Effect of Mediolateral Knee Displacement on Ligaments and Muscles around Knee Joint: Quantitative Analysis with Three-Dimensional Musculoskeletal Ligament Knee Model

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Abstract. Knee osteoarthritis (OA) becomes a major public issue, but a strategy to prevent the disease has not established yet due to lack of an accurate method to measure an internal motion of the knee of individual patients. Therefore mechanical engineering model and a standard of evaluation of the disease is needed to improve the situation. Currently, there are a few studies to develop the model including allowance of joint movement and ligaments. Thus this study shows the model accuracy by forward dynamics and discusses the result of inverse dynamics of various gait patterns. As a result, it can be confirmed that ligaments are more effective than muscles around knee joint with our various models. In addition we propose the important factor of knee OA from gait pattern and models.

1 Introduction

Knee osteoarthritis (OA) is thought to be a major public health issue causing chronic disability [1]. Clinical research has suggested that the instability of a knee joint causes the changing structure of joint and gait disorder. Therefore it is important to research an effect of gait patterns on the knee joint. Although, many efforts have been made to identify an optimal diagnostic tool for this disease, no definitive tools have been reported until now. The most reason is due to lack of objective or accurate method for measurement of the motion. Therefore mechanical engineering knee model and a standard of evaluation method of the disease is needed to achieve prevention of the disease.

One of the important features of the knee joint is that bony limitation of movement is a little. Therefore it is necessary to consider allowance of joint movement such as slide with rolling, soft tissues such as a ligament, a cartilage and a meniscus. Especially a ligament is an important factor to decide the movement of the knee joint; ligaments

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make an axis of the joint, and decide a degree of freedom and the range of knee joint movement, which is related with the disease (OA).

Although recently knee joint models have been developed, there are few models that consider allowance of joint movement, three-dimensional movement and functions of ligaments. Moreover they do not test accuracy of their developed model. Almost all studies made their models just from previous mechanical property data. Therefore they tend to ignore an effect of whole model dynamics. Therefore this study uses a verification methodology by forward dynamics which gives the developed knee joint model some loads and sees its displacement caused by the loads. This displacement can be compared with a past cadaver study or a partial living body experiment [2]. In this study, anterior-posterior displacement and tibial rotation are considered to be important and focused; from clinical study anterior cruciate ligament is known to control anterior-posterior movement and to cause cartilage damage [3] [4] and tibial rotation is also proposed to be a possible cause for the disease [5].

Therefore our objective is to develop the knee model including ligaments and to test its accuracy with forward dynamics calculation. In addition, the effect of mediolateral knee displacement on ligaments and muscles is clarified to elucidate factors of knee OA from our developed model.

2 Knee joint

2.1 Bones and Joints

A knee is made up of four bones; a femur, a patella, a tibia and a fibula. The patella floats over the front of the knee joint. The tibia and the fibula are the two parallel bones in the lower leg. These bones compose three joints; the medical femur-tibia joint, the lateral femur-tibia joint and the femur-patella joint. Where the bones meet they are covered with articular cartilage and the femur-tibia joint has a medial meniscus and a lateral meniscus. These structures work as ”cushions” or ”shock absorbers”. They also provide stability to the knee. Articular capsule covers a whole joint and gives a limitation of vertical knee movement.

2.2 Muscles

There are mainly eleven muscles attached to a knee joint; the medial vastus muscle, the intermediate vastus muscle, the lateral vastus muscle, the rectus femoris muscle, the long head of biceps femoris muscle, the short head of biceps femoris muscle, the semimembranosus muscle, the semitendinous muscle, the sartorius muscle, the gracilis muscle and the gastrocnemius muscle. The former four muscles work as knee extension and latter seven muscles work as knee flexion.

