in the early period after anterior cruciate ligament reconstruction. *Knee Surg Sport Traumatol Arthrosc*. 2000;8:343–348.
9. Taylor RA, Marshall PH, Dunlap RD, Gable CD, Sizer PS. Knee position error detection in closed and open kinetic chain tasks during concurrent cognitive distraction. *J Orthop Sport Phys Ther*. 1998;28:81–87.
10. Glass R, Waddell J, Hoogenboom B. The effects of open versus closed kinetic chain exercises on patients with ACL deficient or reconstructed knees: a systematic review. *N Am J Sports Phys Ther*. 2010;5:74–84.
11. Heijne A, Werner S. Early versus late start of open kinetic chain quadriceps exercises after ACL reconstruction with patellar tendon or hamstring grafts: a prospective randomized outcome study. *Knee Surg Sport Traumatol Arthrosc*. 2007;15:472–473.
12. Luque-Seron JA, Medina-Porqueres I. Anterior cruciate ligament strain in vivo: a systematic review. *Sport Health*. 2016;8:451–455.
13. Keays SL, Sayers M, Mellifont DB, Richardson C. Tibial displacement and rotation during seated knee extension and wall squatting: a comparative study of tibiofemoral kinematics between chronic unilateral anterior cruciate ligament deficient and healthy knees. *The Knee*. 2013;20:346–353.
14. van Melick N, van Cingel RE, Brooijmans F, et al. Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. *Br J Sports Med*. 2016;50:1506–1515.
15. Tran AA, Gatewood C, Harris AH, Thompson JA, Dragoo JL. The effect of foot landing position on biomechanical risk factors associated with anterior cruciate ligament injury. *J Exp Orthop*. 2016;3:13.
16. Ishida T, Yamanaka M, Takeda N, Aoki Y. Knee rotation associated with dynamic knee valgus and toe direction. *The Knee*. 2014;21:563–566.
17. Ishida T, Yamanaka M, Takeda N, et al. The effect of changing toe direction on

knee kinematics during drop vertical jump: a possible risk factor for anterior cruciate ligament injury. *Knee Surg Sport Traumatol Arthrosc*. 2015;23: 1004–1009.

18. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med*. 2004;32:1002–1012.
19. Koga H, Nakamae A, Shima Y, et al. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *Am J Sports Med*. 2010;38:2218–2225.
20. Fuentes A, Hagemeister N, Ranger P, Heron T, de Guise JA. Gait adaptation in chronic anterior cruciate ligament-deficient patients: pivot-shift avoidance gait. *Clin Biomech*. 2011;26:181–187.
21. Hurd WJ, Snyder-Mackler L. Knee instability after acute ACL rupture affects movement patterns during the mid-stance phase of gait. *J Orthop Res*. 2007;25: 1369–1377.