Numerical Simulation of Single and Double Bundle Reconstruction on Knee while Walking

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Abstract

This research studies behavior of ligament reconstruction on knee while walking using the integration of dynamics motion analysis and finite element analysis. The purpose is to calculate stress and strain distribution on single and double bundle reconstruction while walking. First, ligament reconstruction is tested to obtain mechanical properties, which are used for finite element analysis. Next, 3D CAD model and finite element model are constructed. Dynamics motion analysis of femur and tibia while walking is introduced. The degrees of hip and knee motion with respect to time are resulted of dynamics analysis and set as load for finite element analysis. The stress and strain on knee's ligament reconstruction while walking are calculated by finite element method. The maximum stress and strain occur on a top of ligament while extend leg are 33.86 MPa and 0.153 mm/mm, respectively, for single hamstring bundle. The maximum stress is 43.82 MPa and maximum strain is 0.188 mm/mm for double hamstring bundles. The advantage is to understand the biomechanics of the knee ligament reconstruction while walking. This research result can help patients who have tear problem of an Anterior Cruciate Ligaments (ACL) or stroke rehabilitation and be developed for further research about force and behaviors of the other ligament and muscle in body.

***Keywords**: Hamstring, ACL reconstruction, Finite element method, Dynamics motion analysis*

1 Introduction

The primary role of tendons or ligaments is to transmit contractile force to the skeleton to generate joint movement. They do not behave as rigid bodies but nonlinear deformation behavior. Their mechanical functions are to guide normal joint motion and restrict abnormal joint movement. Their mechanical properties have been studied mostly using tensile testing methodologies, in which isolated specimens are stretched by an external force, while both the specimen deformation and applied force are record [1–3].

Ligaments can be subjected to extreme stress while performing their role in restricting abnormal joint motions and can be damaged or completely disrupted when overloaded. The four major groups of ligaments of the knee are the anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), Posterolateral complex (PLC), and medial collateral ligament (MCL). The ACL has been acted as a primary restraint against anterior tibial displacements [4–6] and as a secondary restraint to tibial axial rotation [5, 7–9]. The ACL also provides a minor secondary restraint to varus – valgus displacement and rotation at full extension [5]. An ACL tear is most often a sport – related injury. ACL tears can also occur during rough play, mover vehicle collisions, falls, and work-related injuries. About 80% of sports-related ACL tears are "non-contact" injuries. The ACL stress and strain as well as its behavior are studied by the finite element method [10–14].

The usual surgery for an ACL tear is called an ACL reconstruction. ACL reconstruction surgery is the standard treatment for young, active people who sustain an ACL tear. A repair of the ligament is rarely a possibility, and thus the ligament is reconstructed using another tendon or ligament to substitute for the torn ligament. There are several options for how to perform ACL surgery. The most significant choice is the type of graft used to reconstruct the torn ACL. There are also variations in the procedure, such as the new single-bundle and double-bundle ACL reconstruction.

Despite intensive efforts have been made to obtain the ACL properties from experiments, the stress and strain distribution during walking of the ACL remains unknown. In this research the graft type of ACL reconstruction is hamstring. The ligament behavior and force are studied while patient is walking. Stress and strain of single-bundle and double-bundle ACL reconstruction are investigated by finite element method.

2 Methodology

3D CAD models of femur and tibia are constructed from image processing of CT scan slides. Dynamics motion analysis of femur and tibia is simulated by musculoskeletal system software (ANYBODY software). Results of degrees of hip and knee motion with respect to time while walking from musculoskeletal system software are applied as load input in finite element analysis (ANSYS software). Nonlinear materials are tested by tensile testing machine with freeze grips. Nonlinear material property is used to represent ligament material behavior. Finite element method (FEM) is then used to calculate stress and strain distribution on ACL reconstruction ligament while walking. Input data of FEM are CAD model constructed by SolidWorks software, material properties and walking load as well as constraint. Tetrahedral element is selected to generate finite element model. Hip is fixed as constraint. Two cases, single-bundle and double-bundle ACL reconstruction, are simulated. The proposed procedure used in this research is shown in figure 1.

