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Differences in Stress and Total Deformation Due to Muscle Attachment to the Femur

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Abstract**—**To achieve accurate and precise results of finite element analysis (FEA) of bones, it is important to represent the load/boundary conditions as identical as possible to the human body such as the bone properties, the type and force of the muscles, the contact force of the joints, and the location of the muscle attachment. In this study, the difference in the Von-Mises stress and the total deformation was compared by classifying them into Case 1, which shows the actual anatomical form of the muscle attached to the femur when the same muscle force was applied, and Case 2, which gives a simplified representation of the attached location. An inverse dynamical musculoskeletal model was simulated using data from an actual walking experiment to complement the accuracy of the muscular force, the input value of FEA. The FEA method using the results of the muscular force that were calculated through the simulation showed that the maximum Von-Mises stress and the maximum total deformation in Case 2 were underestimated by 8.42% and 6.29%, respectively, compared to Case 1. The torsion energy and bending moment at each location of the femur occurred via the stress ingredient. Due to the geometrical/morphological feature of the femur of having a long bone shape when the stress distribution is wide, as shown in Case 1, a greater Von-Mises stress and total deformation are expected from the sum of the stress ingredients. More accurate results can be achieved only when the muscular strength and the attachment location in the FEA of the bones and the attachment form are the same as those in the actual anatomical condition under the various moving conditions of the human body.

Keywords**—**Musculoskeletal modeling, Finite element analysis, Von-Mises stress, Deformation, Muscle attachment.

I. Introduction

TOTAL hip arthroplasty or fracture fixation is currently being performed to recover the functionality of the hip and the femur that had been destroyed due to aging, disease, or external injuries. The most important factor here is the strength of the load of the implant during physical activity. Actually, it is difficult to directly measure the load of the hip and the femur. Therefore, simulation is used under various conditions [7].
Finite element analysis is the representative method among these [3], and this creates a model in the same size and shape as the bone of an actual person, and creates a mesh.

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After the properties are set according to the bone conditions, constraints, and boundary conditions identical to the actual values, the analysis is conducted with a numerical study method. This has the advantage of being able to measure not only the stress of the surface of an object with a complicated shape but also the internal region. The most important thing here is the input value of the analysis, which requires estimation of the force of the muscle that is the same as the actual muscle, and the granting of appropriate loading conditions to the various movements. Actual loads could not be used, however, and instead, generally imprecisely pre-defined input values were used [10]. In addition, the preceding studies of Duda (1998) [7] checked the result that the tensile, compressive strain of the femur and the mechanical property was overestimated when the muscle groups attached at the femur were not considered entirely, and concluded that the number of muscles, the attached locations, and the characteristics of the material should be emphasized. In most studies on FEA, the number of used muscles and the attached location were simplified. Therefore, this study intended to check the difference in the mechanical features of the bone as the form of the muscle attached to the femur when the loading condition is changed. Upon analysis of the femur, the inverse dynamic musculoskeletal model was simulated in the mid-stance phase of the actual walking experiment data to achieve an accurate input value. The muscle force and joint force activated based on the results calculated through this was used as an input value of the FEA. The difference in the maximum Von-Mises stress and the total deformation of the femur was examined according to the number of the attached muscle heads.

II. Methods

A femoral model of the mid-stance phase in the walking section was created. A musculoskeletal model was simulated using an actual walking experiment and the ground reaction force to calculate the muscle force and the joint force for use as input values of the analysis. When the FEA of the femur was conducted, the femur was classified into muscles with various heads that were reproduced in the similar form of the anatomical attachment of each muscle (Case 1), and the method of simplifying the attached location was generally used in the analysis (Case 2) (Fig. 1).

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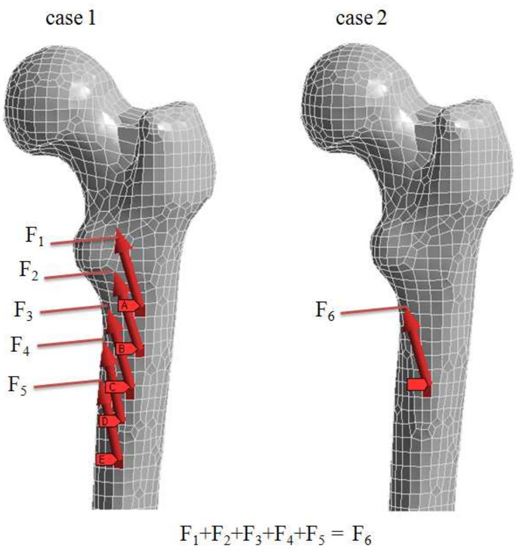

Fig. 1 Consideration of the muscle attachment method (case1 & case2)

A. Gait experiment

The experiment was conducted on a subject who was a normally walking healthy 28-year-old male adult (174.3 cm, 65.2 kg) with no medical history of musculoskeletal diseases. Twenty reflective markers were attached with a Plug-in set (Fig.2), and the gait was repeated at a comfortable pace three times. Motion data and ground reaction force data were obtained at 100 Hz and 1,000 Hz, respectively each using a 3D motion analysis system (CORTEX, Motion Analysis Corp., USA), with six infrared cameras(Eagle, Motion Analysis Corp., USA), and two ground reaction force devices (AMTI, USA).

