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The Effect of Vary Varus Malalignment on Knee Adduction Moment during Walking of Human Normal Gait

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Abstract—**This research aims to study the effect of varus malalignment to knee adduction moment (KAM) during walking using 3D gait simulation. KAM is the product of frontal ground reaction force and frontal lever arm; it is a major cause of pain at the lateral knee that is the general symptom of osteoarthritis (OA). For treatment, lateral fixed wedge insole and variable-stiffness shoes were used to treat OA patient for many years. The device helps reduce KAM while walking by shifting the center of pressure (CoP) from medial side to lateral side. Therefore, shifting CoP to lateral side for reducing frontal lever arm was incorporated into the design of the treatment devices for OA patient. In this paper, program simulation "Adams life module" was used to create 3D human model and simulate 3D gait to observe changes of KAM while vary the adduction angle between thigh and tibia. The simulation model was created based on normal gait profile data during the movement of the model. The result obtained from the simulation showed that the varus malalignment plays important roles on KAM. Increasing of the adduction angle leads to the higher value of peak KAM during walking.**

I. Introduction

Walking is a common way of human locomotion; understand dynamics load in knee joint during walking is essential. Measuring dynamic loading profile of knee joint directly is crucial; hence knee adduction moment or (KAM) obtained from gait laboratory can be applied as a substitute for dynamic loading [1]. The information obtained from gait analysis can be used to determine the cause of injury. Pain and functional disability in the knee are the common symptoms of the knee problem of OA among the elderly population. The OA patients also feel more stiffness and muscle weakness in the lower limb than normal [2]. Previous study found that peak KAM can be used to predict severity and rate of progression of knee OA, whereas peak KAM in OA patient is greater than normal [3], but no relationship between pain intensity and peak KAM was presented in severe OA patient [4]. Furthermore, varus malalignment that induced by KAM may affect to progression of OA severity [5].

KAM is the product of the frontal ground reaction force (GRF) and frontal lever arm in knee joint, which identified by center of pressure (CoP) and the position of the knee joint. Normally, gait analysis is used to estimate biomechanical variables such as GRF and KAM. 3D force plates are used to record frontal GRF and CoP. Simultaneously, the position of knee will be recorded by 3D optoelectronic marker system [6]. KAM is associated with medial compartment load; especially frontal lever arm is the key variable for knee OA study [7]. Hence, several methods were used in OA patients to prevent the increased KAM especially in less severe patients of OA. There are many research paved ways to reduce the magnitude of KAM, one of all is to reduce frontal lever arm by shifting CoP from medial side to lateral side. Lateral wedge sole have been used in OA treatment for many years [8]. They studied the effect of lateral wedges insoles on knee kinetics and kinematics during walking. Erhart et al [9] found that variable-stiffness shoes with stiffer lateral than medial sole can also reduce the KAM during walking and it provides more comfort than lateral fixed wedge.

In this paper, we focus on altering the value of KAM by manipulating the adduction angle between thigh and tibia. Our goal is to study the kinematics of walking which affect the kinetics of the knee part. As mentioned earlier, the important variables that influence magnitude of KAM are frontal lever arm and frontal GRF. While our approach is focusing on using a dynamic simulation of walking in Adams life module to observe the change of KAM, the other related parameters are kept unchanged. Most of the previous works were based solely on human gait analysis which walking dynamics were hardly repeated every time the experiment was done.

II. Methods

A. Subjects

The subject of this study was a healthy 40-50 years old male with no previous history of knee pain and never got a severe accident at the lower limb which could affect his gait character. Our subject was a 45 years old male with height of 165 cm and weight 52.3 kg. The characteristic of gait and malalignment was evaluated by a specialist. In this study, gait profile of this subject was used to create 3D model in a dynamics program for simulation

B. Gait analysis

The eight cameras in Vicon motion analysis system (Vicon MX-F40) were used to capture gait profile of the

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subject. Plug-in gait marker set was used to collect kinetic and movement of any parts of body human at 100 Hz. Fig.1, 35 optical markers were placed on the body of the subject. GRF were measured by three 508x438 mm force plates (AMTI) which installed on the walkway at 1,000 Hz. The proper GRF data were measured on the right contact between foot and force plate which should be on the center of the force plate for each foot. Prior to the walking, a static calibration was done. Only one successful barefoot trial with normal walking speed by the subject was used to create a walking model in Adams life module program. Furthermore, KAM was determined via Body builder program of the Vicon system.

