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Short communication

Analysis of effects of friction on the deformation behavior of soft tissues in unconfined compression tests

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Abstract

Frictionless specimen/platen contact in unconfined compression tests has traditionally been assumed in determining material properties of soft tissues via an analytical solution. In the present study, the suitability of this assumption was examined using a finite element method. The effect of the specimen/platen friction on the mechanical characteristics of soft tissues in unconfined compression was analyzed based on the published experimental data of three different materials (pigskin, pig brain, and human calcaneal fat). The soft tissues were considered to be nonlinear and viscoelastic; the friction coefficient at the contact interface between the specimens and platens was assumed to vary from 0.0 to 0.5. Our numerical simulations show that the tissue specimens are, due to the specimen/platen friction, not compressed in a uniform stress/strain state, as has been traditionally assumed in analytical analysis. The stress of the specimens obtained with the specimen/platen friction can be greater than those with the frictionless specimen/platen contact by more than 50%, even in well-controlled test conditions.
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Keywords: Soft tissue; Unconfined compression; Friction; Non-linear viscoelastic; Finite element model

1. Introduction

The mechanical characteristics of soft tissues in compression have traditionally been obtained via unconfined compressions. In such tests, the cylindrical tissue specimens were placed between two smooth platens and compressed at different speeds in a testing machine. By assuming that the tissues are in uniform stress/strain states during the compressions, the material parameters can be obtained by fitting the analytical model to the experimental data. However, if there is friction between the specimen and platens, the specimen will not be compressed in a uniform stress/strain state. Armstrong et al. (1984) and Brown and Singerman (1986) observed that the peak reaction forces in their unconfined stress-relaxation experiments of articular cartilage exceeded the corresponding maximum values predicted analytically. These authors suggested that this discrepancy might have resulted from the friction between the specimens and platens. Spilker et al. (1990) analyzed the effects of the platen/specimen friction on the mechanical response of cartilage in unconfined compression using the finite element (FE) method. In their study, only two extreme cases in the unconfined compression were conducted and analyzed; i.e., the specimen was either adhered to or contacted without friction with the end-platens. Also, the cartilage was assumed to be linearly biphasic, and an infinitesimal deformation assumption was applied in their analysis. They found that the effects of specimen/platen friction were significant for specimens with large aspect ratios (diameter/height, referred as d/h hereafter), i.e., $d/h = 3.57$. Spilker et al.'s (1990) analysis cannot be used to quantify the effects on friction in many soft tissues tests because the soft tissues (such as skins, calcaneal fat, brain tissues, etc.) are highly non-linear, and viscoelastic; the tissue specimens usually undergo large deformations; and, most importantly, the specimens will slide radially relative to the platens during compression even with great friction at the specimen/platen interface.

In order to minimize the effects of friction on the experimental results, researchers have made many efforts to reduce the specimen/platen friction during unconfined compressions. For example, Miller and

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Chinzei (1997) covered the moving platen with a polytetrafluoroethylene (PTFE) sheet, while Miller-Young et al. (2002) used platens of polished stainless steel. However, regardless of the technique applied, the specimen/platen friction cannot be completely eliminated. Even in a well lubricated contact pair, such as the contact of an articular cartilage layer with stainless steel, in which approximately 80% of the contact pressure is supported by the interstitial fluid, the friction coefficient can still exceed 0.2 (Williams et al., 1993; Wang and Ateshian, 1997). Zhang and Mak (1999) analyzed the in vivo friction properties of human skin in contact with five different common materials and found that friction coefficients varied from 0.37 (skin/nylon) to 0.61 (skin/silicone).

Due to the specimen/platen friction, the tissue specimens in unconfined compression tests may not be compressed in uniform stress/strain states, as has been assumed in the traditional, analytical analysis. The goal of the present study was to analyze, theoretically, the effect of the specimen/platen friction on the mechanical characteristics of soft tissues in unconfined compression tests via an FE model. The soft tissues were considered to be nonlinear and viscoelastic, and the friction coefficient of the specimen/platen contact interface was varied from 0.0 to 0.5. The effects of loading speed were also analyzed.

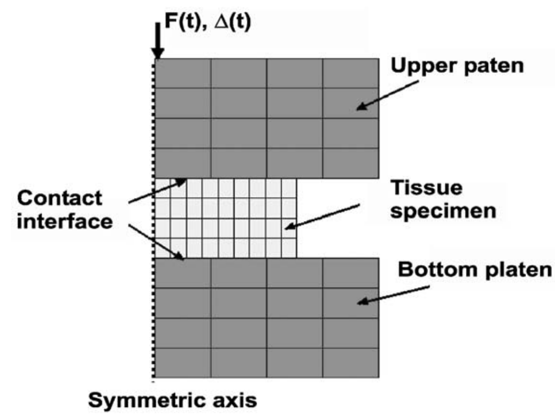

Fig. 1. Schematics of the FE model for unconfined compression tests. A cylindrical soft tissue specimen is squeezed between two steel platens with its lateral side unconstrained. The contact interface between specimen and platens has a friction coefficient of f $(= 0.0, 0.1, 0.3,$ and $0.5)$. The numerical tests were conducted in a displacement-controlled protocol.