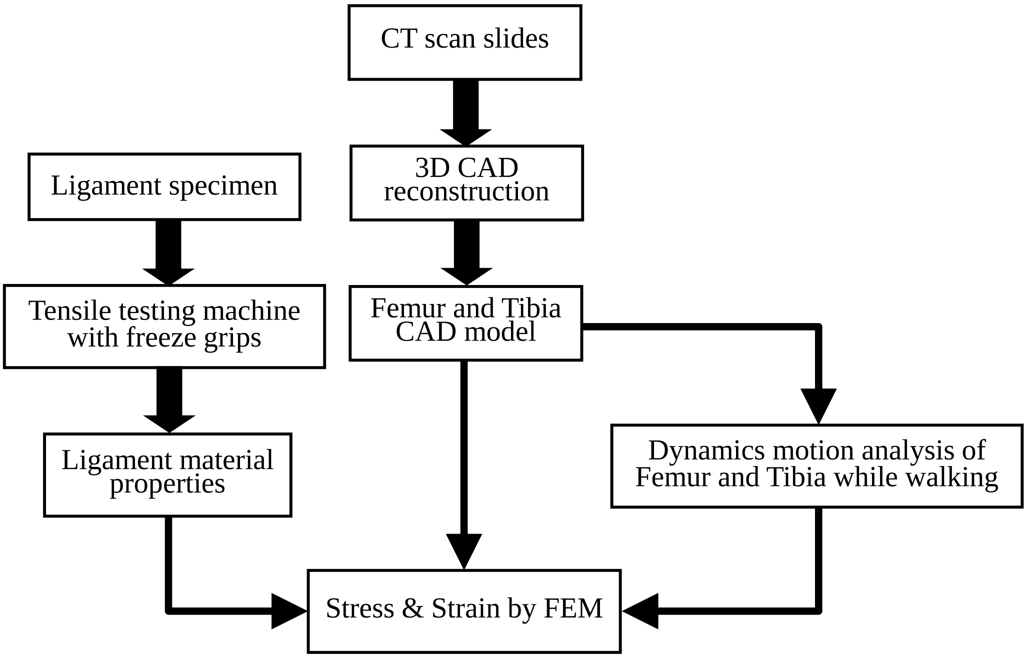


Figure 1: The proposed procedure.

3 Results

The results of four procedures (Ligament material properties, 3D CAD reconstructions, dynamics motion analysis, and finite element analysis) are as following.

3.1 *Ligament material properties*

The freeze grips are used to clamp hamstring specimen as shown in figure 2.

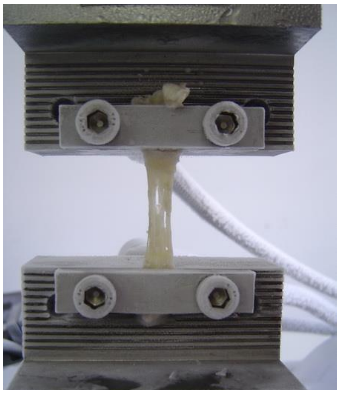


Figure 2: freeze grips clamp specimen.

Average stress – strain curve of hamstring ligament is plotted in figure 3. Nonlinear material property is used to represent stress – strain curve of hamstring.

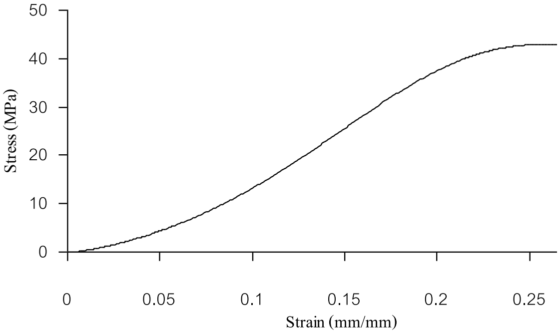
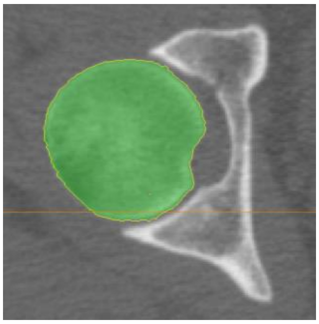


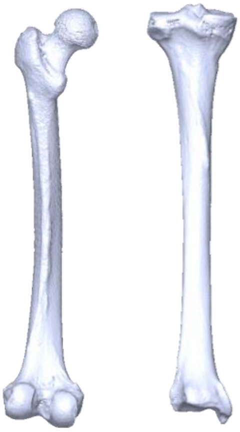
Figure 3: Stress – strain curve of hamstring.

3.2 *3D CAD reconstructions*

The male patient is 36 years old. The CT scan is implemented to capture scan slides. These slides are under image processing process to reconstruct femur and tibia model as shown in figure 4.



(a) CT scan slide



(b) Femur and Tibia CAD reconstruction

Figure 4: 3D CAD reconstructions from CT scan slides.