2.3 Ligaments

Ligaments are like strong ropes that connect bones and provide stability to joints. In the knee, there are four main ligaments; the anterior cruciate ligament (ACL), the posterior cruciate ligament (PCL), the medial collateral ligament (MCL), and the lateral collateral ligament (LCL). Ligaments are composed with some bundles and they are attached to the knee bones to make facets. The ligaments work like a spring which exerts tension force if the length of ligaments is longer than its neutral length.

3 Model

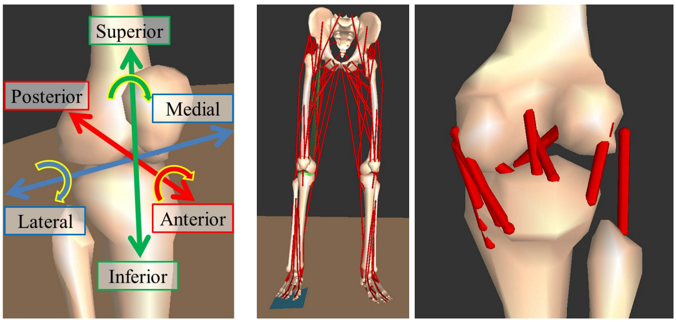
3.1 Simulation Method

SIMM (Corp. MusculoGraphics) is employed to develop and verify the three-dimensional musculoskeletal right leg knee ligament model. This software can calculate the muscle force from a specified musculoskeletal model with body trajectory and floor reaction force data (inverse dynamics calculation)

It can also calculate the displacement from the musculoskeletal model with external forces (forward dynamics calculation).

3.2 Detail

In our suggested model, 6 degrees of freedom movement is allowed and also liga-ments and cartilage are included. In order to consider irregular slide and rolling of the knee joint, 6 degrees of freedom movement is needed. Our developed knee model is designed as Fig. 1 (a). The overall model is shown in Fig. 1 (b). The positions of ligaments are shown in Fig. 1 (c). These positions are decided by anatomical structure. The number of bundles and their stiffness are determined from the previous studies of Shelburne *et al.* and Blankevoort *et al.* [6] [7]. Their strain is determined from trial and error. The length of neutral ligament (L_0) is calculated by equation (1) with the length of ligament when knee is extended (L_e) (Table 1). L_0, L_e and ε represent ligament neutral length, ligament length in knee extended and strain in knee extended. An articular capsule is also given as a function of ligaments. To represent cartilage and meniscus, there are ten



(a) (b) (c)

Fig. 1. Knee model. (a) Coordination. (b) Overall view. (c) Ligaments position.

Table 1. Bundle of ligaments, stiffness and strain

Bundle of ligaments	Stiffness [N/strain][a]	Strain [-]
aACL	1000	0.069
pACL	1500	-0.017
aPCL	2600	-0.087
pPCL	1900	-0.090
aMCL	2500	-0.209
cMCL	3000	-0.006
pMCL	2500	0.016
aCM[b]	2000	-0.299
pCM[b]	4500	-0.087
LCL	4000	-0.020
Mcap[c]	2500	-0.028
Lcap[c]	1000	0.018

[a] Shelburne *et al.* [6]

[b] A deeper part of MCL

[c] An articular capsule

spring points on the surface of femur. These points generate reaction force depending on a distance from bone surface. These mechanical properties are determined from the study of Neptune *et al.* [8].

$$L_0 = \frac{L_e}{1+\varepsilon}. \tag{1}$$

4 Verification of Model

The model is verified by comparing results of either a cadaver study or a living body experiment with the result of forward dynamics simulation. In the forward dynamics simulation, displacement of the knee joint can be observed by giving some load on the developed knee model. This displacement is comparable to the cadaver study or the living body experiment.

4.1 Anterior-Posterior Displacement

Firstly, anterior-posterior displacement is focused. In the past studies, researchers examined tibia displacement with femur by external voluntary load set on the knee joint in vivo and in vitro [9-13]. Since in this paper, range of knee joint movement is 0-30 degrees, this movement range is employed in the model. Then the knee joint of our model is given 100 N loads on anterior or posterior when the knee joint flexion angle is fixed as 0 or 30 degrees.