2. Method

2.1. Finite element model

The FE analyses were performed using a commercial finite element software (ABAQUS, version 6.2). The FE model is axi-symmetric (Fig. 1). The tissue specimen was unconstrained laterally and squeezed between two steel platens (Young's modulus = 200 GPa, Poisson's ratio = 0.3). The bottom platen was fixed, while the upper platen moved downward at a constant speed. The contact between the specimen and the compression platens was modelled using a "contact pair" (an option in ABAQUS). The steel platen was specified as "master" while the specimen was specified as "slave". The friction coefficient (f) at the contact interface of specimen/platen was varied: $f = 0.0$, 0.1, 0.3, and 0.5. The FE model of the soft tissue specimen contained 36 axi-symmetric, eight-node elements.

The mechanical behavior of the soft tissue is considered to be nonlinear and viscoelastic (Wu et al., 2003). The total tissue stress (Cauchy stress) is assumed to be decomposed into an elastic stress, representing instantaneous tissue response, and a viscous stress, representing the delayed tissue response. The nonlinear elastic of the material was modelled using the Ogden's (1997) strain energy functions, while the viscous behavior was simulated using a stress relaxation function based on the Prony series (Tschoegl, 1989). Owing to the large deformation of the soft tissues, a finite deformation analysis was applied in the present study (Ogden, 1997), in which logarithmic strain and Cauchy stress were used.

2.2. Numerical tests

Three numerical tests were performed to investigate the effects of specimen/platen friction. In Test A ($d = 6.35$ mm, $h = 2.00, 3.00$ mm; $d/h = 3.175, 2.117$), unconfined compression tests of pigskin performed in our laboratory (Wu et al., 2003) were simulated. In Tests B and C, unconfined compression tests of pig brains (Miller and Chinzei, 1997; $d = 30$ mm, $h = 13$ mm, $d/h = 2.308$) and human calcaneal fat pads (Miller-Young et al., 2002; $d = 8$ mm, $h = 10$ mm, $d/h = 0.80$) were simulated, respectively. All material parameters in the constitutive equations were obtained by fitting the material model to the published experimental data (Wu et al., 2003; Miller and Chinzei, 1997; Miller-Young et al., 2002). They are listed in Table 1.

In order to investigate the time-dependent effects of specimen–platen friction, the compression tests were performed at four different strain rates ($\dot{\varepsilon} = 1.0$, 1.0×10^{-2}, 1.0×10^{-4}, and $1.0 \times 10^{-6}\ s^{-1}$) in Test A. In all three test series, simulations were performed using four different friction coefficients (i.e., $f = 0.0$, 0.1, 0.3, and 0.5), which encompasses the range typical in soft tissue tests. The specimen deformations and force responses were analyzed to evaluate the effects of specimen/platen friction.

Table 1
Material parameters used in the numerical simulations

i	1	2	3	4	5	6
Test A: Pig skin (Wu et al., 2003)						
α_i (–)	2.000	4.000	6.000	−2.000	−4.000	−6.000
μ_i (MPa)	248.4	−252.7	79.67	−151.4	94.90	−18.83
D_i (MPa^{-1})	42.92	0.1505×10^{-1}	-0.1408×10^{-4}	0.1748×10^{-7}	-0.4996×10^{-10}	0.3771×10^{-12}
Test B: Pig brain (Miller and Chinzei, 1997)						
α_i (–)	2.000	4.000	6.000	−2.000	−4.000	−6.000
μ_i (MPa)	1.406	−1.484	0.4851	−0.7958	0.4832	-0.9440×10^{-1}
D_i (MPa^{-1})	0.0	0.0	0.0	0.0	0.0	0.0
Test C: Human calcaneal fat (Miller-Young et al., 2002)						
α_i (–)	2.000	4.000	6.000	−2.000	−4.000	−6.000
μ_i (MPa)	0.3723	−0.5711	0.2532	-0.5258×10^{-1}	0.9050×10^{-3}	0.1052×10^{-3}
D_i (MPa^{-1})	0.0	0.0	0.0	0.0	0.0	0.0
Viscoelastic parameters for Tests A, B, and C						
g_i (–)	0.4621	0.4959				
k_i (–)	0.3632	0.5948				
τ_i (s)	0.07294	9.610				

3. Results

In order to facilitate comparison of the theoretical predictions with experimental data, the stress and strain are presented as nominal stress and nominal strain, which are defined as the force divided by the un-deformed cross-sectional area and the deformation divided by the un-deformed specimen height, respectively. The relative differences between the stress responses calculated using different friction coefficients ($f = 0.1$, 0.3, and 0.5) and those obtained in frictionless conditions ($f = 0.0$) were evaluated.

