FINITE ELEMENT ANALYSIS FOR MUSCLE STRAIN INJURY OF THE GASTROCNEMIUS MUSCLE AND ITS VALIDATION BASED ON THE CLINICAL CASES

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Introduction

The muscle strain injury is common soft tissue injury and the gastrocnemius medial (GM) muscle is, especially, injured frequently. In most of the cases, the injury occurs near the distal myotendinous junction (MTJ) of the GM muscle. It is thought that the injury occurs when a contracting muscle is stretched acutely. Best et al. [1] showed that the region where the maximum axial strain occurred at the muscle failure location with experiments *in vitro*. Rehorn et al. [2] reported that the peak stretch of the biceps femoris was located near the MTJ with a finite element model. However the injury mechanism and, the reason why a common injury location exists in the GM muscle have not been clearly explained. Purpose of the study was to develop a three dimensional finite element (FE) model of the GM muscle based on magnetic resonance (MR) images to analyze the stress distribution of the muscle during gait. To confirm the validity of the analysis, we compared the results of FE analysis with actual clinical cases that had muscle strain injury in the GM muscle.

Materials and Methods

FE analysis of the GM strain injury

Axial images of 1.5T MRI were obtained from the right lower extremity of a healthy 23-year-old male. A finite element mesh model of the GM muscle was reconstructed from the MR image data. The model consisted of approximately 4400 eight-node hexahedral elements as shown in Figure 1(A). A boundary surface of the soleus muscle medial to the GM muscle model was placed to reproduce an interaction between the GM and the soleus muscle. Stretched length of the GM was obtained from a gait analysis of the same subject using 22 reflective marker with Point Cluster Technique [3], and then the stretched length was calculated from the origin position relative to the insertion. FE analysis was performed with fixing the distal end of the distal tendon, and stretching the proximal tendon based on the kinematics data during gait using a commercial solver (ABAQUS, Simulia). Moony-Rivlin elements were used to simulate muscle strain. We simulated two models: (1) a model with normal properties [4], and (2) aged model with 10 % stiffer properties in the muscle.

Validation of the FE analysis using clinical cases

MR images of 29 cases (ages 20 to 61) that were diagnosed as the GM muscle injuries by two radiologists who were blinded from the study were collected retrospectively. Side and type of the injury in the GM were evaluated for comparison with the FE results.

Results

FE analysis

The maximum stress varies with the knee flexion angle, and the stress reached its peak near toe-off when knee flexion is minimum during gait in both models (Table 1). Stress concentration was found around the border of the proximal and the distal MTJ (Figures 1(B) and (C)).

Validation of FE analysis

Two injury patterns were found as GM muscle strain. Majority of the cases (23of 26) had injury in the border of distal MTJ. Mean age of thecases with this type of injury was 42 (range 31-61). The rest 3 cases had broad muscle injury in proximal of the distal MTJ, which is consistent with the FE results. Mean age of this injury type was 21 (range 20-23).

Table 1. Knee flexion angles and stretched lengths of the GM muscle

	Knee flexion angle (deg)	Stretched length (mm)	Maximum von Mises stress (MPa)	
			Healthy	Aged
Heel strike	3.6	13.6	0.01	0.01
Mid stance knee flexion	13.9	32.1	0.99	1.08
Minimum knee flexion	5.9	42.6	2.25	2.37
Toe off	29.9	30.2	0.82	0.88

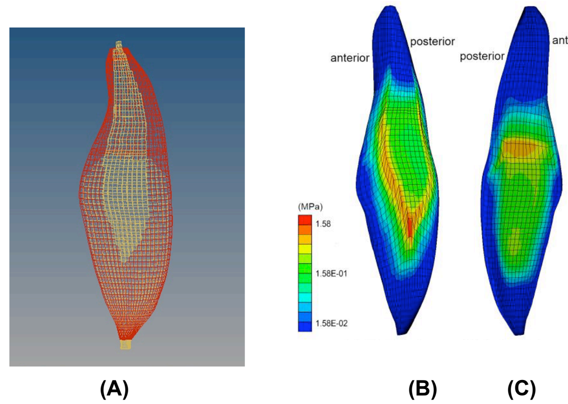

Figure 1. (A): 3D mesh model of the GM muscle, (B) - (C): Distribution of von Mises stress (MPa) at the minimum knee flexion angle during gait in the normal model ((B) medial view, (C) lateral view)

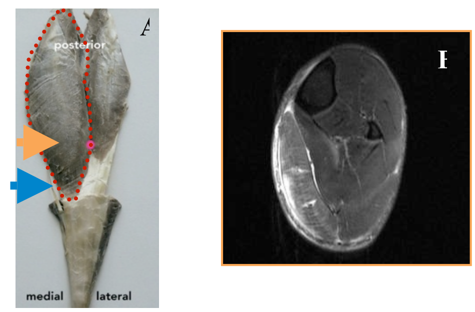

Figure 2. (A): Anatomy of the GM muscle [5] (red line) and two injured locations in clinical cases (orange arrow=20s and blue arrow=over 40s), (B) axial T2 image of a 21 year old subject who had GM strain injury at proximal of the distal MTJ which was consistent with our FE analysis.

Discussion and Conclusion

MR images of clinical cases suggested that location of the GM muscle strain differ between the subjects who are twenties and over forties. Our FE results generally agreed with the clinical cases of younger subjects (i.e. twenties) while majority of the cases that are over forties had muscle injury at more distal site (Figure 2(A)). Since stress distribution pattern in the aged model was similar to that of normal model, difference in the muscle material property should not affect injury location. Difference in the injury location between the ages may be explained by the difference in the muscle morphology such as the muscle volume and shape, and difference in the material property of the tendon. Other issues that require further works are to model self-contraction of the muscle, analysis of the whole triceps surae muscle and involve more details of muscle structures such as muscle fiber orientation and the aponeurosis.

In conclusion, FE analysis of GM muscle strain injury was conducted and the results well agreed with clinical cases of younger subjects but did not agree with the cases over 40 years old.

References

[1] Best TM et al., J Biomech Eng, 3:262-265, 1995. [2] Rehorn MR et al., J Biomech, 43:2574-2581, 2010. [3] Andriacchi TP et al., J Biomech Eng, 120:743-749, 1998[4] Yamada H, Strength of Biolog Mat, 7: 221–230, 1970. [5] Blitz NM, J Foot Ankle Surg, 47(6): 533-40, 2008