Figure 1. Plug-in gait marker set were placed on the subject body

C. *Experiments*

The program used to created 3D model is the Adams life module. It is an additional part of MSC Adams which is a dynamic simulation program. Adams life module provides database of property of human body part such as bones, ligament and muscle. The program can be used to simulate human's movement and to perform computational analysis of biomechanical variable at any joints of the human body. In this study, inverse dynamics were used to determine KAM values via 3D model in Adams life module. First, 3D model was created based on subject's information. Then, gait profile was imported to the model to create a walking model of the subject. The contact properties between ground and foot were set. In this case, stiffness (K) and damping (C) played important role which affected the magnitude of vertical GRF. We compared the simulated GRF to the actual values measured during gait experiment. The configuration of K and C were selected in the range of 1 to 1,000 N/mm and 1 to 1,000 N.s/mm respectively. The selected value of K and C are the ones that resulted in the lowest error in the first and the second peak of vertical GRF.

Next, tracking agent of 3D model or the center of gravity's path was record after calculated in forward simulation process. Tracking agent was configured by varying the rotational stiffness (RoK) and rotational damping (RoC). Tracking agent was projected by the trajectory path of center of mass (CoM). Hence, altering the tracking agent properties could affect the value of KAM. Varying RoK in the range from 100 to 100,000 N/radian and RoC in the range of 100 to 100,000 N.s/radian. The selected RoK and RoC were chosen based on the values which resulted in the lowest error of the first and the second peak of KAM.

We obtained important parameters that could made our 3D model generated the KAM which is close to the values determined based on gait analysis system. We then study the effect of the adduction angle of knee joint on the value of KAM. In our analysis, we increased the angle by increment of 1° at a time until the adduction angle reached 6°. Then, the changing of KAM that was calculated from simulation has been analyzed. Shimada et al [8] use 6° lateral wedge insole for OA patient. The hypothesized of us is varus angle should be treated by same angle of lateral wedge insole.

III. RESULTS AND DISCUSSION

Our first step was to adjust contact properties between ground and foot of the model to yield very close simulation result of vertical GRF. In order to verify our model, we compared the human gait from experiment as measured to the simulation values of the GRF. The experimentally measured GRF peaks are presented in Table 1 and Fig. 2. Altering the parameters K and C affected the first peak of both knee sides as shown in Table 2. In Table 2, K= 140 N/mm and C = 20 N.s/mm were the proper values of K and C that yield the lowest errors in left and right foot, the errors were 5.23% and 5.09% respectively.

TABLE I. THE VALUE OF PEAK GRF FROM GAIT MEASUREMENT

Side	1st Peak GRF (N)	2nd Peak GRF (N)
Left	544.84	580.71
Right	551.55	617.17

TABLE II. CONFIGURATION ERROR SIMULATION RESULT AT PEAK VERTICAL GRF

Side	K (N/mm)	C (N.s/mm)	% Error at 1st Peak	% Error at 2nd Peak	% Absolute Mean Error
Left	100	10	10.90	0.05	5.47
	100	20	8.55	0.39	4.47
	100	30	7.88	0.74	4.31
	120	20	9.03	0.95	4.99
	140	20	9.45	1.01	5.23
	160	20	9.80	1.10	5.45
Right	100	10	-1.36	-7.27	4.32
	100	20	5.61	-8.10	6.86
	100	30	13.87	-8.35	11.11
	120	20	3.64	-8.07	5.86
	140	20	2.18	-8.01	5.09
	160	20	2.73	-7.97	5.35

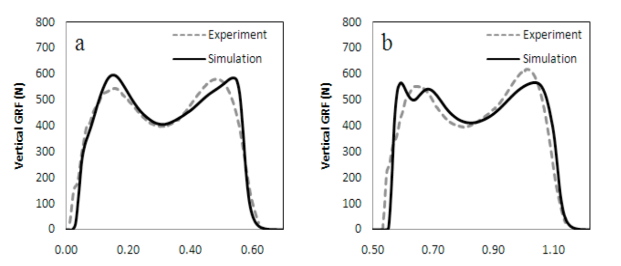

Figure 2. The Vertical GRF from experiment compared to the simulation at stiffness 140 N/mm and damping 20 N.s/mm (a) Left foot (b) Right foot

Tracking agent properties were configured in the next step to yield the closest result of KAM to the actual values. We compared the 1st peak and the 2nd peak KAM from simulation to the value that we obtained via gait system measurement. Table 3 and Fig. 3 show the value of peak KAM that was calculated via Body builder program. The best condition of tracking agent properties that result in minimum error at peak KAM was applied to our model. The value of RoK and RoC were varied as shown in Table 4. The RoK of 26,000 N/radian and RoC of 4,900 N.s/radian were the proper values that resulted in the lowest of error of 2.63% on the left side and 2.81% on the right side respectively.