For numerical Test A, the stress/strain curves of pigskin in unconfined compression tests as a function of specimen/platen friction at four different loading rates ($\dot{\varepsilon} = 1.0,\ 1.0 \times 10^{-2},\ 1.0 \times 10^{-4}$, and $1.0 \times 10^{-6}\ \mathrm{s}^{-1}$) were predicted (Figs. 2A–D). The stress/strain relations for $f = 0.0$ were obtained by fitting the material model to the experimental data (Wu et al., 2003) (Fig. 2A). It is seen that the specimen/platen friction has a significant influence on the stress response of the tissue specimens at all loading speeds.

In order to determine if the effect of the specimen/platen friction on the tissue stress responses is time-dependent, the differences of the stress responses are plotted as a function of strain rate for two friction coefficients, $f = 0.1$ and 0.3 (in Figs. 3A and B, respectively). These tests were performed under four different loading speeds ($\dot{\varepsilon} = 1.0,\ 1.0 \times 10^{-2},\ 1.0 \times 10^{-4}$, and $1.0 \times 10^{-6}\ \mathrm{s}^{-1}$). Our simulation results show that the differences of the stress responses obtained at different loading speeds virtually overlap (Fig. 3), indicating that the effects of the specimen/platen friction on the tissue stress responses is time-independent. Therefore, in the simulations depicted in the subsequent graphs, the stress responses were computed using a single loading speed.

The effects of the specimen aspect ratio (d/h) were studied by comparing the stress responses of the tissue specimens with the same diameter (6.35 mm) but different heights (2.00 and 3.00 mm). The differences in stress response as a function of strain and friction coefficient are depicted for specimen heights of 2 and 3 mm (in Figs. 4A and B, respectively). The difference in stress is reduced by approximately 50% when the specimen height is increased by 50% (from 2.00 to 3.00 mm).

The deformation patterns of pig brain tissues in unconfined compressions (Test B), as performed by Miller and Chinzei (1997), were simulated (Fig. 5). The deformations and the axial strain distributions (logarithmic strain, labelled LE22 in the figure) of the brain specimens as a function of nominal strain and specimen/platen friction are predicted (Fig. 5). Without friction, the tissue specimen is deformed in a uniform stress/strain and expands uniformly in the lateral direction with increasing axial nominal strain, ε (Fig. 5A, $f = 0.0$). When there is friction between the specimen and platens, the strain distribution in the specimen becomes non-uniform, and the specimen buckles externally in the middle of the lateral side (Figs. 5B–D). The amount of lateral buckling increases with increasing friction coefficients. In these cases, the specimen is deformed non-uniformly because of the frictional restraints at the ends of the specimen. However, even with the friction coefficient (f) as great as 0.5, the specimen is not constrained completely on the ends, i.e., there is relative sliding between the specimen and the platens in the lateral direction (Fig. 5D).

