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Original Article

Factors associated with dynamic knee valgus angle during single-leg forward landing in patients after anterior cruciate ligament reconstruction

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ABSTRACT

Background: A few studies have reported on how to predict increased dynamic knee valgus angle (KVA), a risk factor for second anterior cruciate ligament (ACL) injury after ACL reconstruction. This study aimed to identify the factors with the potential to predict the KVA during single-leg hop landing.

Methods: Using three-dimensional motion analysis systems, knee motion during a single-leg hop landing task was measured in 22 patients who had undergone ACL reconstruction at 8–10 months postoperatively. The KVA at initial contact (IC) and maximum KVA during the 40-ms period after IC were calculated using the point cluster technique; correlations between the KVA and other factors were assessed. We performed multiple regression analysis to determine whether KVA could be predicted by these parameters.

Results: The KVA was significantly negatively correlated with the static femorotibial angle (FTA; $P < 0.01$) and patient height ($P < 0.01$). It was positively correlated with the body mass index ($P < 0.05$). Multiple regression analysis showed that a small FTA could predict the KVA at IC (β : 0.52, 95% confidence interval (CI): 2.24–(–0.42); $P < 0.01$). The maximum KVA during the 40-ms period after IC was associated with the FTA (β : 0.46, 95% CI: 2.22–(–0.26); $P = 0.02$) and height (β : 0.40, 95% CI: 0.59–(–0.02); $P = 0.04$).

Conclusion: At 8–10 months after ACL reconstruction, the KVA was significantly correlated with the FTA, with reduced FTA being associated with an increased dynamic KVA during single-leg hop landing. The measurement of anatomical parameters may aid in predicting the second ACL injury risk after reconstruction.

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Introduction

The revision rate after anterior cruciate ligament (ACL) reconstruction in younger athletes is 7% for an ipsilateral re-injury and 8% for a contralateral injury, according to a systematic review and meta-analysis.¹ Revision ACL reconstruction results in dysfunction of the reconstructed ligament in 40% of the patients² and is associated with lower mean International Knee Documentation Committee subjective score (74.8 points)³ compared with primary ACL

reconstruction (84 points).⁴ As repeated reconstruction is associated with inferior knee function and reduced activity in daily life, there is need for research on the prevention of ACL re-injury. The risk factors for secondary ACL injury include body mass index (BMI) $> 35 \text{ kg/m}^2$,⁵ younger age at reconstruction (especially for men aged < 21 years),^{5–7} return to sports in the first 12 months after reconstruction,⁸ and receipt of an allograft or hamstring autograft rather than a bone-patellar tendon-bone autograft.^{5,9} Therefore, multiple factors should be considered for reducing the risk of a second ACL injury.

A three-dimensional motion analysis is used to assess knee function during dynamic movements, such as jumping, and to

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determine the appropriate time for return to sports after ACL reconstruction. Koga et al.¹⁰ reported that rapid valgus motion occurs on ACL injury, and female soccer players who return to sports after ACL reconstruction have significantly increased knee valgus angle (KVA) compared with those with no ACL injury history.¹¹ Paterno et al.¹² found that the risk of a second ACL injury can be predicted by analysing the effects of a landing task on the transverse plane hip kinetics, frontal plane knee kinematics, and sagittal plane knee moment. Therefore, 3-D motion analysis of the KVA may aid in assessing the risk of secondary ACL injury.

Only a few studies have examined the relationship between the biomechanics of landing and measures of physical power, such as muscle strength.^{13,14} Drop vertical jump studies involving athletes who had undergone ACL reconstruction reported that athletes with lower quadriceps strength had lower external knee flexion moment¹³ and landed more asymmetrically (with knee excursion and trunk flexion).¹⁴ Another drop vertical jump study found no significant relationship between knee joint laxity and peak knee power.¹⁵ Studies on frontal knee kinematics during landing have reported that in healthy people, these kinematics is affected by sex,¹⁶ static KVA, and height.¹⁷ However, a few studies have been conducted with an emphasis on the risk factors for secondary ACL injury.¹⁵ Moreover, to the best of our knowledge, previous studies on factors predicting KVA during landing have not used common clinical assessments, such as tests of knee muscle strength or measurement of the femorotibial angle (FTA) based on X-ray imaging.

