Restrained tibial rotation may prevent ACL injury during landing at different flexion angles

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Abstract

Background: Internal tibial rotation is a risk factor for anterior cruciate ligament (ACL) injury. The effect of restraining tibial rotation (RTR) to prevent ACL injury during single-leg landing is not well understood. We aimed to investigate the effect of impact load and RTR on ACL injury with respect to flexion angle. We hypothesized that RTR could protect the knee from ACL injury compared to free tibial rotation (FTR) regardless of flexion angle and create a safety zone to prevent the ACL.

Methods: Thirty porcine specimens were potted in a rig manufactured to replicate single-leg landing maneuvers. A mechanical testing machine was used to apply external forces in the direction of the tibial long axis. A 3D displacement sensor measured anterior tibial translation (ATT). The specimens were divided into 3 groups of 10 specimens and tested at flexion angles of 22 ± 1°, 37 ± 1° and 52 ± 1° (five RTR and five FTR) through a consecutive range of actuator displacements until ACL failure. After dissection, damage to the joint was visually recorded. Two-way ANOVA were utilized in order to compare compressive forces, torques and A/P displacements with respect to flexion angle.

Results: The largest difference between peak axial compressive forces (~3.4 kN) causing ACL injury between RTR and FTR was reported at a flexion angle of 22°. Tibial torques with RTR was in the same range and ~20 Nm at the instance and just before ACL failure, compared to a significant reduction when cartilage/bone damage (no ACL failure) was reported. Isolated ACL injuries were observed in ten of the 15 FTR specimens. Injuries to bone and cartilage were more common with RTR.

Conclusions: RTR increases the threshold for ACL injury by elevating the compressive impact load required at lower flexion angles. These findings may contribute to neuromuscular training programs or brace designs used to avoid excessive internal/external tibial rotation. Caution must be exercised as bone/cartilage damage may result.

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1. Introduction

The anterior cruciate ligament (ACL) acts as a primary restraint to anterior tibial translation (ATT), and axial tibial rotation (i.e. internal or external tibial rotation) has been shown to strain the ACL during high impact loads such as single-leg landing [1–3]. It has been demonstrated in both cadaveric and porcine knee studies that impact compression forces can induce ACL injury through ATT and axial tibial rotation causing internal or external tibial torques [2,4–6]. In another cadaveric study, ACL force was found to increase due to application of internal tibial torque when compared to external tibial torque [7]. Oh et al. revealed that internal tibial torque plays an important role in aggravating ACL strain during pivot landing as opposed to external tibial torques at an initial flexion angle of 15° [8]. In addition, Meyer et al. demonstrated that excessive compressive loading and/or internal tibial torque may not only rupture the ACL but can also cause significant damage to the articular cartilage and the underlying subchondral bone [4,9,10]. These studies emphasize the significant role of ATT and axial tibial rotation in ACL injury.

The role of inhibiting tibial rotation (RTR) by means of training/bracing in preventing ACL injury is still controversial because there is no clear evidence that RTR can mitigate the effect of high impact load on ATT and axial tibia rotation at different flexion angles [11]. Previous studies have shown that braces to restrict excessive movements at the knee joint might not protect the ACL from injury, although the specific role of RTR has not been thoroughly investigated [1,12]. In addition, the secondary effects of inhibiting tibial rotation (RTR) on bone and cartilage damage have not been addressed in previous studies.

Yeow et al. in an in-vitro experiment using porcine knee joints concluded that the risk of ACL injury would be lessened if ATT and axial tibial rotation were inhibited at 70° of knee flexion [1]. However,
ACL injuries due to drop landing have been reported to occur more commonly at lower knee flexion angles of 20°–30° [13–15]. In this study, the effects of restricting tibial rotation on ACL strain at lower flexion angles during impact compression were investigated. We hypothesized that RTR could protect the ACL from injury and create a safety zone by increasing the threshold of injury when compared to free tibia rotation (FTR) regardless of flexion angle. The results would provide more information on knee brace designs and muscle training programs that restrict excessive knee motion during impact loading.