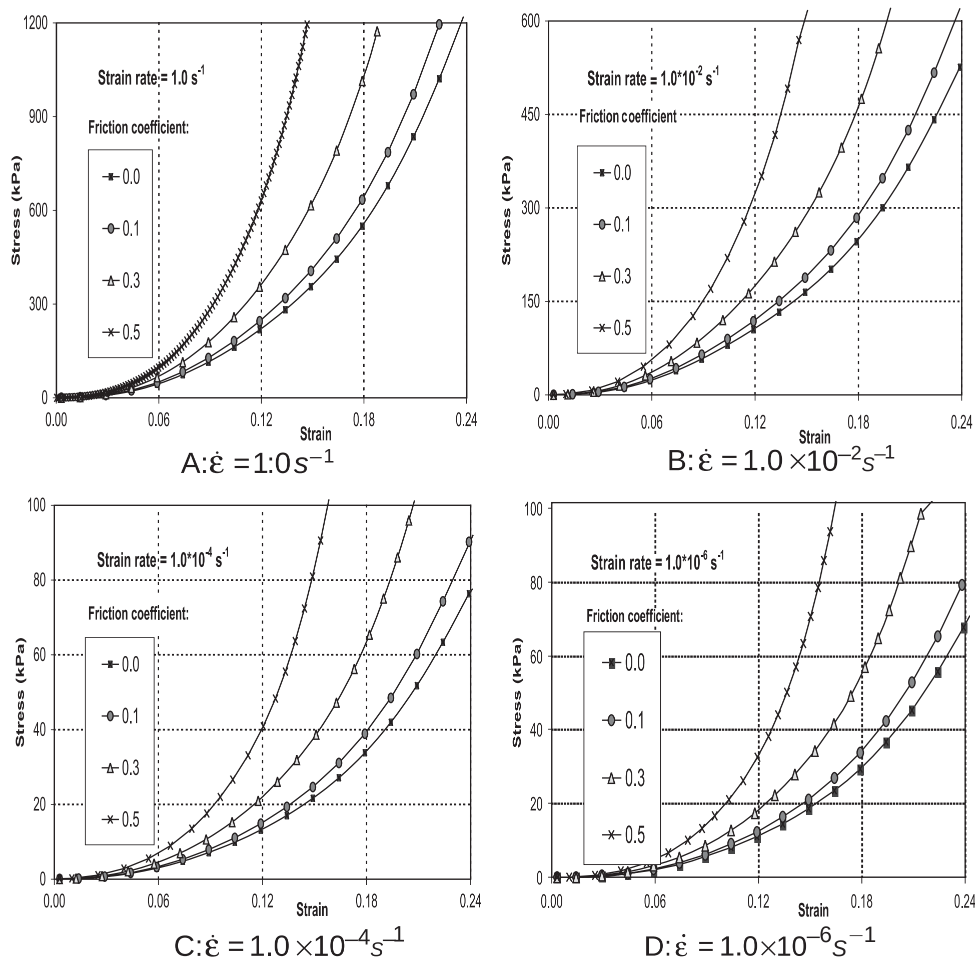

Fig. 2. Predicted stress/strain relations of the pigskin tissue (Wu et al., 2003) as a function of the specimen/platen friction for four different loading speeds (strain rates). (A) $\dot{\varepsilon} = 1.0\ \mathrm{s}^{-1}$; (B) $\dot{\varepsilon} = 1.0 \times 10^{-2}\ \mathrm{s}^{-1}$; (C) $\dot{\varepsilon} = 1.0 \times 10^{-4}\ \mathrm{s}^{-1}$; (D) $\dot{\varepsilon} = 1.0 \times 10^{-6}\ \mathrm{s}^{-1}$.

The deformation behavior of the human calcaneal fat pad in unconfined compressions (Test C), as performed by Miller-Young et al. (2002), were also simulated. The deformation and the vertical strain (logarithmic strain, labelled LE22 in the figures) distribution in the specimen as a function of the nominal strain and the specimen/platen friction were calculated (Fig. 6). In this case, the specimen ($d/h = 0.8$) is much slimmer than in the previous two cases, and the specimen has a different deformation pattern compared to Test B (Fig. 5). Under unconfined compression with frictionless specimen/platen contact, the specimen expands uniformly on the lateral side (Fig. 6A: $f = 0.0$). With a small specimen/platen friction (Fig. 6B: $f = 0.1$), the specimen buckles outwards on the lateral side, with increasing nominal strains, ε. With a greater specimen/platen friction (Figs. 6C and D: $f = 0.3$–0.5), the specimen begins to lose stability in the regions near the specimen/platen contact interfaces under large compressive strains (Figs. 6C and D, $\varepsilon = 0.423$). The edges on the lateral side of the specimen turn outwards and, finally, the lateral surfaces near the ends of the specimen come into contact with the compression platens (Figs. 6C and D, $\varepsilon = 0.423$–0.500). The numerical simulations show that the specimen is compressed in rather uniform strain, except in the regions near the contact interfaces between the specimen and platens.

The stress/strain curves as a function of the friction coefficient for Test B were computed (Fig. 7A). The unconfined compression tests were performed at a slow loading rate of $0.64 \times 10^{-5}\ \mathrm{s}^{-1}$, and the stress/strain curve for $f = 0.0$ was obtained by fitting the constitutive model to Miller and Chinzei's (1997) experimental data (Fig. 7A). The error of the stress response due to the specimen/platen friction as a function of the compressive strain and the friction coefficient was computed (Fig. 7B). The error of the stress response increases dramatically with increasing friction coefficients. The stress response in the experiment with a specimen/platen friction of 0.5 could be greater than that obtained in the ideal, frictionless test condition by more than 100%.

The stress/strain curves as a function of the friction coefficient for Test C were computed (Fig. 8A). The unconfined compression tests were performed at a fast