Table 2 shows results of knee displacement of our dynamics simulation and past studies. When 100 N is given to knee joint at flexion of 0 degree, our simulation result shows 4.17 mm anterior displacement. Almost all other studies indicate about 5 mm in the same situation. Therefore this model can be confirmed to be correct to represent anterior displacement of the knee joint. At knee joint flexion of 30 degree, knee displacement is larger than the one at 0 degree. Also other studies suggest change of knee displacement at 0 degree should be larger than the one of 30 degrees. From this result, this model can be confirmed to be correct to represent mechanism of the knee joint.

Table 2. Anterior-posterior displacement

Searcher	Status (Vivo/Vitro/ /Simulation)	Force [N]	Flexion angle [degree]	Displacement [mm] Anterior	Posterior
The current study	Simulation	100	0	4.17	3.22
		100	30	9.90	6.23
Fukubayashi *et al.* [9]	Vitro	100	0	5.2	3.9
		100	30	7.1	6.0
Daniel *et al.* [10]	Vivo	89	20	5.6	2.8
Shoemaker and Markolf [11]	Vitro	100	0	2.3	3.1
		200	0	3.4	4.7
		100	30	5.7	3.6
		200	30	7.0	5.0
Lim *et al.* [12]	Vivo	134	20	4.9	3.4
LaPrade *et al.* [13]	Vitro	88	0	3.4	5.1
		88	20	3.9	6.4
		88	30	3.8	5.5

4.2 Tibial Rotation

Secondary, tibial rotation is examined to verify the developed model. In the past studies, researchers examined tibial rotation with femur by generating external voluntary torque on knee in vitro [13-15]. The displacement of tibial rotation is analyzed when 5 or 10 Nm torque is exerted on the developed knee joint model when its flexion angle is fixed to 0 or 30 degrees.

Table 3 shows results of our simulation and past cadaver studies. At the knee joint flexion of 0 degree, our simulation result is 18.7 degree internal angle by 10 Nm torque. On the other hand, almost all other studies indicate approximately 10 degrees or slight higher. Therefore this model can be confirmed to be correct to represent internal rotation of the knee joint. Our simulation result is 29.0 degree external angle by 5 Nm torque. On the other hand, almost all other studies indicate smaller than 20 degrees. Therefore this model is more soft than those studies in external rotation of the knee joint.

At knee joint flexion of 30 degree, knee rotation is larger than that at 0 degree. Also other studies suggest change of knee rotation at 0 degree should be larger than the one of 30 degrees. From this result, this model can be confirmed to be correct to represent mechanism of the knee joint.

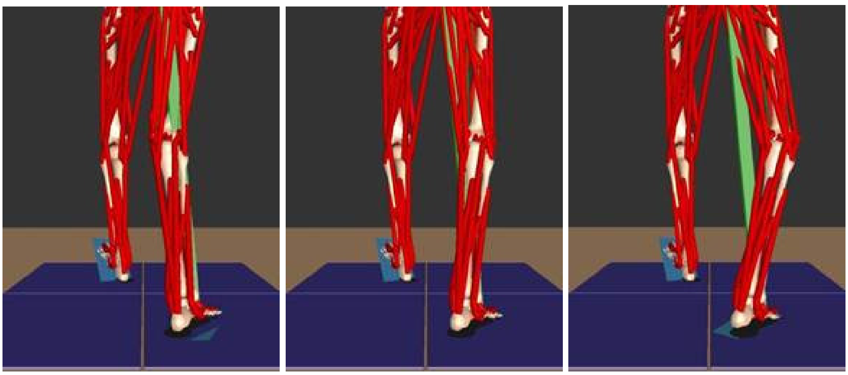
Table 3. Tibial rotation (Internal-external)