2. Materials and methods

2.1. Specimen preparation

Thirty fresh porcine knees were obtained (aged between two to three months and weighing ~70 kg) from a local abattoir. Specimen preparation was based on a previous study by Yeow et al [1]. Each knee was confirmed clinically for ligamentous integrity via an anterior drawer test prior to testing. The specimens were sectioned through the femur 15 cm proximal to the joint line and through the tibia/fibula 15 cm distal to the joint line. All soft tissues such as muscles and connective tissues on the proximal seven centimeters of the sectioned femur and distal seven centimeters of the sectioned tibia were removed to aid potting. Each end of the sectioned bones was potted in casting plaster (betal general casting plaster) to the center of the aluminum cups in a way that repeatable mounting could be achieved before they were attached to the servo hydraulic mechanical testing machine (Instron 8874, UK) via a rig as shown in Fig. 1. All precautionary measures were undertaken to ensure consistency among prepared specimens. For this purpose, a separate manufactured rig was developed to pot the knee undertook to ensure consistency among prepared specimens. For this program was based on a previous study by Yeow et al [1]. Each specimen was setup using the FTR configuration. These specimens were returned to the original position with the same preloading. The following variables were collected in real-time during impact: axial compressive force, tibial torque, ATT and axial displacement of the tibia.

2.2. Experimental setup

Fig. 1 shows the setup used in this experiment that was similar to a previous established study [1]. A magnetic tracking system (TrackStar model 180) was used to measure ATT. The accuracy of the sensor was confirmed with displacement of the Instron shaft before the experiments. The sensor was placed on the side plate that held the tibia and potting cup. Tibial rotation was inhibited by tightening four screws on the mechanical testing machine axial shaft attached to the tibial component. With RTR experiments, tibia axial load and torque were measured with a load cell (Instron 8872, ±10 kN). In the FTR experiments the four screws were loosened. Ten knee specimens were flexed to 22° ± 1°, another 10 specimens to 37° ± 1° and another 10 specimens to 52° ± 1°, thus simulating a range of knee flexion angles at which ACL injury may occur. Each of knee flexion angle groups was further divided into two groups—five specimens were setup using the FTR configuration and the other five in the RTR configuration. These flexion angles were chosen to represent angles at which ligaments or other injuries are more likely to occur [2,16].

2.3. Compression testing and analysis

The specimens were mounted onto the mechanical testing machine, and the tibia-femoral joint alignment was maintained by removing any pre-tensile or compressive forces. The setup was placed in its previous place using the Instron machine. Next, a compressive pre-load of ≤10 N was applied to the joint to ensure joint contact prior to impact load exertions. Impact compressive loads were applied by means of a displacement control at a single 10 Hz frequency of a sine profile (with a time to peak load of approximately 50 msec) simulating landing impact. The specimens were loaded in a consecutive displacement-control manner from 1.5 mm with 0.5 mm increments until catastrophic failure was observed in the specimen. We set the displacement, applied the load once, returned the shaft to the original position and then added 0.5 mm to previous displacement for the next impact load.

Catastrophic failure was achieved if either of the following was observed: 1) visible bone fracture or other soft tissue failure and a sudden drop in the force-displacement curve recorded, and/or 2) ACL failure that was confirmed through clinical examination i.e. classic ‘popping’ sound associated with ACL failure combined with a positive Lachman test. Each specimen was dissected carefully after the test to document bone and cartilage damage to the knee joint. Prior to each consecutive axial compressive impact loading, the specimen was returned to the original position with the same preloading. The following variables were collected in real-time during impact: axial compressive force, tibial torque, ATT and axial displacement of the tibia.

2.4. Statistical testing

Statistical analyses were executed in Minitab software (Minitab Inc. 16.2.1) for all forces, torques and displacement data. The hypotheses were tested using a generalized linear model and two-way ANOVA. Samples were normally distributed to the knee joint configuration, additional injuries to the bone and cartilage were more common. Regarding the role of knee flexion angles on measured variables, Fig. 4 shows that the mean ATT increased with RTR, whereas this was decreased with FTR. However, external peak forces did not show any pattern of changes when compared at different flexion angles for both groups.