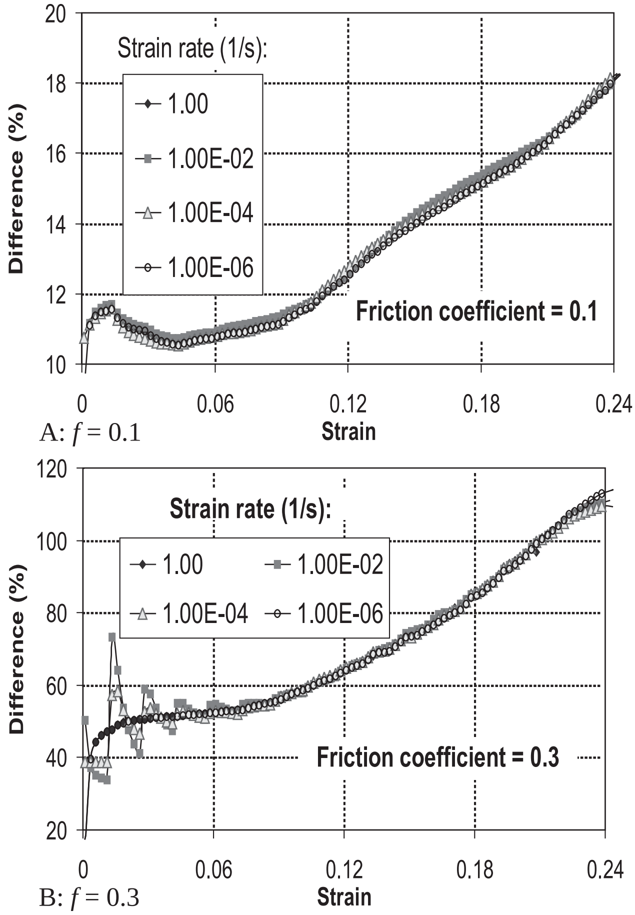

Fig. 3. Differences of the stress responses of the pigskin tissue (Wu et al., 2003) as a function of strain and loading speeds (strain rates). (A) $f = 0.1$; (B) $f = 0.3$. The results show that the effects of the specimen/platen friction on the stress responses are loading-speed-independent.

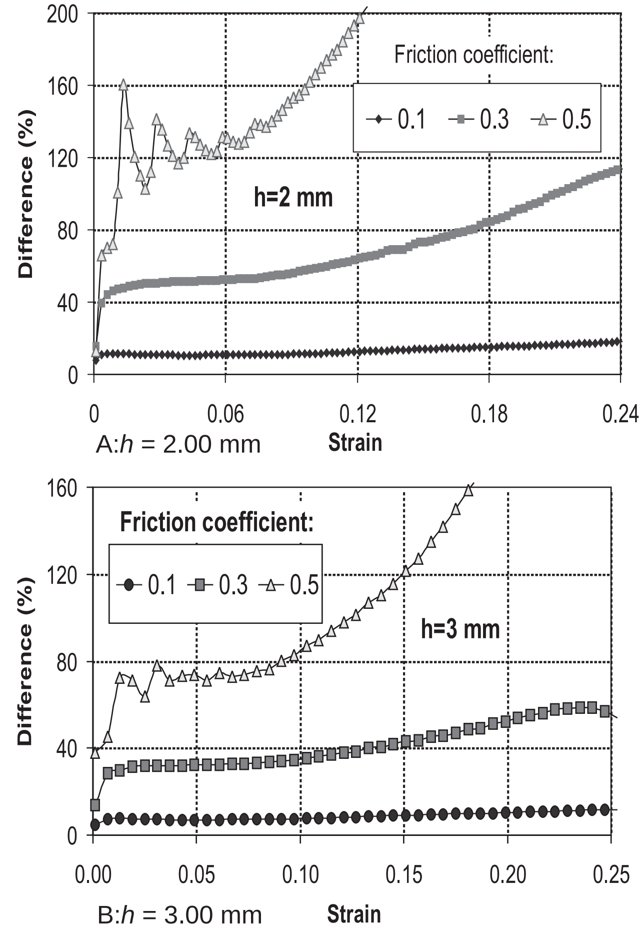

Fig. 4. Differences of the stress responses of the pigskin tissue (Wu et al., 2003) as a function of the specimen/platen friction for specimens with two different aspect ratios (d/h). (A) $h = 2.00$ mm ($d/h = 3.175$); (B) $h = 3.00$ mm ($d/h = 2.116$). The simulations were performed at a strain rate $\dot{\varepsilon} = 1.0 \times 10^{-6}\ s^{-1}$.

loading rate of $35.0\ s^{-1}$, and the stress/strain curve for $f = 0.0$ was obtained by fitting the constitutive model to Miller-Young et al.'s (2002) experimental data (Fig. 8A). The error of the stress responses due to the specimen/platen friction is plotted as a function of the compressive strain (Fig. 8B). The effect of friction on the stress response does not increase significantly with increasing friction coefficients. Even when the specimen/platen friction reaches values as large as 0.5, differences in the stress response are limited to 60% from that in an idealized condition.

4. Discussion and conclusion

In any practical unconfined compression tests, the friction between the specimen and platens cannot be eliminated, even in well-controlled test conditions. The friction is known to influence the measured force responses (Spilker et al., 1990; Miller et al., 2000). The effects of friction on the force/stress response of soft tissues in unconfined compression tests cannot be quantified experimentally, since any experimental set-up will introduce friction between the specimen and the compression platens. Therefore, the published data on the compressive behavior of soft tissues contain errors induced by friction, which have not been quantified. The proposed theoretical approach makes it possible, for the first time, to estimate the errors of the experimentally measured stress due to friction effects.

The friction coefficient between soft tissue specimens and platens in unconfined compression has not been measured. However, based on Zhang and Mak's (1999) study of friction properties of human skin on different materials, it can be reasonably assumed that the friction coefficient of the specimen/platen contact may lie between 0.1 and 0.3 in well-controlled experimental conditions. According to our analysis, the stress levels of soft tissues can be overestimated by 10–50% in such cases and, consequently, most published data on soft tissues obtained in unconfined compression may not reflect their true mechanical properties.