3.3 *Dynamics motion analysis*

Femur and tibia models are imported in musculoskeletal system software as shown in figure 5.

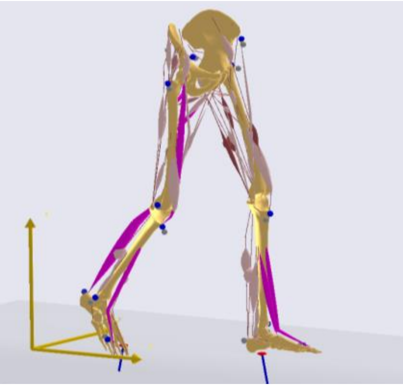
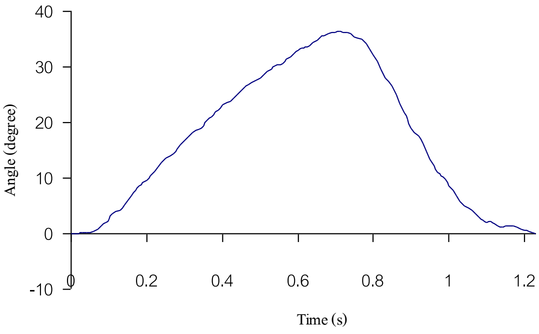
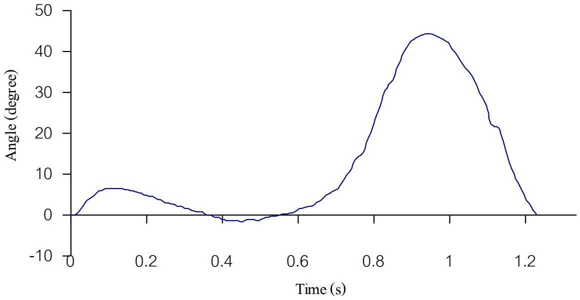


Figure 5: Modeling of Femur and Tibia.



(a) Degrees of hip motion vs time



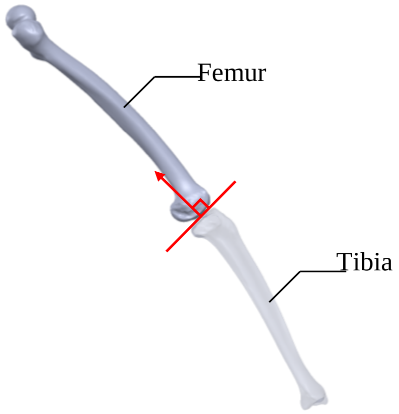
(b) Degrees of knee motion vs time

Figure 6: Degrees of hip and knee motion with respect to time.

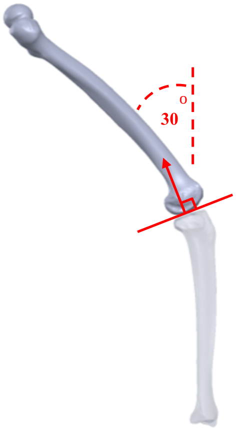
Inverse kinematics analysis is applied to calculate rotational angle and translation of hip and knee with respect to time while walking as shown in figure 6.

3.4 *Finite element analysis*

Finite element analysis including geometry, material properties and boundary conditions computes stress and strain solutions. Femur and tibia models from 3D CAD reconstruction are imported by ANY2ANS software. Single–bundle and double–bundle ACL reconstruction are constructed. Degrees of hip and knee motion are manipulated as load. Figure 7 shows initial and final angular conditions of walking simulations.



