Varus Alignment Leads to Increased Forces in the Anterior Cruciate Ligament

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Background: Varus thrust of the knee is a dynamic increase of an often preexisting varus angle and it is suspected to be a major reason for failure of anterior cruciate ligament reconstructions. However, it is not known if a direct relationship exists between varus thrust and forces in the anterior cruciate ligament.

Hypothesis: Forces in the anterior cruciate ligament increase with increasing varus alignment, and consequently an anterior cruciate ligament deficiency in a varus-aligned leg leads to more lateral tibiofemoral joint opening.

Study Design: Controlled laboratory study.

Methods: Six human cadaver legs were axially loaded with 3 different weightbearing lines—a neutral weightbearing line, a weightbearing line that passes through the middle of the medial tibial plateau (50% varus), and a line passing the edge of the medial tibial plateau (100% varus)—that were used to create a varus moment. The resulting lateral tibiofemoral joint opening and corresponding anterior cruciate ligament tension were measured. The tests were repeated with and without the anterior cruciate ligament in place.

Results: In the neutral aligned legs, there was no apparent lateral joint opening, and no anterior cruciate ligament tension change was noted. The lateral joint opening increased when the weightbearing line increased from 0% to 50% to 100%. The lateral joint opening was significantly higher in 10° of knee flexion compared with knee extension. In the 100% varus weightbearing line, the anterior cruciate ligament tension was significantly higher (53.9 N) compared with neutral (31 N) or the 50% weightbearing line (37.9 N). A thrust could only be observed in the 100% weightbearing line tests. In the absence of an anterior cruciate ligament, there was more lateral joint opening, although this was only significant in the 100% weightbearing line.

Conclusion: There is a direct relationship between varus alignment and anterior cruciate ligament tension. In the absence of an anterior cruciate ligament, the amount of lateral opening tends to increase. With increasing lateral opening, a thrust can sometimes be experimentally observed.

Clinical Relevance: A varus alignment in an anterior cruciate ligament–deficient knee does not necessarily lead to a varus thrust and therefore does not always need operative varus alignment correction. However, in an unstable anterior cruciate ligament–deficient knee with a varus thrust, it might be safer to perform a high valgus tibial osteotomy to minimize the risk of an anterior cruciate ligament reconstruction failure.

Keywords: varus alignment; varus thrust; anterior cruciate ligament (ACL); ACL tension

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Varus thrust of the knee is a clinical observation of an abrupt, excessive varus moment of the knee. A thrust occurs due to the opening of the lateral tibiofemoral compartment on initiation of load-bearing during normal gait. This phenomenon is mostly observed in varus-aligned knees with an abrupt increase of the preexisting varus alignment.[6] Several anatomic structures stabilize the knee actively and passively against the varus thrust motion: the popliteal muscle-tendon, posterior joint capsule, iliotibial band, and lateral collateral ligament (LCL). It has been suggested that these posterolateral structures of the knee act as a unit to balance a varus moment.[10,21] The LCL is the most important passive stabilizer against a straight lateral thrust force. Insufficiency of this ligament will cause increased lateral compartment opening when external

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varus forces are applied. It has been demonstrated that this effect will be lower if the knee is in full extension and will be most pronounced in the 10° to 30° flexion range.[10] It is also known that a varus moment significantly correlates with high medial tibiofemoral compartment loads and high lateral soft tissue tensile forces.[20]

It is not entirely clear what role the anterior cruciate ligament (ACL) plays in the lateral stability of the knee. It is known that the ACL is relatively slack at higher knee flexion angles, but near knee extension, ACL tension increases considerably.[3,4,15,16] The knee encounters 2 peak adduction moments, or varus moments, during normal walking. The first is just after heel-strike and the second is in the swing phase.[5,9,26] A varus thrust appears in the early stance phase after heel-strike when the knee is flexed about 10°.[5,20,26] One might expect the ACL to be loaded excessively when the lateral structures are insufficient.