3. Results

The largest difference between peak axial compressive forces (~3.4 kN) causing ACL injury between RTR and FTR was reported at 22° flexion angle (See Fig. 3). In addition, mean ATT was greater in FTR than in RTR for all specimens (p = 0.001) (Table 1A). Mean ATT did not significantly change due to the knee flexion angle (p = 0.638). Isolated ACL injuries were observed in 10 of the 15 specimens in the RTR configuration and were primarily observed at a knee flexion angle of 22° ± 1°. Damage to the knee joint is shown in Fig. 2 and listed in Tables 1A, 1B and 1C for different flexion angles. Different types of damage to the knee joint were reported between FTR and RTR groups. In experiments involving RTR configuration, additional injuries to the bone and cartilage were more common.

Regarding the role of knee flexion angles on measured variables, Fig. 4 shows that the mean ATT increased with RTR, whereas this was decreased with FTR. However, external peak forces did not show any pattern of changes when compared at different flexion angles for both groups.

4. Discussion

The effect of inhibiting tibial rotation to prevent ACL injury during single-leg landing is not well understood. The aim of this study was to investigate the effects of RTR on ACL injury prevention during simulated landing maneuvers at knee flexion angles between 20° to 60°.
There were several limitations associated with this study. First, as lower limb muscles were absent, we were not able to fully simulate real-life jump landing situations. Muscles such as the quadriceps, hamstrings and ankle dorsal/plantar flexors play a major role in knee stabilization during jump landing. Second, while porcine specimens have been shown to accurately represent the human knee joint in the study of ACL biomechanics [1,16,17], human in-vitro experiments are more realistic and may offer more conclusive support for the

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Failure</th>
<th>Tibial axial displacement (mm)</th>
<th>Peak force (kN)</th>
<th>Peak internal torque (Nm)</th>
<th>Anterior tibial translation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 ± 1°</td>
<td>ACL partial tear at femoral attachment</td>
<td>9.2</td>
<td>6.3</td>
<td>0.1</td>
<td>17.3</td>
</tr>
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<td>Free tibial rotation</td>
<td>ACL partial tear at femoral attachment</td>
<td>4.4</td>
<td>4.4</td>
<td>1.1</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td>Avulsion fracture at ACL femoral attachment &amp; distal tibia complete oblique fracture</td>
<td>8.3</td>
<td>7.7</td>
<td>0.8</td>
<td>26.8</td>
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<tr>
<td></td>
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<td>6.9</td>
<td>3.2</td>
<td>0.7</td>
<td>23.5</td>
</tr>
<tr>
<td></td>
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<td>18.4 ± 6.9</td>
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<td>22 ± 1°</td>
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<td>6.6</td>
<td>8.3</td>
<td>17.16</td>
<td>5.0</td>
</tr>
<tr>
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<td>Partial ACL rupture at postero-lateral bundle tibial attachment</td>
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<td>7.6</td>
<td>11.6</td>
<td>14.0</td>
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<tr>
<td></td>
<td>Complete oblique femoral fracture proximal to joint</td>
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<td>10.1</td>
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<td>Partial ACL tear in antero-medial bundle at tibial attachment</td>
<td>6.8</td>
<td>10.0</td>
<td>15.0</td>
<td>3.7</td>
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<tr>
<td></td>
<td>Partial PCL tear and Complete transverse tibia and fibula fracture distal to joint</td>
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<td>8.4</td>
<td>11.8</td>
<td>0.00</td>
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<tr>
<td>Mean (SD)</td>
<td></td>
<td>8.0 ± 1.7</td>
<td>8.9 ± 1.1</td>
<td>14.2 ± 2.5</td>
<td>6.5 ± 5.5</td>
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FTR experiments resulted in a higher number of ACL injuries. Tibial axial displacement, peak compressive forces, peak internal torques and posterior femoral displacement for all specimens flexed to 22 ± 1°.