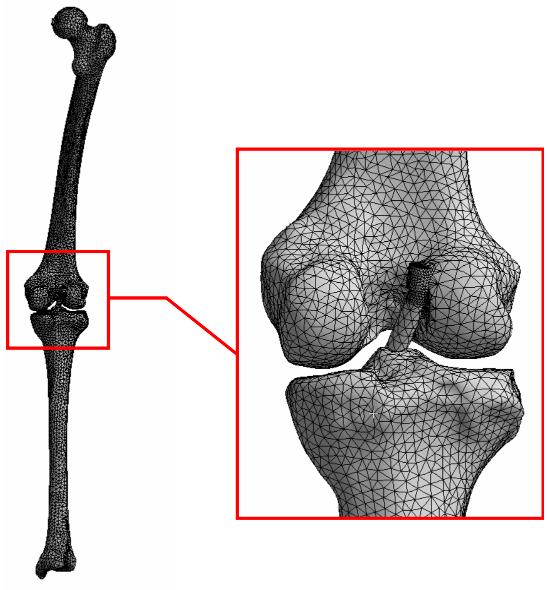
(a) Initial condition



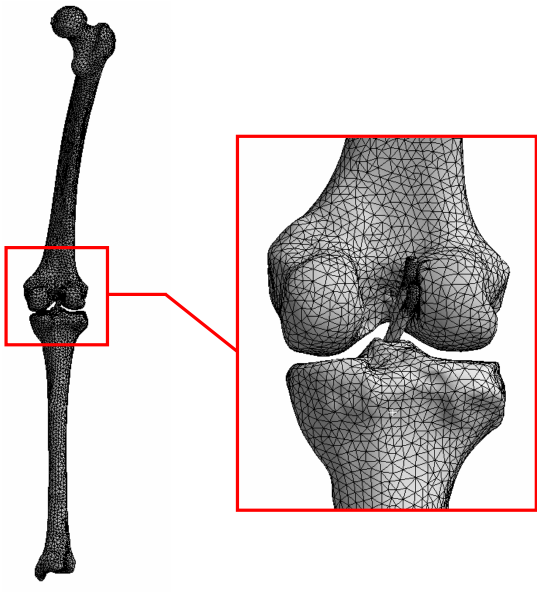
(b) Final condition

Figure 7: Initial and final angular conditions of walking simulations.

Finite element model of single – bundle and double – bundle geometry is constructed as shown in figure 8. Mesh sensitivities are done to eliminate the effect of element size.



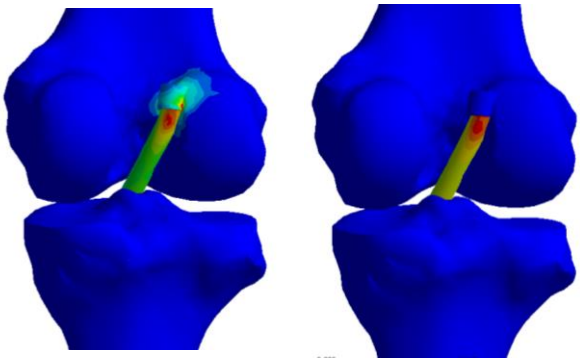
(a) Single – bundle



(b) Double – bundle

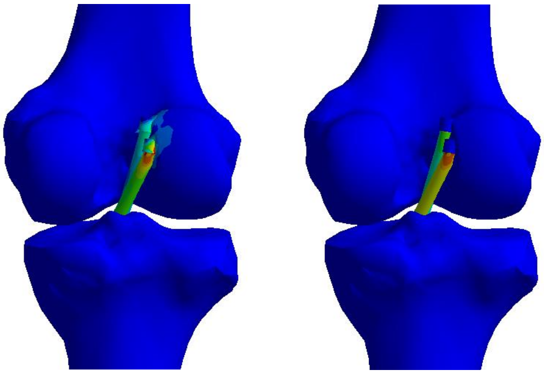
Figure 8: Finite element models of single–bundle and double–bundle.

Stress and strain solutions of single – bundle and double – bundle models are shown in figure 9 and 10, respectively. The maximum stress and strain occur on a top of ligament while extend leg are 33.86 MPa and 0.153 mm/mm, respectively, for single–bundle model. While the maximum stress is 43.82 MPa and maximum strain is 0.188 mm/mm for double–bundle model.



(a) Stress distribution (b) Strain distribution

Figure 9: Stress and strain distribution of single – bundle.



(a) Stress distribution (b) Strain distribution

Figure 10: Stress and strain distribution of double – bundle.

4 Conclusions

The proposed biomechanics simulation method is developed to study the stress and strain of single and double – bundle reconstruction while walking. 3D CAD model of femur and tibia are reconstructed from CT scan slides. Walking simulation is analyzed by musculoskeletal system software. Dynamics motion results show the degrees of hip and knee motion with respect to time. Nonlinear material properties of hamstring is selected. Finite element method is then applied to solve stress and strain of single and double bundle reconstruction while walking. Regarding the results of single hamstring bundle, the maximum stress and strain occur on a top of ligament reconstruction while extend leg are 33.82 MPa and 0.153 mm/mm, respectively. The maximum stress is 43.82 MPa and maximum strain is 0.188 mm/mm for double hamstring bundles. The advantage is to understand the biomechanics of the single and double knee ligament reconstruction while walking. The results of this research can help patients who have tear problem of an Anterior Cruciate Ligaments (ACL) or stroke rehabilitation and be developed for further research about force and behaviors of the other ligament and muscle in body.

Acknowledgments

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