It is a common clinical observation that ACL reconstructions in knees with a varus thrust have a tendency to fail secondarily if the varus alignment was not addressed.[18,20] It is also thought that ACL deficiency will enhance the thrusting pattern in a preexisting varus-deformed knee.[20,25] An ACL reconstruction might therefore fail as a result of this persistent lateral laxity. It is not clear whether every varus-aligned knee with or without a clinically apparent varus thrust should be treated before an ACL reconstruction is performed.

The relationship between ACL tension and varus angulation has been addressed in a number of studies.[4,7,10,12,15-17] The experiments were conducted as cadaver studies where external forces were applied to the knee. These situations do not resemble a natural thrust that occurs in a weightbearing knee. Axial compressive loads were applied in combination with varus or valgus moments in only 1 study, and resultant ACL strain was measured in parts of the anteromedial bundle of the ACL.[7] This report shows that varus or valgus stress applied on the knee significantly increased ACL strain in a weightbearing status, whereas it did little in a non-weightbearing situation. The study, however, was executed using a fixed flexion angle of 20°.

The available literature lacks complete ACL force measurements in 10° or 0° of knee flexion when creating a varus moment by applying axial compressive loads in combination with different weightbearing lines (WBLs). Changing the WBL while applying axial loads generates a varus angle that more closely resembles what would happen during normal walking instead of applying external varus forces to the knee alone. Some studies were performed measuring or calculating tension in parts of the ACL instead of the complete ACL.[4,7,13] Moreover, we were interested in measuring the ACL tension in 0° and 10° flexed knees, because beyond this point the ACL is already slack.[15,16] The aim of this study was to (1) measure the forces in the complete, intact ACL under compressive limb forces with 3 different standardized WBLs resembling increasing varus alignment; and (2) measure the difference in lateral joint opening (LJO) in the presence or absence of the ACL.

The hypothesis is that forces in the ACL will increase with the varus alignment, and secondly that ACL deficiency in a varus-aligned leg will lead to more LJO.

MATERIALS AND METHODS

Six whole fresh-frozen human cadaver legs were stored frozen until needed and then thawed overnight. There were 3 female and 3 male legs with an average age of 72 years (range, 64-98 years). The knees were examined clinically for any signs of abnormal laxity and radiographically for the presence of degenerative changes.

Preparation of the Specimens

All muscles and soft tissues of the upper and lower leg were removed, including the patella. The ligaments, joint capsule, muscles, and fat tissue around the knee were left intact and were kept moist. The proximal fibula was fixed to the tibia with pins, in its original position, to ensure correct placement and stability of the LCL. The distal part of the fibula was then removed after the center of rotation of the ankle was determined. The tibia was sectioned so it could be potted in a device that hinged at the original point of rotation of the ankle. The proximal femur was then sectioned and potted in a loading cylinder. Subsequently, the whole leg could be placed in the loading machine (Figure 1). Posterior to the knee joint, a hinging device consisting of 2 interlocking plates was affixed to the femur and tibia to prevent all other movements except varus-valgus rotation and axial compression.

A tibial bone plug with the ACL footprint attached was then drilled out, as described earlier.[3] To do this, a guidewire was directed from the anteromedial proximal tibial cortex to the center of the ACL footprint. The wire was in a straight line with the ACL, with the knee in 10° of flexion. After the bone plug was drilled with a coring reamer, the ACL–bone plug complex was free to slide within the tibia without friction (Figure 2). This was also checked by pushing the bone plug back a few millimeters toward the knee joint, resulting in a completely slack ACL. A screw was placed in the center of the bone plug and was attached to a tensiometer. The tensiometer was fitted to a frame, which was anchored to the tibia with 2 sharp pins so it was placed in line with the ACL–bone plug. The angle between the ACL and tensiometer changed very little when extending the leg from 10° to 0°. The force sensor was a custom-made transducer consisting of a connector for the tension rod instrumented with strain gauges.[2] The sensor was connected to a bridge amplifier, which was linked to a personal computer. Before each measurement, the device was calibrated. Forces were measured with a frequency of 10 Hz. The accuracy of the system was ±1 N.

An extensiometer (MTS Systems, Minneapolis, Minnesota) was mounted on the lateral side of the knee to measure lateral compartment opening. It was attached to pins drilled in the proximal and distal insertions of the LCL. Between these pins, the extensiometer was connected with springs, which were also linked to a personal computer and could measure the LJO in the frontal plane within 12 μm.

