Accepted for review: 30-09-2020
Accepted for publication: 14-12-2020

The Effect of ACL Stiffness on the Mechanics of Intact Knee: A Finite Element Study

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ABSTRACT

There are many factors that affect the mechanics of an intact knee and one of the factors is the mechanism of anterior cruciate ligament (ACL). ACL rupture has been one of the most common injuries in sports. In order to choose the graft for ACL reconstruction, many factors should be taken into consideration. A 3- dimensional finite element model of knee was developed to investigate the effect of ACL stiffness on the mechanics of intact knee. The femur and tibia were assumed to be rigid body and the grafts was modeled to be hyperelastic. Three different grafts; Bone-patellar tendon-bone (BPTB), double and quadruple semitendinosus (DST and QST respectively) were analyzed for the ACL reconstruction under simulated 134 N anterior force on tibia at full extension (0° of flexion angle) and deep squatting (135° of flexion angle). Based on the computational simulation, the QST graft gave a better ACL reconstruction to the knee compared to another two types of graft. A decent selection of ACL graft is crucial as higher stress induced after ACL reconstruction can lead to graft rupture and consequently affect the knee stability.

Keywords: *ACL Reconstruction; ACL Graft; Finite Element Analysis*

Introduction

The anterior cruciate ligament (ACL) is the most common ligament at knee joint to be totally damaged. ACL connects the lateral femoral condyle to the tibial plateau between the medial intercondylar eminence and anterior horns of menisci [1]. Over the past 2 decades, the number of ACL injuries in young athletes (below age of 18) has increased. The rates of ACL injury in young children are relatively low, however increase tremendously when they become teenagers. In same sport, girls gain higher rates of non-contact ACL injuries as compared to boys. Athletes with ACL injuries are likely to develop degenerative knee arthritis up to 10 times compared to athletes without ACL injuries history [2].

ACL reconstruction of knee joint is a well-known surgical procedure to treat severe knee instability due to ACL deficiency. The aspects that are likely to affect the success of the ACL reconstruction surgery include the effectiveness of secondary restraints, the knee laxity before the surgery, the condition of knee cartilage, the selected graft material, the graft tension and the rehabilitation process after the procedure [3]. The most common reconstruction grafts used in ACL surgical reconstruction are Bone-patellar tendon-Bone (BPTB), double (DST) and quadruple semitendinosus (QST). BPTB has been considered as the “gold standard” for ACL reconstruction among the surgeons, however other types of grafts also have been increasingly popular [4].

There are few studies in Malaysia that related to ACL reconstruction and one of them is the study on the activity that leads to ACL injury and the ability to recommence task after reconstructive surgery among Malaysia military patients. The activities that the patients were engaged in when the ACL injury took place were identified and divided into three groups, i.e. sports-related activity, military activity and other activities. All the surgeries were performed by two trained sports surgeons using either bone-patella-bone or hamstring autograft, according to the surgeons’ preferences [5]. Several factors affecting biomechanical outcome of ACL reconstruction have been studied. However, there are only a few studies conducted to investigate on the effect of graft stiffness on knee mechanics. Therefore, this study intended to prove that graft stiffness has a significant impact on knee mechanical behavior following ACL reconstruction. An optimum ACL reconstruction might be achieved if the ACL is substituted by a tendon graft with identical structural stiffness [6].

Method and Analysis

The 3-D knee models of intact knee developed in this study was taken from an open-source website, GrabCAD. The knee model was reconstructed to flex at two different angles (full extension at 0° and full flexion at 135°) in CATIA as shown in Figure 1. The bone tunnels were constructed depending on the size of the inserted graft. The graft length can significantly influence graft stiffness and the ACL reconstruction; hence the graft length was defined from previous clinical surgery [6]. The fixation position is dependent on the length of patellar tendon. Therefore, the length of graft was considered to be 55 mm based on prior statistical data [4]. Three grafts for the ACL reconstruction were built in cylindrical shape with the same length but different cross-sectional area. In surgery, the graft was commonly sewed up to be cylindrical, with average cross-sectional area of 33.4 mm^2 for BPTB while the average cross-sectional area of DST and QST were 23.3 mm^2 and 55 mm^2, respectively [4]. ACL was substituted with the new graft; each graft replaced the ACL for both knee angles of 0° and 135°, making a total of six 3-D models to be analyzed.