Several different landing tasks may be used for physical assessments. Heebner et al.¹⁸ compared the biomechanics of several landing tasks and reported no significant difference in the KVA between forward jump to single-leg landing and double-leg drop landing. However, since the single-leg hop landing allows us to focus exclusively on the reconstructed knee, we chose it as the most appropriate task for studying the effect of ACL reconstruction.

This study aimed to investigate factors affecting KVA during single-leg hop landing in ACL reconstruction patients. We hypothesised that sex and FTA would be at the same time significantly correlated with and predictive of KVA during landing.

Materials and methods

Study participants

This was a retrospective study. We included both men and women who were evaluated at our clinic for unilateral ACL injury and underwent unilateral ACL reconstruction or augmentation. This study was approved by the ethics committee of our institution (reference number E–397) and the protocols conformed to the guidelines of the Declaration of Helsinki. All participants provided informed consent.

The inclusion criteria for the present study were, as follows: age <40 years; BMI <35 kg/m²; no visible evidence of knee osteoarthritis in plain radiographs; no macroscopic or radiographic evidence of injury to articular or meniscus cartilage in the tibiofemoral and patellofemoral joints during ACL reconstruction; no limitation in the range of knee motion postoperatively; no self-reported knee pain or apprehension on landing after the surgery; absence of other injuries or functional limitations in either lower limb preoperatively or postoperatively; attendance at 6-month follow-up after reconstruction; and absence of neurological disease.

All ACL reconstruction and augmentation procedures were performed by experienced surgeons using previously described surgical procedures.^{19–23} For patients with a remnant of approximately one-third or more of the original ACL, which could serve as a ligamentous bridge between the tibia and femur, augmentation

was performed using a quadrupled semitendinosus tendon graft. In the absence of sufficient ACL remnants, reconstruction was performed using a quadrupled semitendinosus tendon graft, with either the single- or double-bundle technique, depending on the diameter of the graft and size of the tibia and femur. The reconstructed knee was immobilised using a soft knee brace for 3 days postoperatively. The patients were allowed knee movement exercises with the brace at 3 days postoperatively; partial weight-bearing, 10 days postoperatively; and full weight-bearing, 17 days postoperatively. After leaving the hospital, they were followed-up at the outpatient clinic and continued to use the braces until 3 months postoperatively. Running was allowed at 4.5 months following the surgery and sports training (such as jumping) was allowed at 6 months postoperatively.

Measurement of the muscle strength and anterior tibial translation

The clinical assessments of knee muscle strength and anterior tibial translation (ATT) relative to the femur were performed by a skilled physiotherapist at 6 months after ACL reconstructed. Specifically, we measured the quadriceps and hamstring strength on the reconstructed side and side-to-side differences in the ATT. After these assessments, the patients were permitted to start sports training.

The muscle torque during knee extension and flexion was measured using a Biodex Multi-Joint System isokinetic dynamometer (Biodex Medical Systems, Shirley, NY). Patients performed 10 repetitions of maximal reciprocal concentric knee extension–flexion cycles at an angular velocity of 180°/s. The maximum torque values for flexion and extension, normalised to the body weight, were used as the index of muscle strength.

The ATT was measured using a Kneelax 3 joint arthrometer (Monitored Rehab Systems, Haarlem, Netherlands) to apply a force of 133 N with the knee flexed at 20°. The side-to-side difference in the ATT was calculated by subtracting the value for the uninjured side from that for the injured side. The FTA was measured by an experienced orthopaedic surgeon using full-length anteroposterior radiographs of the lower limbs.

Landing task

After performing the point cluster technique (PCT) described by Andriacchi et al.,²⁴ we placed 21 reflective skin markers on the reconstructed leg of each participant. Three-dimensional motion analysis was performed using a VICON MX system (Vicon Motion Systems, Oxford, UK) with 16 infrared cameras capturing motion data at a sampling frequency of 100 Hz. The cameras were calibrated prior to data collection, with a mean residual error of <1.0 mm. To allow calculation of the dynamic KVA, the static knee angle was measured before the PCT analysis. First, a 5-s static standing trial was recorded, during which participants looked straight ahead with their arms folded across their chest and their feet shoulder width apart. For dynamic KVA measurements, the participants hopped forward to 50% of their height on their reconstructed leg, maintaining a forward gaze and a natural motion of the upper limbs. The trials were repeated until 3 successful landings were made, with participants maintaining a single-leg stance for 5 s after landing. Initial contact (IC) was defined as a ground reaction force >10 N, measured with 8 force plates (AMTI, Watertown, MA).