![Figure 2](https://example.com/figure2.png)

**Fig. 2.** Different types of damage observed in the knee joint with FTR and RTR. Partial tears in the ACL, avulsion fracture at ACL femoral attachment, partial ACL rupture at tibial attachment were evident in FTR. Femoral fractures, articular cartilage fractures and tibial fractures were observed more frequently with RTR. The arrows point to the injury.
ACL failure was significantly higher in RTR than in FTR at low flexion angle, thereby confirming our first hypothesis that RTR could potentially protect the ACL from injury when compared to FTR especially at a flexion angle of 220. This finding may suggest that RTR is able to provide a safety zone for the ACL by increasing the peak compressive force required for ACL failure. However, this safety zone may have a ceiling point at which caution must be exercised as bony/cartilaginous may result from RTR. Peak compressive forces required for ACL failure were slightly higher in our study when compared to previous porcine experiments [18]. The higher forces observed in this study can be accounted for by differences in the knee flexion angle and anterior tibial pre-loading i.e. 50 N in a previous study [1,4]. Nonetheless, our current setup was sufficient to distinguish the relative differences between RTR and FTR experiments. Furthermore, the amount of ATT during ACL failure recorded in FTR was consistent with previous studies [2,16]. On the other hand, ATT observed with RTR was greater when compared to experiments conducted by Yeow et al at 70° of knee flexion [1]. This is in agreement with previous findings that the larger axial compressive forces seen in this study would increase anterior tibia shear forces at the joint [31], resulting in an increase in ATT.

Our results also showed that RTR, while increasing the threshold for ACL failure, might lead to secondary bone and cartilaginous injury. This finding is in line with the study by Yeow et al, in which they concluded that ACL injury was prevented when tibial rotation was restricted at a high knee flexion angle of 70° [1]. However, most ACL injuries occur at less than 40° of knee flexion angle [19]; this study has shown that ACL injury can be prevented at lower knee flexion angles with RTR.

Our results also showed that RTR, while increasing the threshold for ACL injury, might lead to secondary bone and cartilaginous injury. This was confirmed with the high number of visible bone and cartilage damage in the RTR specimens when compared to FTR specimens, with ten out of the 15 FTR specimens resulting in isolated ACL injuries. It has been well documented that increased ATT leads to high ACL strain.

### Table 1B
<table>
<thead>
<tr>
<th>Specimen</th>
<th>Failure</th>
<th>Tibial axial displacement (mm)</th>
<th>Peak force (kN)</th>
<th>Peak internal torque (Nm)</th>
<th>Anterior tibial translation (mm)</th>
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</thead>
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<td>37 ± 1°</td>
<td>Lateral femoral condyle fracture</td>
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<td>8.3</td>
<td>2.1</td>
<td>11.4</td>
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<td>Free tibial rotation</td>
<td>Partial ACL tear in postero-lateral bundle</td>
<td>7</td>
<td>5.9</td>
<td>0.9</td>
<td>16.2</td>
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<td>Partial ACL tear in antero-medial bundle near tibial attachment</td>
<td>7</td>
<td>5.6</td>
<td>0.8</td>
<td>3.3</td>
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<tr>
<td></td>
<td>Complete transverse femoral fracture</td>
<td>8.5</td>
<td>4.3</td>
<td>1.8</td>
<td>24.3</td>
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<td></td>
<td>Oblique fracture of medial femoral condyle articular cartilage</td>
<td>8</td>
<td>7.2</td>
<td>1.3</td>
<td>14.9</td>
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<td>Mean (SD)</td>
<td>Partial ACL tear in postero-lateral bundle at tibial attachment</td>
<td>7.6 ± 0.6</td>
<td>6.3 ± 1.5</td>
<td>1.4 ± 0.6</td>
<td>14.0 ± 7.6</td>
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<tr>
<td>37 ± 1°</td>
<td>Femoral fracture</td>
<td>8.5</td>
<td>10.2</td>
<td>18.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Inhibited tibial rotation</td>
<td>Avulsion fracture at ACL femoral attachment</td>
<td>5.5</td>
<td>6.8</td>
<td>18.2</td>
<td>8.9</td>
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<td></td>
<td>Partial ACL rupture in postero-lateral bundle at tibial attachment</td>
<td>9</td>
<td>6.1</td>
<td>11.6</td>
<td>11.8</td>
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<td></td>
<td>Partial ACL rupture in postero-lateral bundle at tibial attachment</td>
<td>8.5</td>
<td>5.2</td>
<td>3.7</td>
<td>26.4</td>
</tr>
<tr>
<td></td>
<td>Femoral fracture</td>
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<td>7.0</td>
<td>7.8</td>
<td>1.1</td>
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<tr>
<td>Mean (SD)</td>
<td>Femoral fracture</td>
<td>7.3 ± 1.9</td>
<td>7.1 ± 1.9</td>
<td>11.9 ± 6.4</td>
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FTR experiments resulted in a higher number of ACL injuries. Tibial axial displacement, peak compressive forces, peak internal torques and posterior femoral displacement for all specimens flexed to 37 ± 1°.