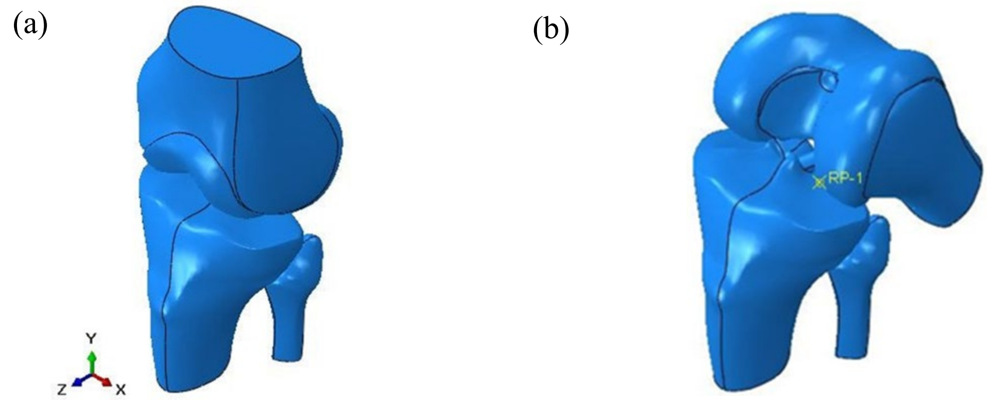


Figure 1: 3-D knee model with femur, tibia and ACL graft at (a) full extension 0° (b) full flexion 135°

As the bone stiffness is much higher than that of the graft, its deformation can be ignored and hence assumed to be rigid [4]. The graft was considered to be hyperelastic following the Neo-Hookean model [7]. The parameters C10 in Neo- Hookean model for BPTB, DST and QST are shown in Table 1. Anterior force of 134 N was applied on the tibia and the femur was fixed based on previous study [3].

Table 1: The parameters of biomechanical properties of different grafts

Graft	Parameter C10 (Neo- Hookean Model)
BPTB	58.23
DST	19.37
QST	19.37

The finite element modeling and analysis were implemented in ABAQUS. The assembled model was meshed using tetrahedral type of element with an average length of 3 mm. The number of elements for knee models with BPTB, DST and QST at 0° of flexion were 91294, 96504 and 93191, respectively. The number of elements for knee models with BPTB, DST and QST at 135° of flexion angle were 128907, 143010 and 139954, respectively. The von Mises stress of all grafts and the corresponding anterior displacement of the tibial bone were observed.

Results and Discussion

Under the 134-N anterior tibial load for knee joint at 0° (full extension) and 135° (full flexion) with three different graft reconstructions, the results of anterior tibial translations are presented in Table 2.

Table 2: The joint kinematics (anterior tibial translation) for ACL reconstruction under 134 N anterior tibial load

Graft	Anterior Tibial Translation for 0° (mm)	Anterior Tibial Translation for 135° (mm)
BPTB	0.287	0.110
DST	4.468	0.731
QST	0.327	0.231

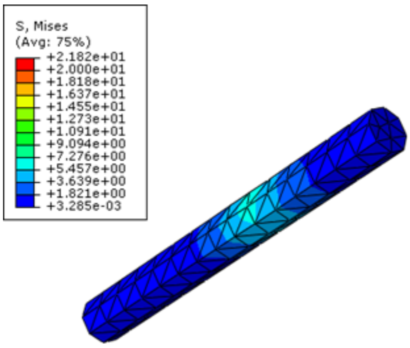
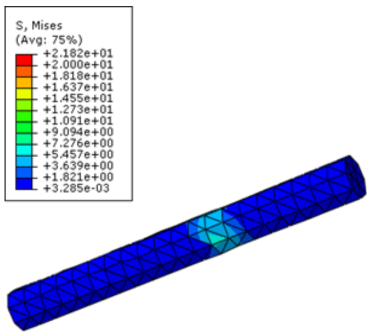
As for BPTB graft reconstruction, at 0° and 135° of knee flexion angles, tibia moved 0.287 mm and 0.110 mm anteriorly; for DST graft reconstruction, at 0° and 135° angle of knee flexion, tibia moved in anterior direction for 4.468 mm and 0.731 mm, respectively; while for QST graft reconstruction, at 0° and 135° angle of knee flexion, tibia moved anteriorly at 0.327 mm and 0.231 mm, respectively. To prevent ACL rupture, translocation, or high amount of anterior tibial translation (>7mm) must be avoided [8]. Therefore, BPTB, DST or QST graft can be chosen as none of them exceed the maximum allowable value of anterior tibial translation.

Table 3: The maximum von Mises stress in mid-part of graft reconstruction

Graft	Von Mises Stress at 0° flexion (MPa)	Von Mises Stress at 135° flexion (MPa)
BPTB	8.148	7.029
DST	21.82	13.17
QST	5.143	4.695

Table 3 shows the maximum value of Von Mises stress at the mid-part of graft reconstructions. In 0° knee flexion graft reconstructions of BPTB, DST and QST, the highest Von Mises stress occurred in the mid-part of graft were 8.148 MPa, 21.82 MPa and 5.143 MPa, respectively; while in 135° knee flexion graft reconstructions of BPTB, DST and QST, the highest Von Mises stress occurred in the mid-part of graft were 7.029 MPa, 13.17 MPa and 4.695 MPa, respectively. Table 4 shows the von Mises stress distribution in BPTB, DST and QST grafts at full extension and full flexion, respectively.