Koga et al. found that ACL injury is likely to occur within 40 ms of IC.¹⁰ In individuals with reconstructed ACL, Paterno et al. found that hip internal rotation moment and net knee flexor moment during IC were predictive of second ACL injury.¹² Therefore, we measured both KVA at IC and maximum KVA over the 40-ms period

after contact. Each participant's dynamic KVA values are expressed in relation to their static knee angle.

Statistical analysis

Statistical analysis was performed using JMP Pro 13.0 (SAS, Cary, NC). Spearman rank correlation coefficients for the KVA at IC and maximum KVA during 40 ms after IC (P -values <0.05 were considered significant) were calculated for the following factors: age, height, weight, BMI, maximum muscle torque during knee extension and flexion, ATT, and FTA. Logistic regression analysis was performed to determine the differences in the KVA and other variables according to sex, measurement side, and surgical method. We also performed multiple regression analysis for the variables (FTA nearly static KVA, and height) reported to be associated with the KVA during landing by Nilstad et al.,¹⁷ and checked the normality of the residual error using the Shapiro–Wilk test.

Results

The mean KVA at IC was $0.2 \pm 6.3^\circ$ and the maximum KVA during the 40-ms period after IC was $-1.1 \pm 6.3^\circ$ ($1.1 \pm 6.3^\circ$ varus). Eight patients (three men and five women) had a valgus landing at IC. The patient characteristics and the results of the physical assessment are shown in Table 1 and Table 2.

The correlation analysis showed that both KVA values were significantly negatively correlated with the FTA and patient height (Table 3). The KVA and BMI were positively correlated (Table 3). There were no significant correlations between the KVA and age, weight, muscle torque during knee extension and flexion, or ATT (Table 3).

Logistic regression analysis revealed that female sex was associated with an increase in both KVA values during landing compared with male sex ($P < 0.05$; Table 4) and with smaller FTA (odds ratio [OR] 0.54, 95% confidence interval [CI] 0.32–0.93; $P < 0.01$) and smaller height (OR 0.42, 95% CI 0.03–1.33; $P < 0.01$). There was no relationship between the BMI and sex (OR 1.01, 95% CI 0.77–1.31; $P = 0.95$).

Multiple regression analysis revealed that the FTA was a predictive factor for the KVA during IC (β : 0.52, 95% CI: 2.24–(-0.42); $P < 0.01$; Table 5). The FTA was likewise predictive of the maximum KVA during the 40 ms after IC (β : 0.46, 95% CI: 2.22–(-0.26); $P = 0.02$), as was height (β : 0.40, 95% CI: 0.08–0.78; $P = 0.04$; Table 6). With respect to residual error, the normality was obtained with the Shapiro–Wilk in either model ($P = 0.77$ and 0.11).

Discussion

The most important findings of the present study are as follows: First, the FTA is predictive of the KVA during single-leg hop landing. Second, the KVAs are not significantly correlated with the knee muscle strength or ATT. Thus, our hypothesis was partially proven. To the best of our knowledge, this study is the first study to examine the FTA as a predictor of landing kinematics after ACL reconstruction.

In previous meta-analyses of people with reconstructed ACL, KVA values of 3.9° – 7.2° have been reported.^{25,26} In this study, KVA was 0.2° at initial contact, which is comparatively small.^{25,26} However, these studies involved a single-leg drop landing rather than a hop landing. Due to the difference in the landing task, our results differ from those of previous studies. Welling et al.²⁷ conducted a single-leg hop test at 6 months after ACL reconstruction and found that participants had KVAs of 1.5° (men) or 1.4° (women); this finding supports our results.

The KVA on landing was significantly correlated with the FTA,

Table 1
Participant characteristics (n = 22).