Testing Procedure

The legs were put in a compression machine (MTS Systems), which applied dynamic axial loads of 0.5 Hz

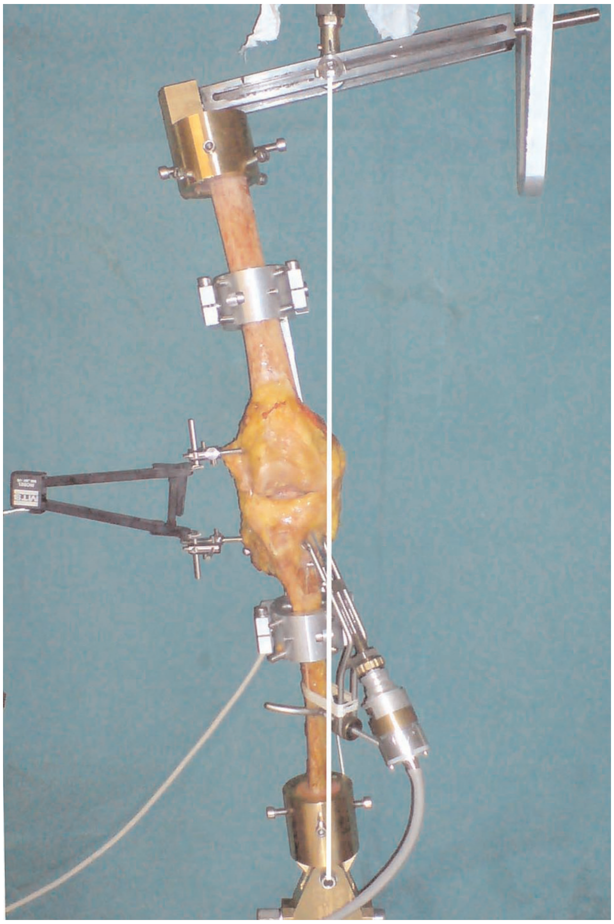

Figure 1. A specimen in the compression machine. The anterior cruciate ligament tensiometer and lateral extensiometer are mounted. The 100% weightbearing line (white line) passes through the medial edge of the tibial plateau.

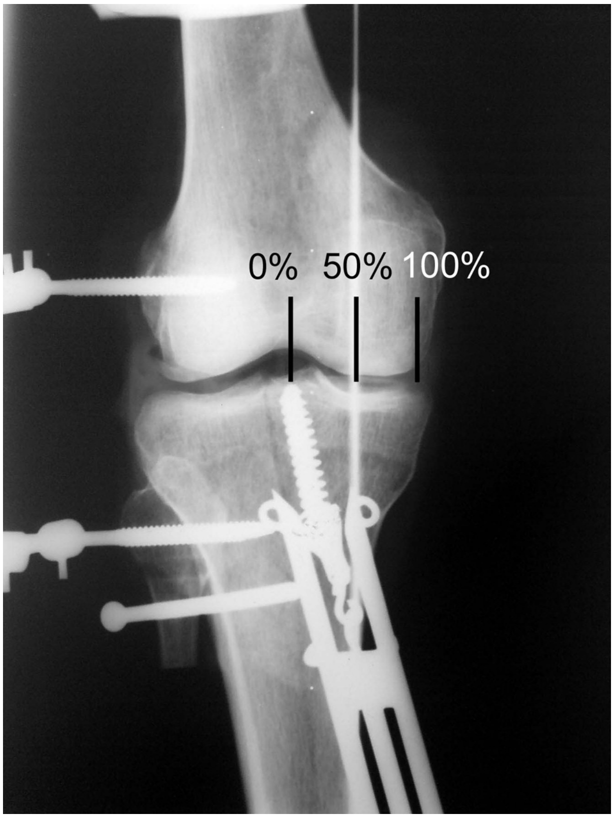

Figure 2. An AP radiograph of a knee with the anterior cruciate ligament bone plug, tensiometer, and lateral extensiometer in place. The weightbearing line passed 50% as indicated by the metal wire.