Fig. 2 The scene of experiment & Plug-in marker set

B. Musculoskeletal model

Anybody software (Anybody Technology, Denmark) was used to obtain the muscle force that was activated in the mid-stance phase during the gait phase. The human body model (Fig. 3) that was used in the simulation was the Gait Low Extremity model based on the Hill-type muscle, which consists of a total of 56 muscles and 176 heads. In this study, 16 muscles that were attached to the femur were used. The names of the muscles and the number of their heads, as well as the muscle force, are shown in Table I.

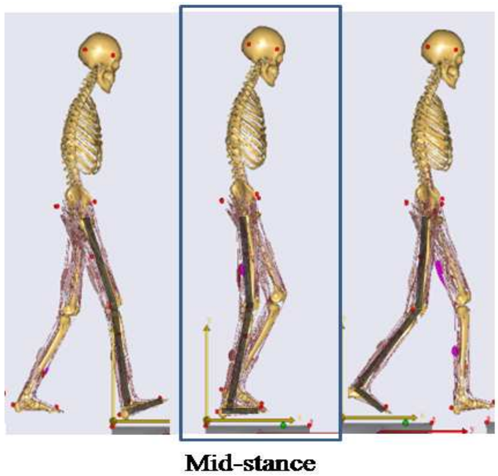

Fig. 3 Mid-stance phase during walking

TABLE I
FEMORAL MUSCLE FORCE AT MID-STANCE PHASE & NUMBER OF BRANCHS

Muscles	Case1	Case2	Mid-stance force[N]
Gluteus max	5	3	406
Gluteus med	12	4	840
Gluteus min	3	3	516
Inferior gemelli	1	1	62
Superior gemelli	5	1	54
Obturator exter	3	1	27
Obturator inter	4	1	404
Piriformis	1	1	180
Quadratus femoris	4	1	17
Biceps femoris	2	1	115
Ten fas latate	2	1	14
Gastro- lateral	1	1	372
Gastro- medial	1	1	530
Vastus lateralis	8	8	11
Vastus medialis	10	10	2
Vastus intermedius	6	6	2
Total	68	44	3552

C. Finite element analysis of femur model

A FEA software, ANSYS v11 (ANSYS Inc., USA), was used for mesh generation and analysis by producing the right femur of the subject based on its CT (computed tomography) image at 1.5mm intervals. The generated mesh had 17,220 2mm tetrahedral elements, and its properties were divided into those of the cortical bone and those of the cancellous bone [2, 3], in reference to the preceding studies of Duda [7]. The Young's modulus were 17,000 MPa and 1,500 MPa [1], respectively, and the Poisson's ratio was set at 0.33 [2]. Furthermore, homogeneous isotropic materials and linear elastic deformation were assigned. The maximum Von-Mises stress and the total deformation were shown through analysis.

III. Results

The muscles that showed high activity from the results of the muscle force that were calculated using the musculoskeletal model were the Gluteus maximus, Gluteus medius, and Gluteus minimus, which were 406, 840, and 516 N, respectively. When the maximum Von-Mises stress that acted on the femur was checked using 16 muscle forces as the input values in the FEA, Cases 1 and 2 showed values of 69.64 and 63.78 MPa, respectively, and maximum total transformation values of 1.43 and 1.34 mm, respectively. The values and area that represent the activity level are shown in Figs. 4, 5 and 6.

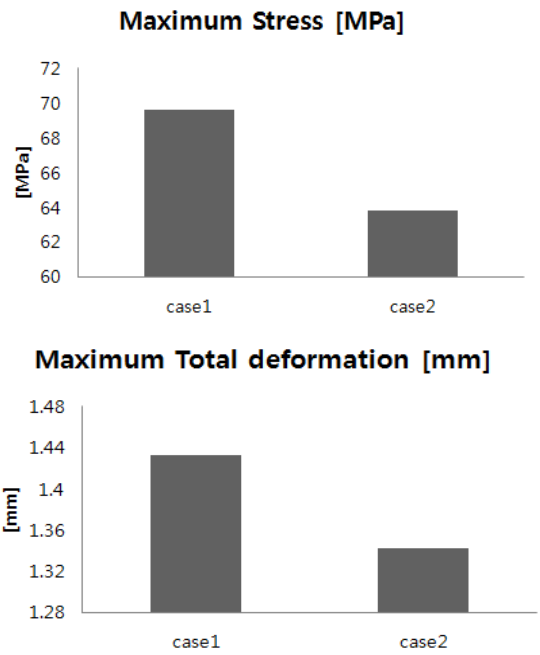

Fig. 4 Maximum Von-Mises stress and Total deformation at Mid-stance phase with Cases