Characteristic	
Age (years)	21.5 ± 6.7
Body height (cm)	166.7 ± 8.5
Body weight (kg)	62.7 ± 10.9
Body mass index (kg/m ²)	22.5 ± 3.5
Preoperative Tegner activity score	6.5 ± 1.0
Time post-injury (days)	84.2 ± 45.0
Sex, men/women (n)	13/9
Measurement side, left/right (n)	9/13
Surgical methods, SBA/DB (n)	11/11
Injury situation, contact/non-contact (n)	6/16

Values are reported as the mean ± standard deviation, or as number of patients. DB, double-bundle reconstruction; SBA, single-bundle augmentation.

Table 2
Knee valgus angle (KVA) at landing and clinical assessment of patients after anterior cruciate ligament reconstruction.

Clinical parameter	Mean ± SD
KVA at IC (°, +; valgus, -; varus)	0.2 ± 6.3
Maximum KVA during the 40-ms period after IC. (°, +; valgus, -; varus)	-1.1 ± 6.3
Maximal torque of knee extension (% Nm/kg)	130.0 ± 32.5
Affected/non-affected ratio of knee extension torque (%)	76.8 ± 11.6
Maximal torque of knee flexion (% Nm/kg)	77.4 ± 20.5
Affected/non-affected ratio of knee flexion torque (%)	90.2 ± 13.9
Side-to-side difference in ATT (mm)	-0.3 ± 1.5
FTA (°)	174.5 ± 2.4

Values are reported as the mean ± standard deviation. ATT, anterior tibial translation; FTA, femorotibial angle; IC, initial contact.

participant height, and sex. A relationship between the static FTA and dynamic KVA may seem natural; however, previous studies have not reported such a relationship for single-leg hop landing in individuals with reconstructed ACLs. In healthy individuals performing a two-legged drop landing task, those who have a more externally rotated knee and valgus knee alignment experience a greater dynamic KVA compared with those who have neutral alignment.²⁸ Schmitz et al.²⁹ found healthy adult men to have smaller KVA than women during a two-legged drop landing. Our study is the first to show that in people with a reconstructed ACL, KVA during a single-leg hop landing task is linked to FTA and sex. However, we found shorter patients to have a bigger KVA during landing, and this result differs from a previous study that included only female athletes.¹⁷ Both men and women were recruited in our study; the women were significantly shorter and presented with larger KVA during landing and smaller FTA compared with men. This indicates that height and FTA are associated with sex. Thus, when using the FTA to predict the KVA during landing, we should consider the smaller FTA and shorter stature of women.

In this study, we noted a significant correlation between the dynamic KVA during landing and BMI. A previous study reported that increased BMI is associated with a greater risk of secondary ACL injury.⁵ Our results show that KVA during landing increases with an increase in the BMI. There is also a strong association between the BMI and knee varus/valgus malalignment in overweight young adults.³⁰ We believe that static valgus alignment is the best predictor of a large dynamic KVA.

In contrast, there was no significant relationship between the KVA and quadriceps or hamstring strength. Previous studies on sagittal plane kinematics have shown that low quadriceps strength leads to an asymmetric and impaired landing manoeuvre.^{13,14} Our results show that strengthening the quadriceps and hamstring muscles improves the landing manoeuvre, for instance by ensuring

Table 3
Spearman rank correlations between valgus angle at initial contact and participant characteristics.

Variables	KVA at IC		Maximum KVA during the 40-ms period after IC	
	Spearman rank correlation values (ρ)	P Value	Spearman rank correlation values (ρ)	P Value
Age	-0.29	0.19	-0.31	0.17
Body height	-0.60	< 0.01	-0.65	< 0.01
Body weight	0.09	0.69	0.05	0.81
Body mass index	0.45	0.04	0.46	0.03
FTA	-0.61	< 0.01	-0.59	< 0.01
Preoperative Tegner activity score	0.02	0.94	-0.04	0.85
Side-to-side difference in ATT	0.05	0.81	0.04	0.87
Maximal torque of knee extension	-0.26	0.24	-0.30	0.17
Affected/non-affected ratio of knee extension torque	0.35	0.12	0.31	0.16
Maximal torque of knee flexion	-0.15	0.51	-0.18	0.43
Affected/non-affected ratio of knee flexion torque	0.23	0.30	0.23	0.30

P values in bold type are significant. ATT, anterior tibial translation; FTA, femorotibial angle; IC, initial contact; KVA, knee valgus angle.