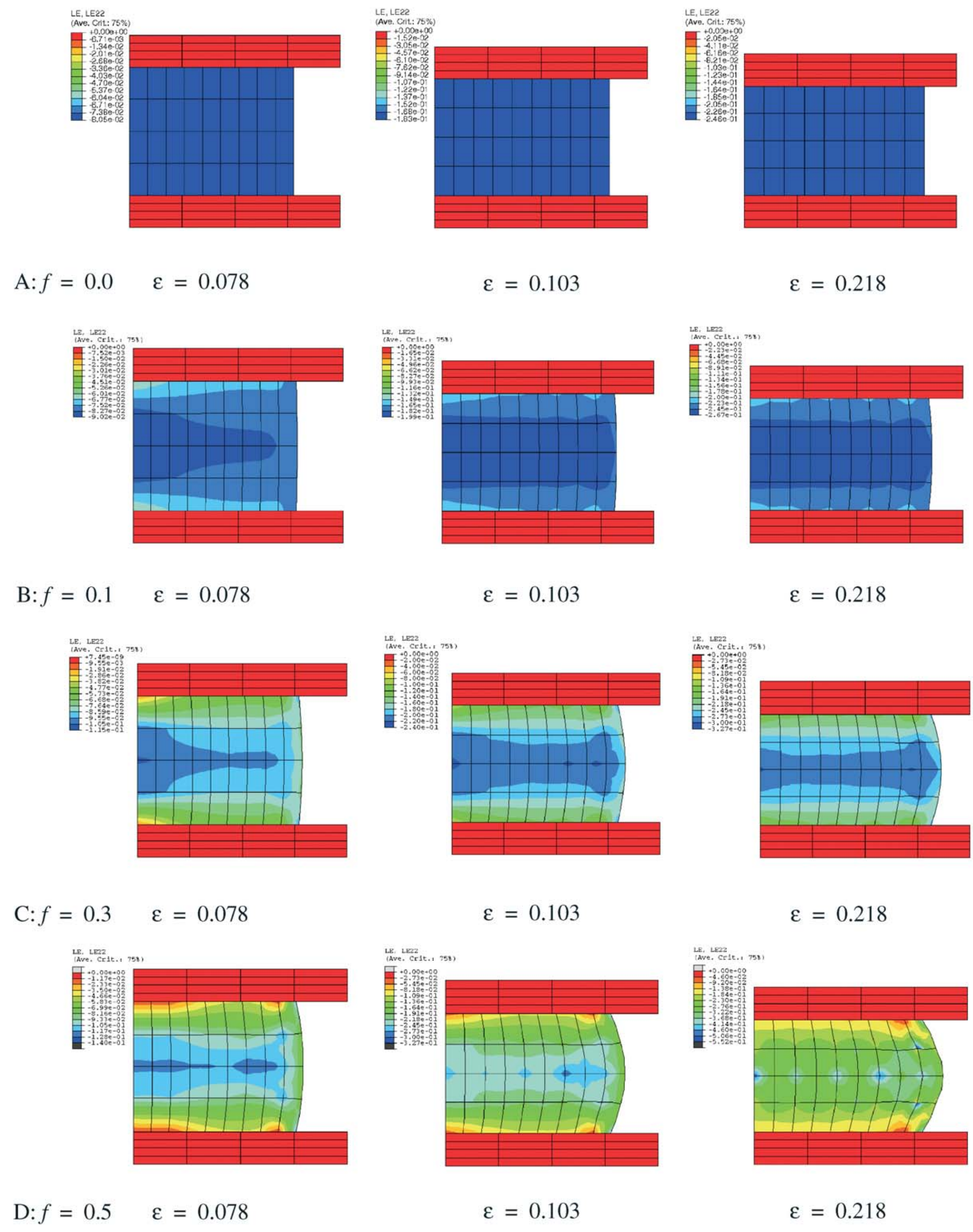

Fig. 5. Predicted deformation behaviors of the pig brain samples (Miller and Chinzei, 1997) under unconfined compressions as a function of the nominal strain (ε) and specimen/platen friction (f). ($d = 30$ mm, $h = 13$ mm, $d/h = 2.308$). (A) $f = 0.0$; (B) $f = 0.1$; (C) $f = 0.3$; (D) $f = 0.5$.