### Table 1C
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<tr>
<th>Specimen</th>
<th>Failure</th>
<th>Tibial axial displacement (mm)</th>
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<th>Peak internal torque (Nm)</th>
<th>Anterior tibial translation (mm)</th>
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<tr>
<td>52 ± 1°</td>
<td>Partial ACL rupture, Avulsion fracture at ACL femoral attachment</td>
<td>7</td>
<td>4.5</td>
<td>0.9</td>
<td>12.6</td>
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<tr>
<td>Free tibial rotation</td>
<td>Avulsion fracture at ACL femoral attachment</td>
<td>8</td>
<td>5.1</td>
<td>0.7</td>
<td>6.5</td>
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<tr>
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<td>Partial ACL tear in postero-medial bundle</td>
<td>9.5</td>
<td>4.2</td>
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<td>22.9</td>
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<td>Avulsion fracture at ACL femoral attachment</td>
<td>8.5</td>
<td>6.4</td>
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<td>10.1</td>
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<tr>
<td></td>
<td>Avulsion fracture at ACL femoral attachment</td>
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<td>Sagittal fracture of lateral femoral condyle articular cartilage</td>
<td>8.3 ± 0.9</td>
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<td>12.2 ± 6.4</td>
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<td>Mean (SD)</td>
<td>Complete ACL tear, Avulsion fracture at ACL femoral attachment</td>
<td>7.5</td>
<td>6.1</td>
<td>16.9</td>
<td>29</td>
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<td>52 ± 1°</td>
<td>Avulsion fracture at ACL femoral attachment</td>
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<td>Inhibited tibial Rotation</td>
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<td>9.1</td>
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<td>Mean (SD)</td>
<td>Avulsion at ACL femoral attachment</td>
<td>7.8 ± 1.9</td>
<td>7.6 ± 1.5</td>
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</table>

FTR experiments resulted in a higher number of ACL injuries. Tibial axial displacement, peak compressive forces, peak internal torques and posterior femoral displacement for all specimens flexed to 52 ± 1°.
which predisposes towards ACL failure [20]. In this study, FTR specimens recorded higher ATT than RTR. Restricting tibial rotation could reduce ATT thus protecting the ACL; however, this could lead to a higher tibial compressive force and bony/cartilaginous damage. This can be explained in part by the posterior tibial displacement caused by tibial fractures resulting from the large compressive load exerted upon the tibia.

Finally, our results suggest that mean peak ATT was dependent on the flexion angle when comparing RTR with FTR specimens. This was not the case with external peak forces. Fig. 4 shows that mean ATT for different flexion angles showed opposite patterns when RTR and FTR were compared. Mean ATT was increased with the RTR group while it was observed to decrease with the FTR group. However, external peak forces did not show any pattern of changes when compared at different flexion angles for both groups. Furthermore, the results suggested that the reduction of excessive ATT (as a risk factor for ACL injury) was more evident at a lower flexion angle (Fig. 4). Such a high reduction of the excessive ATT at a lower flexion angle compared to higher flexion angles may suggest that RTR could potentially increase the threshold of injury, thereby creating a safety zone for the ACL.

Fig. 3. Representative profiles of compressive forces vs. mechanical testing machine actuator shaft displacements for FTR and RTR at catastrophic failure. Horizontal lines indicate compressive force drops during each experiment. The two time points were used to define force drops: the instances at which peak force and peak vertical displacement occurred.

Fig. 4. Tibial axial displacement, peak force, peak torque and anterior tibia translation for all the specimens (their mean and standard deviation are presented).
5. Conclusion

This study demonstrated that inhibition of axial tibial rotation increases the compressive load threshold for ACL injury to occur at a range of low flexion angles i.e. increasing the safe zone for the ACL. However, this may result in other types of damage to the articular cartilage and bones.

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References