cycles. There was a 25-N preload after which 30 cycles of 100, 200, and 300 N were applied. The WBL was determined before each experiment by stringing a metal wire between the loading cylinder and the ankle. The WBL was checked with AP radiographs of the knee after every adjustment (Figure 2). All knees were tested with (1) a neutral or 0% WBL, where the weight is transferred through the center of the knee (no varus); (2) a WBL at 50%, where the mechanical axis passes halfway through the medial tibial plateau, resulting in approximately 6.5° of hip-knee-ankle varus angle; and (3) a WBL at 100%, which was at the medial edge of the tibial plateau, resulting in a 12° hip-knee-ankle varus angle.[8] Adjusting the offset of the proximal femur cylinder allowed setting the desired WBL (Figure 1). This was done for every leg independently and checked with radiographs. Knee flexion angles were set at either full extension or 10° of flexion. Within these set flexion angles, the only degree of freedom allowed when loading the leg was either varus or valgus or compression.

Each leg was preconditioned with a few cycles between 0 and 50 N and then loaded with a 25-N static preload. With this axial preload set, the ACL was tensioned at 10 N with the knee in 10° of flexion. This ACL pretension was applied according to previous measurements in normal ACLs.[3] The knees were then dynamically loaded. Simultaneously, the ACL tension and the LJO were measured. After each run, the ACL tension was reset at 10 N if necessary. After the 10° of flexion testing, the knee was put in full extension. Again, the leg was axially loaded up to 300 N. The ACL was henceforth disconnected, allowing free movement of the ACL–bone plug. The same procedure was followed, measuring the LJO, now without a functional ACL. For the 50% and 100% WBL measurements, the same protocol was followed.

Because the change in ACL tension and LJO was linear from 25 to 100 to 200 to 300 N axial loading, data analysis was only done on the change between 25 N minimum and 300 N maximum load (Figure 3).

Lateral joint opening was analyzed using a linear mixed-effect model for repeated measures, including fixed effects for the WBL (intercept, linear, and quadratic terms), for the experimental factors of knee flexion (0° versus 10° flexed) and ACL integrity (ACL in place and functional vs ACL disconnected), and for all first-order interactions. A random intercept and linear and quadratic terms per knee were included in the model to account for repeated measures within each knee for each experimental setting.

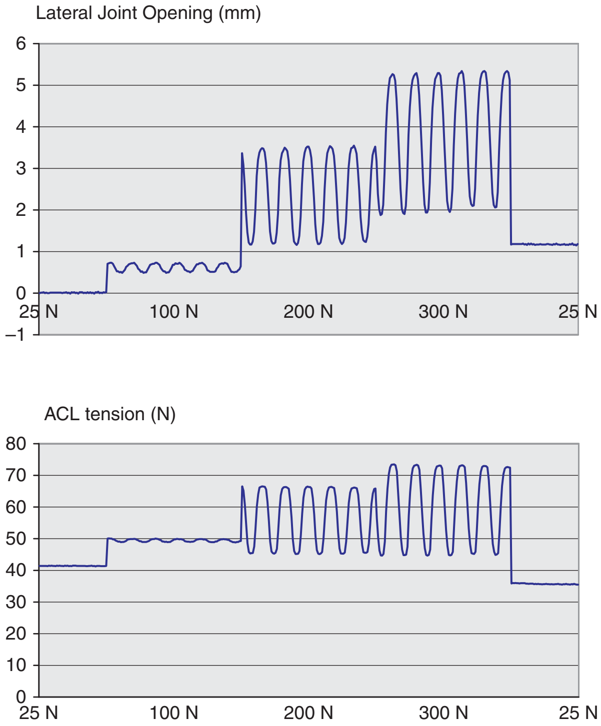

Figure 3. An example of a few loading cycles of an extended leg with the weightbearing line at the edge of the tibial plateau (100%), resulting in a visual thrusting pattern. The lateral joint opening (top) and anterior cruciate ligament (ACL) tension (bottom) curves are shown. The test was started with a 25-N preload and increased to 100, 200, and 300 N before returning to 25 N.