Searcher	Status (Vivo/Vitro/ /Simulation)	Torque [Nm]	Flexion angle [degree]	Rotation [degree] Internal	angle External
The current study	Simulation	5	0	13.2	29.0
		10	0	18.7	42.5
		5	30	22.6	27.9
		10	30	26.7	39.9
LaPrade *et al.* [13]	Vitro	5	0	7.7	8.8
		5	20	15.3	17.1
		5	30	17.0	17.7
Ahrens *et al.* [14]	Vitro	12.8	0	10.3	-
		14.8	0	-	12.3
		11.1	30	12.2	-
		13.9	30	-	12.6
Coobs *et al.* [15]	Vitro	10	0	11.1	11.8
		10	15	15.0	14.8
		10	30	17.5	14.8

5 Simulation

5.1 Gait Patterns

SIMM has normal gait pattern data (body trajectory and reaction force data) which is obtained by motion capture camera and floor reaction force sensor. To make mediolateral gait patterns we change the data of knee marker in mediolateral axis.



(a) Med50 (b) Normal (c) Lat50

Fig. 2. Gait patterns. (a), (b) and (c) represent the situation of walking with medial, normal and lateral knee displacement.

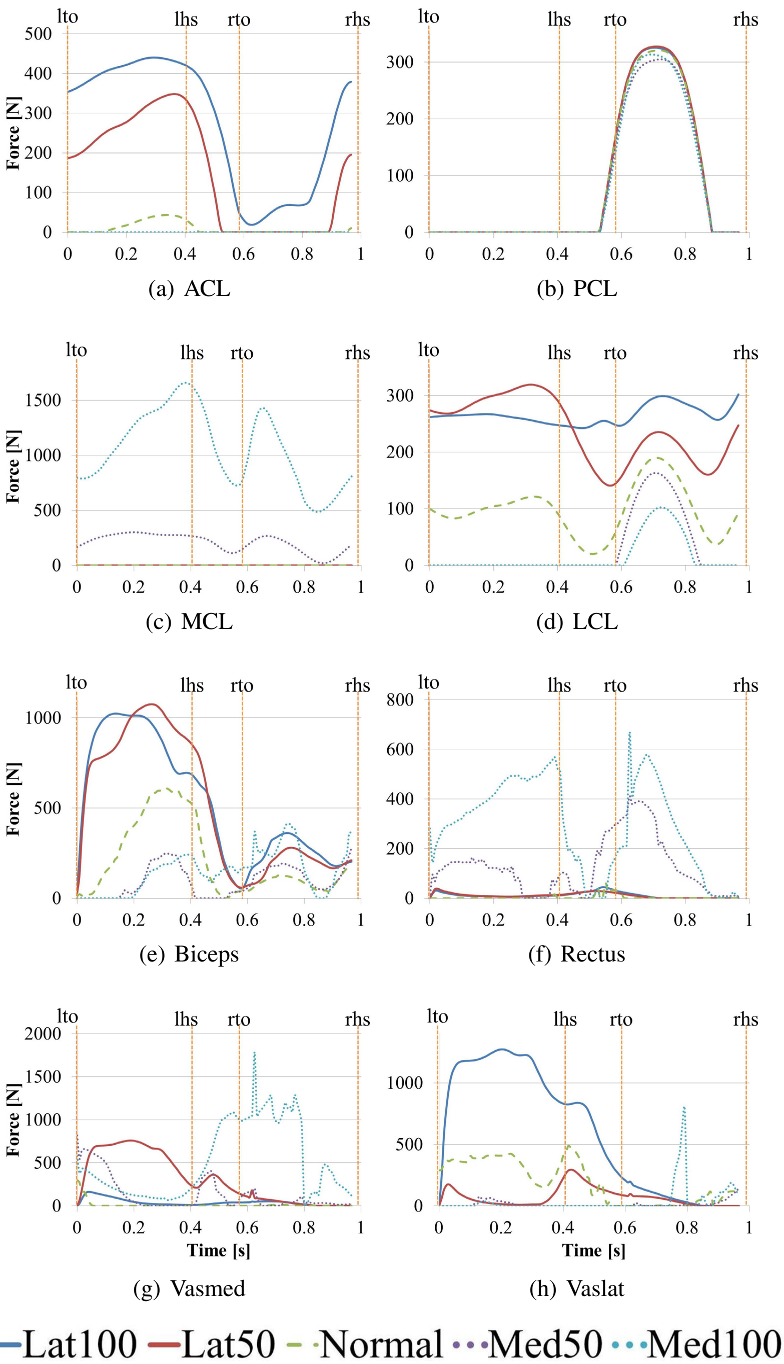


Fig. 3. Ligaments and muscles force. rto, rhs, lto and lhs represent right toe off, heel strike, left leg toe off and heel strike

Then five different gait patterns are tested including a normal walking (Normal); walking with 100 mm medial (Med100), 50 mm (Med50), 50 mm lateral (Lat50), and 100 mm lateral (Lat100) right knee displacement. Walking with medial knee displacement means baker-legged walking and walking with lateral knee displacement means bandy-legged walking. A knee position in each gait patterns at the same point during a walking phase is shown in Fig. 2. Figure 2(a) shows Med50, center (b) shows Normal and (c) shows Lat50. Gait data is cropped from left heel strike to right heel strike.

5.2 Force of Ligaments and Muscle

We input the former five gait patterns to our model and calculate the force of ligaments and muscles by inverse dynamics. Force of ACL, PCL, MCL and LCL is obtained. Also force of the biceps femoris muscle (Biceps), the rectus femoris muscle (Rectus), the medial vastus muscle (Vasmed) and the lateral vastus muscle (Vaslat) is obtained.

6 Result and Discussion