Our simulation results show that the specimen aspect ratio (d/h) greatly influences the frictional effect on the stress response of the tissue samples. Frictional effects decrease with decreasing specimen aspect ratio. However, for small specimen aspect ratios, the specimen may lose structural stability locally near the specimen/platen contact interfaces with increasing compressive loading (Fig. 6). The model predictions on the buckled specimen shape in large deformations are consistent with the experimental observations by Miller-Young

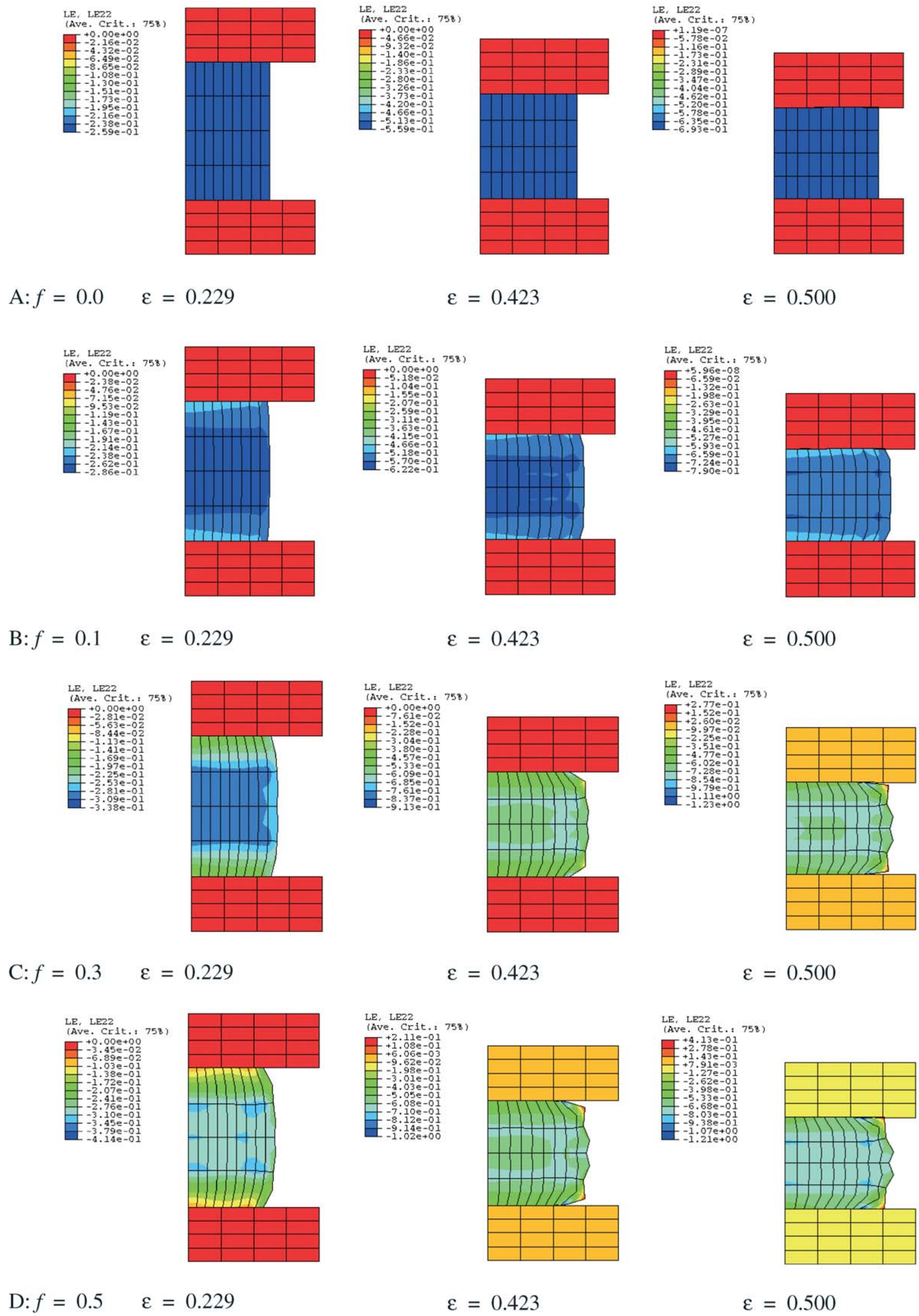

Fig. 6. Predicted deformation behaviors of the human calcaneal fat samples (Miller-Young et al., 2002) under unconfined compressions as a function of the nominal strain (ε) and specimen/platen friction (f). ($d = 8$ mm, $h = 10$ mm, $d/h = 0.80$). (A) $f = 0.0$; (B) $f = 0.1$; (C) $f = 0.3$; (D) $f = 0.5$.