Anterior cruciate ligament force data were analyzed using the same model, with obvious exclusion of the experimental factor ACL integrity.

RESULTS

The LJO and ACL tension increased proportionally from 100 to 200 to 300 N (example in Figure 3) when axially loading in all testing positions in the 50% and 100% WBL tests. This pattern was seen in both knee extension and 10° of flexion.

Anterior Cruciate Ligament Tension

In both the flexed and extended knee position, the ACL tension increased significantly when changing the WBL (Figure 4). There was no significant interaction between knee flexion and the WBL ($P = .65$). This increase was linear by an average 6.3 N (95% confidence interval [CI] = 0.9, 11.6; $P = .03$) when the WBL passed from 0% to 50%. When changing the WBL from 0% to 100%, the ACL tension increased by an average 12.6 N (95% CI = 1.9, 23.2; $P = .03$).

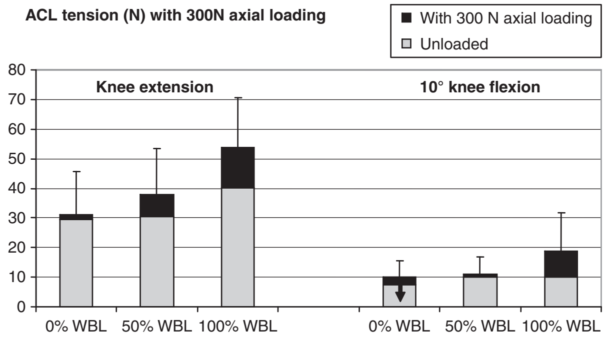

Figure 4. The average anterior cruciate ligament (ACL) tension in both knee extension and knee flexion for the 3 weightbearing lines (WBLs). Because there was no interaction between flexion and ACL tension, the ACL tension increased linearly when passing the WBL from 0% to 50% and also from 50% to 100% with 6.3 N (95% confidence interval = 0.9, 11.6; $P = .03$).

Lateral Joint Opening

Changing the WBL from 0% to 50% and from 50% to 100% increased the LJO significantly, except for the setting where the ACL was intact and the knee was extended. Anterior cruciate ligament integrity generally made the LJO smaller, although the latter effect was only significant for the 100% WBL situation (95% CI = –1.3, –0.2; $P < .01$). There was significantly more LJO in knee flexion compared with extension, except in the 0% WBL. Interaction between flexion angle and ACL integrity was not statistically significant ($P = .27$).

0% WBL. With a neutral WBL, there was no LJO when the legs were loaded in either knee extension or 10° of flexion (Figure 5). There was, rather, an average of 0.25 mm lateral joint closure due to compression of the system and cartilage structures. When the legs were loaded in 10° of flexion, the ACL tension decreased slightly from an average 10 N to 7.4 N (range, 0-10.4 N). When the legs were then loaded in extension, the resultant ACL force only slightly increased from an average 29.5 to 31.0 N (range, 18.2-56.2 N). After releasing the ACL and loading the legs in the same way, there was no difference in LJO compared with the ACL attached.

50% Varus WBL. With the WBL set at 50%, or halfway through the medial tibial plateau (Figure 2), there clearly was an LJO when loading the legs as opposed to joint compression in the neutral WBL. There was statistically less LJO in knee extension (average 0.55 mm) than in knee flexion (average 1.18 mm) while loading the legs (95% CI = 0.07, 1.21; $P < .05$) (Figure 5). When the legs were loaded in 10° of knee flexion, the ACL tension only slightly increased from 10 to 11 N. When the legs were loaded in full extension, the resultant ACL force increased by 7.4 N (Figure 4).