IV. Discussion and Conclusion

An inverse dynamic simulation was conducted by performing an actual gait experiment to enhance the accuracy of the activated muscle power, which was the input value in the FEA of the femur. Then the results were given as the loading conditions in the FEA, and the difference in the maximum Von-Mises stress and the total deformation was verified according to the method of considering the part where the muscles were attached. The Von-Mises stress is an expression of the maximum distortion energy according to the stress elements at each object location, and is generally used as the basis of the prediction of the destruction of the objects [6]. The FEA results showed that the maximum Von-Mises stress and the maximum total deformation in Case 2 decreased by 8.42% and 6.29%, respectively, compared to those in Case 1.

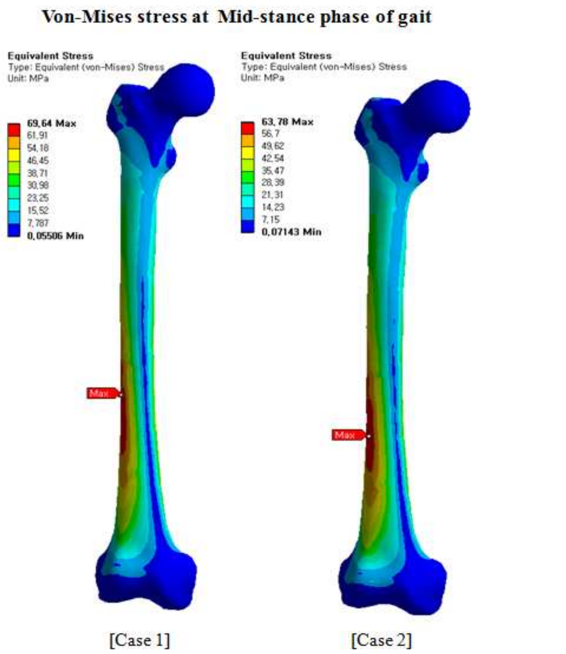

Fig. 5 Contour image of the Von-Mises stress (Maximum Von-Mises stress point (Red tag) of Case1 was different with Case2)

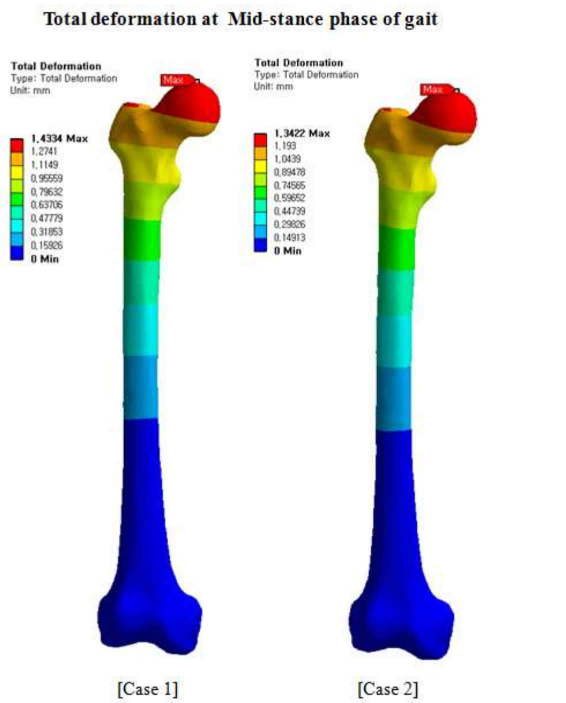

Fig. 6 Contour image of the Total deformation at Case1 & Case2

These are deemed to have been due to the significant formation of the torsion energy and the bending moment when the stress distribution was wide [11], despite the same value of the muscle force due to the geometrical and morphological features of the femur, which has a long bone shape [8, 13].

In previous studies, it was found that the material properties [8, 14], muscle force [4, 5], constraints and boundary conditions [10, 12], and region where the muscle was attached are the important conditions that must be considered in the FEA of the bone; and to check if the results for such conditions are as precise and similar to the maximum extent under the assumption that an invasive way is impossible, optimized reproduction of the actual femur model was needed [9, 10]. In the succeeding studies, the muscles in the region where they are attached to the femoral head will be constructed in greater detail, and the effect of the various gait cycles and motions on the bones will be verified.

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