TABLE III. THE VALUE OF PEAK KAM FROM LABORATORY

Side	1st Peak KAM (N.mm)	2nd Peak KAM (N.mm)
Left	19,095.68	15,669.31
Right	23,301.72	22,943.35

TABLE IV. ERROR SIMULATION RESULT AT PEAK KAM

Side	RoK (N/radian)	RoC (N.s/radian)	% Error at 1st Peak	% Error at 2nd Peak	% Absolute Mean Error
Left	20,000	1,000	21.86	-24.61	23.24
	25,000	1,000	16.39	-22.37	19.38
	26,000	1,000	15.32	-21.64	18.48
	27,000	1,000	14.27	-20.83	17.55
	26,000	2,000	8.07	-15.11	11.59
	26,000	3,000	2.64	-9.40	6.02
	26,000	4,000	-1.62	-4.75	3.18
	26,000	4,500	-3.18	-2.56	2.87
	26,000	4,600	-3.47	-2.15	2.81
	26,000	4,700	-3.75	-1.75	2.75
	26,000	4,800	-4.02	-1.35	2.69
	26,000	4,900	-4.30	-0.96	2.63
	26,000	5,000	-4.56	-0.57	2.56
Right	20,000	1,000	32.78	-36.46	34.62
	25,000	1,000	5.91	-43.04	24.48
	26,000	1,000	1.08	-42.51	21.80
	27,000	1,000	-3.58	-41.67	22.62
	26,000	2,000	-3.17	-26.39	14.78
	26,000	3,000	-4.53	-14.60	9.57
	26,000	4,000	-5.38	-5.88	5.63
	26,000	4,500	-5.35	-2.34	3.85
	26,000	4,600	-5.35	-1.69	3.52
	26,000	4,700	-5.35	-1.05	3.20
	26,000	4,800	-5.34	-0.43	2.89
	26,000	4,900	-5.34	0.27	2.81
	26,000	5,000	-5.35	0.86	3.10

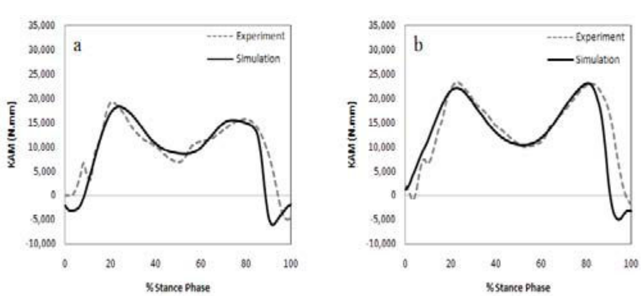

Figure 3. KAM as measured from experiment compared to simulation at rotational stiffness 26,000 N/radian and rotational damping 4,900 N.s/radian (a) Left foot (b) Right foot

Once we determined the proper parameters of contact property and tracking agent, our simulated model was used to represent a human walking model for further analysis. We then performed additional analysis on the effect of the knee angle on KAM. We adjusted the adduction knee angle on both left and right simultaneously by increment of 1° from 0° to 6°. Fig. 4 and Fig. 5 show the result of the KAM peak. We found that the KAM peak increased when the adduction knee angle increased. In Table 5, the progression of peak KAM of the left knee was 5.77%/° at the 1st peak and 9.79%/° at the 2nd peak. At the same time, there were progression at 1st peak and 2nd peak of the right knee 5.06%/° and 7.09%/° respectively.

TABLE V. RESULT OF PEAK KAM IN VARIOUS ADDUCTION ANGLE

Knee Angle (°)	1st peak KAM (N.mm)		2nd peak KAM (N.mm)		Mean Peak KAM (N.mm)	
	Left	Right	Left	Right	Left	Right
1	20,046	23,692	16,556	22,777	18,301	23,235
2	21,224	24,861	18,259	24,775	19,742	24,818
3	22,459	26,121	20,092	26,544	21,275	26,333
4	23,749	27,388	21,964	28,348	22,857	27,868
5	25,178	28,548	23,849	30,215	24,514	29,382
6	26,452	29,909	25,774	31,968	26,113	30,939
Percent increase of peak KAM per degree (%/°)	5.77	5.06	9.79	7.09	7.78	6.07