Table 4
Logistic regression analysis for the risk of sex, reconstructive surgery and measurement side.

Variables	Kinematics	Odds ratio	95% Confidence interval	P Value
Sex	KVA at IC	1.21	1.03–1.51	0.02
(Referent; men)	Maximum KVA during the 40-ms period after IC	1.20	1.03–1.47	0.02
Surgical methods	KVA at IC	0.99	0.86–1.14	0.86
(Referent; SBA)	Maximum KVA during the 40-ms period after IC	0.99	0.86–1.13	0.83
Measurement side	KVA at IC	1.08	0.93–1.27	0.92
(Referent; left)	Maximum KVA during the 40-ms period after IC	1.06	0.92–1.22	0.94

P values in bold type are significant. DB, double-bundle reconstruction; IC, initial contact; KVA, knee valgus angle; SBA, single-bundle augmentation.

Table 5
Multiple regression analysis the knee valgus angle at initial contact.

Factor	Estimate	Standardized partial regression coefficient (β)	Standard error	Confidence interval		P value
				Lower 95%	Upper 95%	
Constant	275.7		68.8	131.7	419.6	< 0.01
Body height		-0.35	0.16	-0.52	0.01	0.06
FTA		-0.52	0.43	-2.24	-0.42	< 0.01
F Statistic	12.4					< 0.01
Adjusted R-square (R^2)	0.52					

P values in bold type are significant.

Table 6
Multiple regression analysis in the maximum knee valgus angle during the 40-ms period after initial contact.

Factor	Estimate	Standardized partial regression coefficient (β)	Standard error	Confidence interval		P value
				Lower 95%	Upper 95%	
Constant	266.9		74.0	120.0	421.9	< 0.01
Body height		-0.40	0.13	-0.08	0.78	0.04
FTA		-0.46	0.47	-2.22	-0.26	0.02
F Statistic	11.3					< 0.01
Adjusted R-square (R^2)	0.50					

P values in bold type are significant.

adequate knee flexion, but does not directly affect the dynamic KVA.

There are several limitations of this study. First, our sample size was small; therefore, we used only two parameters in our multiple regression analysis. Before we can use dynamic motion analysis to accurately predict the risk of a second ACL injury, we need to examine more ACL reconstruction patients. Second, our measurements of joint kinematics and muscle strength were limited to the knee joint, the quadriceps, and the hamstring. However, previous studies have shown that hip muscle strength and trunk and hip kinematics^{31,32} also affect landing in ACL reconstruction patients. A recent systematic review³³ found a possible early onset of muscle

activity in the quadriceps and hamstring of ACL reconstruction patients during landing tasks. We did not measure the electromyography of the knee muscles, so we could not investigate muscle activity as a potential predictor of KVA during landing. Third, we used only the hamstring tendon for ACL reconstruction and did not compare bone-tendon-bone grafts or other grafts. Additionally, this was a retrospective study; therefore, we did not investigate the revision rate in our patients. Finally, we focused only on the kinematics of landing and did not describe the knee abduction moment during landing. Increased knee abduction moment predicts ACL injury in healthy female athletes³⁴; therefore, this factor should also be considered in individuals with a reconstructed ACL.

The clinical implication of the current study is that measuring the static FTA may aid in evaluating the risk of secondary ACL injury. X-ray evaluations are commonly performed during follow-up after ACL reconstruction; therefore, if the radiographs show that a patient has a small FTA, this information could aid in managing the risk of re-injury and encourage progressive rehabilitation.

Conclusion

At 8–10 months after ACL reconstruction, some patients had valgus knee alignment on initial contact during single-leg hop landing. Valgus angle was significantly correlated with patient height and static FTA, but not with isokinetic knee muscle strength or ATT. Shorter patients stature and smaller static FTA are the predictors of a larger dynamic KVA during single-leg hop landing after ACL reconstruction.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.asmart.2020.07.002>.

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