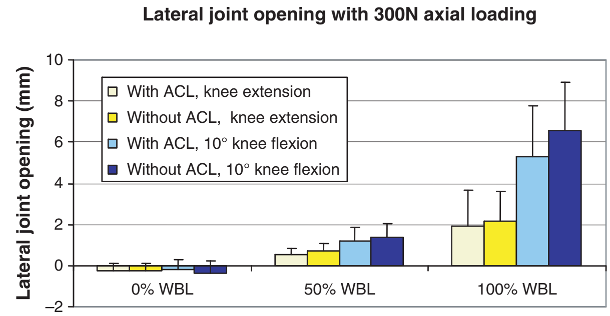

Figure 5. In the 0% weightbearing line (WBL) there was some compression of the lateral compartment. In the 50% and 100% WBL, there was significantly more lateral joint opening. The opening was more obvious when the anterior cruciate ligament (ACL) was detached, although only significant in the 100% WBL situation. There was also significantly more lateral joint opening in the 10° flexed knees in all WBLs.

The increase for both knee extension and flexion was an estimated 6.3 N average (95% CI = 0.9, 11.6; *P* = .03). After the ACL was released, the LJO increased from an average 0.55 mm to 0.69 mm in knee extension and from 1.18 mm to 1.36 mm in 10° of flexion. This difference in LJO was not significant in the 50% WBL tests in either knee extension or flexion.

100% Varus WBL. With the WBL set at 100%, there was an obvious LJO, and in some cases a very rapid and large LJO could be observed when loading the legs (Figure 3). The average LJO was 1.90 mm in knee extension and 5.30 mm in 10° of flexion while loading the legs. The estimated LJO difference between 10° of knee flexion and extension was 3.9 mm (95% CI = 3.34, 4.47; *P* < .01) (Figure 5). Loading the legs in 10° of flexion, the ACL tension increased from an average 10 N to 19 N. When the legs were loaded in extension, there was a significant ACL force increase from 40.2 to 53.9 N (Figure 5). Here, the estimated increase in ACL tension adjusted for knee flexion and repeated measures was 12.55 N (95% CI = 1.86, 23.23; *P* = .029) After the ACL was released, the LJO significantly increased from an average 1.90 mm to 2.18 mm in knee extension and from 5.30 mm to 6.59 mm in 10° of knee flexion (Figure 5). The estimated average effect of ACL integrity on LJO for both knee flexion and extension is 0.78 mm (95% CI = 0.21, 1.34; *P* = .0079).

DISCUSSION

The goal of this study was to assess the relationship between varus alignment and forces in the ACL. It was conducted to identify points of recommendation for the treatment of varus-aligned knees with an ACL deficiency. The in vivo situation was simulated in vitro by axially loading human legs in different varus alignments and knee flexion angles, with and without the ACL. We chose to compress the knees with a 300-N axial load because this approximates 40% of the human body weight.[7] This may be an underestimation of the real loading magnitudes, as in vivo active lateral stabilization of the iliotibial band muscles also influence loading of the knee. A limitation of this study is the absence of these muscles; because of this, our lateral thrust results may be somewhat exaggerated. Still, we are not aware of any study showing how much force the dynamic lateral stabilizers can withstand before a joint opening occurs. Whole legs were used to closely imitate the natural varus or valgus rotation point as would also happen in normal walking. Full knee extension and 10° of knee flexion were used because it is known that varus thrust appears in the early stance phase when the knee is slightly flexed at 10°, or shortly thereafter when the knee transfers to full extension in the midstance phase.[6,9,22] Our experiments enabled us to test different WBLs in 1 knee. Changing the femoral offset changes the WBL and creates varus, as would happen when performing a supracondylar varus osteotomy.[24]

We tested and confirmed our hypothesis that the LJO and ACL tension would increase with increasing varus alignment. In our experiments, the LJO was most obvious in the 100% WBL situations. In these cases, significantly higher ACL forces were measured. The only experimental setting where the LJO did not increase significantly while changing the varus angle was when the knee was extended and the ACL was intact. In our most pronounced LJO case, a thrusting pattern could be observed and a lateral opening of 5.3 mm in knee extension and 7.1 mm in 10° of flexion was found while compressing the leg. Here, the ACL tension also increased most noticeably (78% increase in extension and 218% increase in 10° of flexion). Although the lateral structures were found to be sufficient, in vivo such a case would possibly result in a clinical varus thrust, depending on the stabilizing effect of the iliotibial band.