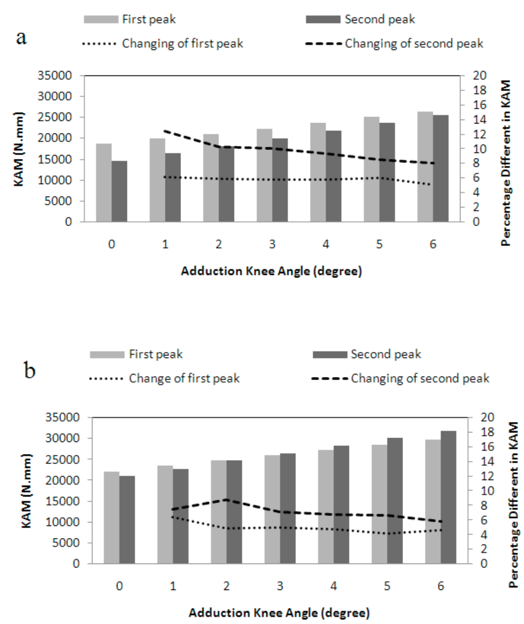

Figure 4. Changing of peak KAM in different adduction knee angle (a) Left knee (b) Right knee

Fig. 6 shows the simulation model which was created in Adams life module. When knee was more varus, lever arm which is the distance perpendicularfrom the center of knee joint to frontal GRF increased as well. In our model, we used one set of gait profile from a sucessful trial to perform the simulation. Hence, the frontal GRF is the same in all cases.

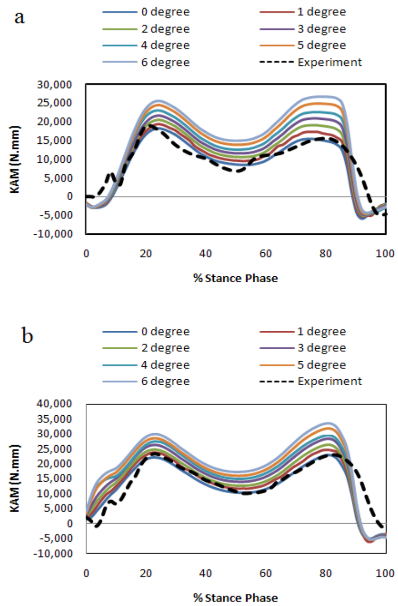

Figure 5. The effect of varying adduction knee angle to KAM (a) Left knee (b) Right knee

When the GRF is kept unchanged, the parameter which is the length of the lever arm becomes significant factor of KAM. Furthermore, the results show an increasing trend of KAM peak approximately the same in both left and right knees. The results show the much higher impact as we varied the knee angle, the second KAM peak increased with higher percentage than the first peak of both side as shown in Fig.7. It is possible that the value of varus has higher impact on human gait at toe-off phase than heel-strike phase.

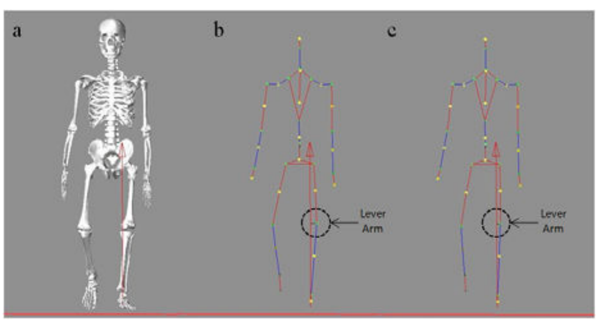

Figure 6. Changing of lever arm at knee point in different Adduction knee angle (a) Skeleton model with 6° varus (b) Stickman model with 6° varus (c) Stickman model with 0° varus

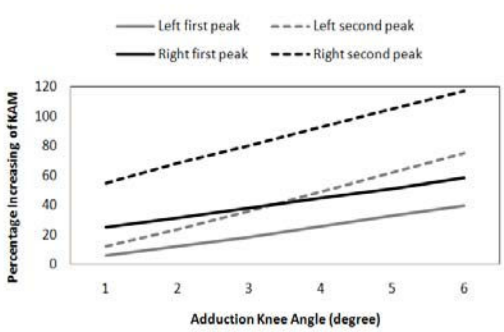

Figure 7. Increasing of KAM in different adduction knee angle

IV. Conclusion

We created a 3D model by Adams life module program to determine biomechanical variables i.e. GRF and KAM. The accuracy of result depends upon various parameters that we set on our model. In this paper, variation of stiffness and damping values were used to find the minimum tolerance of KAM. The simulation result shows that the peak of KAM increased when adduction knee angle increased. It is expected because KAM is a product of frontal ground reaction force and frontal lever arm. Normally, adduction angle is affected to lever arm length. We found an increasing trend of peak KAM while adduction knee angle is higher. The average of increasing of peak KAM at left and right side were 7.78 percent per degree and 6.07 percent per degree respectively as shown in Table 5. This model simulation could be used to predict the value of KAM instead of directly measure from gait analysis laboratory and could be used to perform further analysis on KAM and OA disease progression.

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