Figure 3 shows gait simulated results of ligaments and muscles force. Force of ACL rises with increased lateral displacement. Shelburne *et al.* showed that maximum force of ACL is about 200 N and force-time curve has two peaks in normal walking [2]. This feature can be found in our result. Therefore the function of ACL is thought to be correct though the result of anterior-posterior displacement is different. Force of PCL has mostly the same curve shape in all case. In a left leg stance phase, force of PCL has a peak. This reason is thought that the length of PCL is stretched by a swing leg movement of knee in right leg extension. Force of MCL rises with increased medial displacement. This reason is thought that the length of MCL is stretched by a medial movement of knee in right leg extension. Force of LCL rises with increased lateral displacement. Shelburne *et al.* showed that maximum force of LCL is about 100 N in normal walking [2]. Therefore our result is thought to be correct.

Force of Biceps rises with increased lateral displacement. This reason is thought that Biceps is antagonistic to Vasmed and Vaslat which have the same peak. Force of Rectus totally rises with increased medial displacement. This reason is thought that LCL alternately generates a moment of valgus in lateral displacement. Force of Vasmed in Med100 has a large peak in left leg stance phase. This reason is thought that Vasmed generates a moment of varus to suspend right leg. Force of Vaslat rises with increased lateral displacement and has a peak in right leg stance phase. This peak is thought that Vaslat lifts right leg. Generally Vaslat of patients of knee OA is weaker than one of healthy people. In such a case, it is difficult to support a lateral knee movement by Vaslat. Our result indicates that LCL and Vaslat, which are also generating a moment of valgus, raise a burden on lateral displacement. Therefore it can be suggested that lateral displacement is one of the factors of medial knee OA.

7 Conclusion and Future Works

Three-dimensional musculoskeletal knee model with ligaments is developed. Validity of the model could be tested with our suggested forward and inverse dynamics simulation. Also the effect of gait patterns on ligaments and muscles around a knee joint is discussed during considering knee OA.

For the future study, more sets of parameters, such as mechanical property and attachment position of ligaments, will be tested to improve accuracy of the model for individuals. Then we will make the system of diagnosis of the knee joint.

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