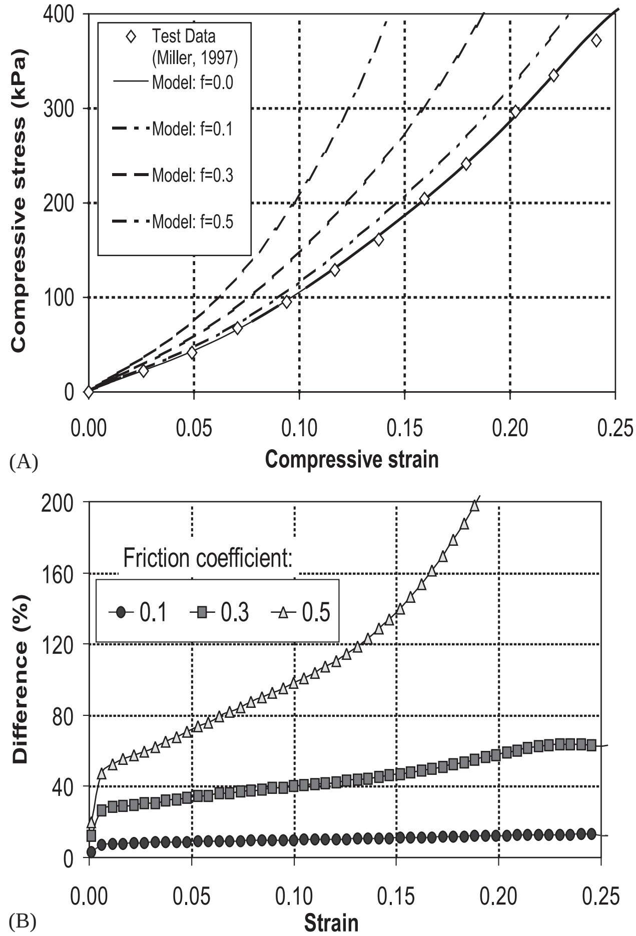

Fig. 7. Predicted stress/strain relationships of the pig brain samples (Miller and Chinzei, 1997) under unconfined compressions as a function of the specimen/platen friction. (A) Stress/strain relationships; (B) Differences of the stress responses as a function of the nominal strain and the specimen/platen friction.

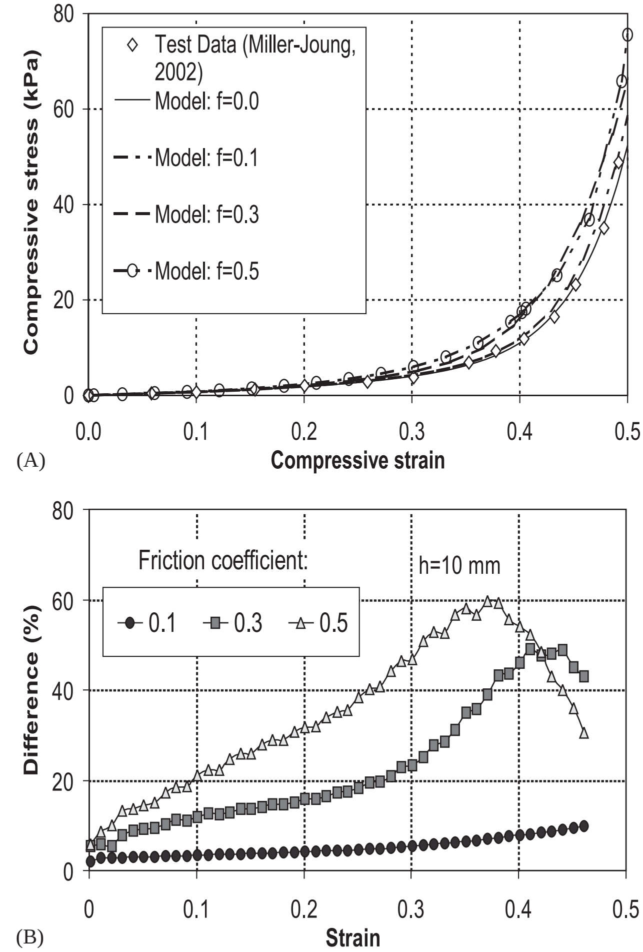

Fig. 8. Predicted stress/strain relationships of the human calcaneal fat samples (Miller-Young et al., 2002) under unconfined compressions as a function of the specimen/platen friction. (A) Stress/strain curves; (B) Differences of the stress responses as a function of the nominal strain and the specimen/platen friction.

et al. (2002). Our results indicate that, even in that case when the specimen loses its local, structural stability, the errors of the stress responses of the tissue specimen due to the friction will be limited to a range of 60% for $f < 0.5$.

In the present study, the specimen/platen friction value at the steady-state was used for the FE analysis. During actual friction coefficient measurements, friction is observed to be sliding-speed-dependent (e.g., Birznieks et al., 1998; Wang and Ateshian, 1997): it increases with increasing sliding speed and stabilizes around a steady-state value. Since in the soft tissue tests, one is more interested in the mechanical characteristics of the tissues at constant compressive loading speeds, the effects of the transient frictional effects, which may influence the mechanical behaviors of the specimens in low stress/strain at the beginning of the deformation, were neglected in our analysis.

In the present analysis, the stress/strain curves for $f = 0.0$, the reference stress response curves, are fitted to the experimental data. Since all experimental data were obtained with friction at the specimen/platen interface, the stress/strain curves with $f > 0.0$ predicted in the present study tend to overestimate the real values. However, the predicted, relative errors of the stress response, should be reasonable. A further limitation of the study is that the effects of the material anisotropy was neglected in the analysis.

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