Table 4: The distribution of Von Mises stresses in BPTB, DST and QST grafts, respectively

<table>
<tr><th>Type of graft</th><th>Full extension (0°)</th><th>Full flexion (135°)</th></tr>
<tr><td>BPTB</td><td>
</td><td>
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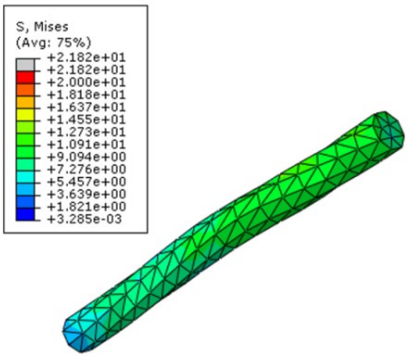
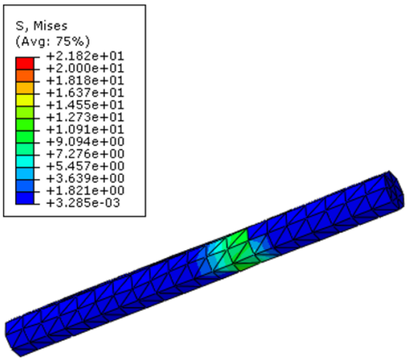
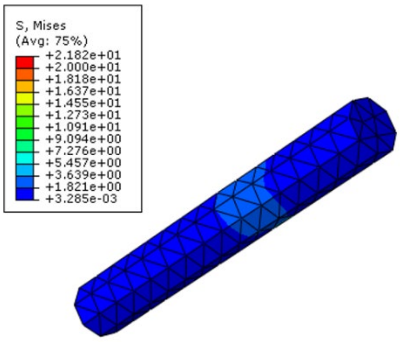
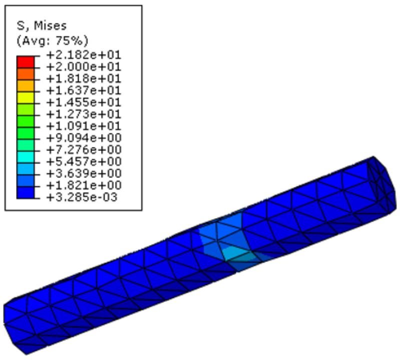
<tr><td>DST</td><td></td><td></td></tr>
<tr><td>QST</td><td></td><td></td></tr>
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The stiffness of various types of ACL graft is different due to unique mechanical properties and cross-sectional area of the muscle tendon at which the graft is extracted from. In the present study, the response of different ACL (graft) stiffness on the intact knee has been expressed in two essential parameters: the anterior tibial translation and the maximum Von Mises stress in the mid-part of graft reconstructions. To restore the ACL function, anterior tibial translation should not be more than 7 mm as high anterior translocation of tibia value can lead to the rupture of ACL while the values the maximum Von Mises stress in the mid-part of graft reconstructions should be in the range of that of intact ACL [9]. The anterior tibial translation of tibiofemoral joint was less than 7 mm for all three types of ACL grafts in both full extension and full flexion. Previous reports, however, have proposed different threshold of tibial subluxation for ACL rupture. Chan el al. suggested that greater than 5 mm of anterior tibial translation as the key indicator of ACL complete tears [10]. In the other hand, 3.5 mm of passive anterior tibial subluxation threshold was proposed by Hardy et al based on the calculation of mean medial and lateral condyle translation from magnetic resonance images (MRI) [11]. QST and BPTB exhibited less than 3.5 mm of anterior tibial translation in full extension. QST, however, is found to be more superior in both aspects of responses as it obtained relatively lower von Mises stress in comparison to BPTB. The outcomes are in agreement with the clinical study by Laxdal et al. The use of ST autograft resulted in more comfort during knee-walking test as it offered better knee stability compared to BPTB autograft. Knee laxity test, however, revealed insignificant different between both grafts [12].

There are some limitations in this study. The model only consists of three parts of the knee which are femur, tibia and ACL. There are a few more ligaments e.g. posterior cruciate ligaments (PCL), medial and lateral cruciate ligaments (MCL and LCL) at the knee joint that might contribute to significant response if they were constructed in the model. However, ACL with different types of graft is only our focus in this study. Other than that, the graft reconstructions were assumed to be rigidly fixed to the bone to simplify the graft-bone contact model. However, it has been shown in prior study that the graft fixation may not be rigid [4]. The graft attachment points were also positioned based on the average location of intact ACL due to unavailability of MRI scanning image that could give the exact position of ACL.

Conclusion

The study that has been carried out to perform ACL reconstruction and to evaluate the response of different ACL stiffness on intact knee. In conclusion, after comparing three different grafts, it is found that QST graft is the best graft for the ACL reconstruction due to its low resulting anterior tibial translation that can possibly reduce the occurrence of tibial anterior subluxation, besides obtained the lowest stress induced during knee full extension and knee full flexion.

A decent selection of ACL graft is crucial as higher stress induced after ACL reconstruction can lead to graft rupture and consequently affect the knee stability.

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