Because of the obvious relationship between LJO and ACL tension, we also expected to see a difference in the joint opening when the ACL was detached. As seen in Figure 5, this was only mildly the case. Only a small increase in LJO was observed when the ACL was disconnected. This indicates that the ACL is strained with an extreme varus moment, but is not a structure designed to prevent a lateral thrust. Clearly the LCL plays a more important role in this situation.

In our experiments, we also observed that the LJO was more pronounced in the 10° flexed knee compared with full extension (Figure 5). This is probably due to the well-known stabilizing effect of the osseous and ligamental structures around the knee in full extension. Consequently, a relatively large ACL force increase occurred in the 10° flexed knees compared with extension (178% average increase in 10° of flexion vs 74% average increase in extension). However, because the baseline ACL tension in 10° of flexion is only 10 N, the increase in absolute values is small compared with the extended knee.

Several studies report that axial compressive loading stabilizes the knee and therefore decreases anteroposterior tibial translation.[1,11,13,14,23,24] Other studies focus on the effect of anteroposterior, varus-valgus, or tibial rotation on the ACL tension in the non-weightbearing knee.[4,7,9,15,16] In a flexed knee beyond 10°, varus or valgus stress is thought to have little effect on ACL tension.[16,17] In the extended knee, however, varus can produce increased ACL strain.[16,17] A combination of external forces in the non-weightbearing knee was also studied by Markolf et al,[15] showing that the most dangerous loading conditions for the ACL are anterior tibial force plus a valgus moment in the extended knee. In the flexed knee, anterior tibial force combined with varus was a dangerous loading condition. As far as we know, only 1 study applied a combination of axial compressive loads and external varus or valgus stress and measured the resultant ACL strain.[7] These investigators found that weightbearing increases the strain on the ACL. They also showed that varus or valgus stress applied on the knee significantly increases ACL strain in the weightbearing status, doing little to the ACL in a non-weightbearing knee. In contrast to our bone-plug method, which captures the whole ACL, most other experiments were done with transducers that measured only a part of the ACL. This might also explain why these experiments in 20° of knee flexion show similar results to ours.[7]

Noyes et al[19] introduced a grading system of varus: primary, double, and triple varus. Primary varus refers to tibiofemoral osseous alignment. Varus alignment with separation of the lateral compartment due to deficiency of the lateral ligamentous tissues is called double varus. A combination of double varus with varus recurvatum, due to deficient posterolateral ligamental structures resulting in external tibial rotation and hyperextension, is called triple varus. The properties of the LCL also play an important role with regard to varus thrust. Although the LCL was intact in all our specimens, it is not known whether the subjects previously suffered from lateral instability. Nor is it known how much LJO is physiologic and when LJO becomes a varus thrust. In 1 case, we observed a maximum 9.6-mm LJO, which showed visual signs of a thrust. It is not known whether this is within the normal range. Noyes et al[20] observed gait adaptations in patients with ACL deficiency and took an increase of 5 mm lateral opening compared with the opposite uninvolved knee as a criterion for LCL injury. In most situations, the extended knee will be sufficiently balanced by its osseous and ligamentous structures to prevent thrusting. In case of a sufficient LCL, no dramatic effect will be seen on the ACL. It can be expected that in case of varus alignment and chronic instability, a thrusting pattern may develop and the LCL may become insufficient over time, resulting in more strain on the ACL. We observed thrusting only in the 100% WBL tests, but in clinical cases of chronic instability this might also happen in less varus-angulated (<50% WBL) knees.

In conclusion, this study shows that the slightly flexed knee is more susceptible to developing a varus thrust. It also shows that lateral compartment opening increases the tension in the ACL. A slight varus alignment does not seem to yield clinically relevant ACL tensions. However, a severe varus alignment, especially with a varus thrust, can yield high ACL tensions that can be responsible for the failure of an ACL reconstruction. It is therefore important to rule out a varus thrust by carefully examining patients, especially young athletes, among whom the combination of ACL lesion and varus alignment is a common finding. In this clinical situation, it might be appropriate to address the varus alignment with a high tibial valgus osteotomy to neutralize the WBL and eliminate the thrust, together with an ACL reconstruction. How much varus alignment is acceptable in these situations is still unknown.

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