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Technical note

# The effect of friction on indenter force and pile-up in numerical simulations of bone nanoindentation

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A B S T R A C T

Nanoindentation is a useful technique for probing the mechanical properties of bone, and finite element (FE) modeling of the indentation allows inverse determination of elastoplastic constitutive properties. However, all but one FE study to date have assumed frictionless contact between indenter and bone. The aim of this study was to explore the effect of friction in simulations of bone nanoindentation. Two-dimensional axisymmetric FE simulations were performed using a spheroconical indenter of tip radius 0.6 μm and angle 90°. The coefficient of friction between indenter and bone was varied between 0.0 (frictionless) and 0.3. Isotropic linear elasticity was used in all simulations, with bone elastic modulus $E = 13.56$ GPa and Poisson's ratio of 0.3. Plasticity was incorporated using both Drucker–Prager and von Mises yield surfaces. Friction had a modest effect on the predicted force–indentation curve for both von Mises and Drucker–Prager plasticity, reducing maximum indenter displacement by 10% and 20% respectively as friction coefficient was increased from zero to 0.3 (at a maximum indenter force of 5 mN). However, friction has a much greater effect on predicted pile-up after indentation, reducing predicted pile-up from 0.27 to 0.11 μm with a von Mises model, and from 0.09 to 0.02 μm with Drucker–Prager plasticity. We conclude that it is potentially important to include friction in nanoindentation simulations of bone if pile-up is used to compare simulation results with experiment.



## 1. Introduction

Nanoindentation is an established technique for probing the mechanical properties of materials at the nanoscale, and has also been extensively applied to investigate the mechanical properties of natural biomineralized tissues such as bone, scales, and teeth (Zioupos, 2005; He and Swain, 2007; Chevalier et al., 2007; Bruet et al., 2008; Ferguson, 2009; Kruzic et al., 2009; Mullins et al., 2009; Galli and Oyen, 2009; Brockaert et al., 2009).

While the indenter force versus depth curve provides a basic indication of local tissue stiffness, more detailed information on the elastoplastic constitutive properties of the tissue under test can be inferred using a combination of high resolution three-dimensional imaging to examine the indentation profile (including the degree of pile-up around the

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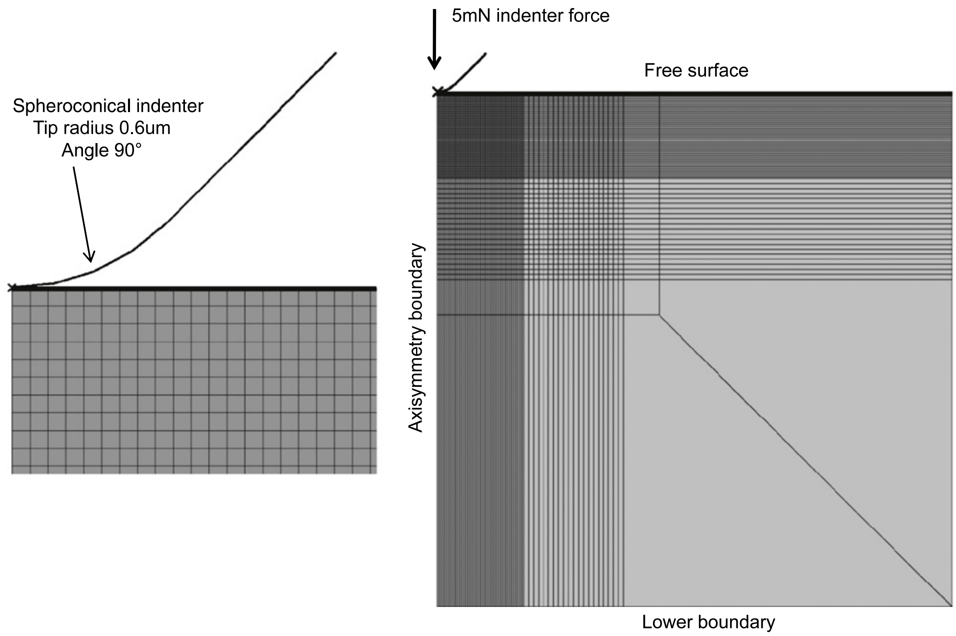


**Fig. 1 – Axisymmetric FE mesh showing boundary conditions and indenter force (right), close-up view of mesh in the vicinity of indenter tip (left).**

indenter), and Finite Element (FE) modeling of the indentation to inversely determine elastoplastic constitutive properties for the material. However, with only one recent exception (Carnelli et al., 2010), FE simulations of bone nanoindentation to date have assumed frictionless contact between indenter and bone (Tai et al., 2005, 2006; Wang et al., 2008; Mullins et al., 2009; Galli and Oyen, 2009; Brockaert et al., 2009; Paietta et al., 2010). Given that the actual indenter–bone interface will be subjected to frictional forces, the aim of this study was to investigate the importance of incorporating friction at the interface between indenter and bone in numerical simulations of bone nanoindentation.

## 2. Material and methods

### 2.1. *Geometry and FE mesh*

To explore the effect of friction in simulations of bone nanoindentation, two-dimensional axisymmetric finite element simulations were performed based on a recent study by Mullins et al. (2009) using a spheroconical indenter of tip radius 0.6 μm and angle 90°. The total FE domain was 60 μm × 60 μm (100 times the indenter tip radius). A graded mesh of reduced integration, linear 4-node axisymmetric elements (ABAQUS CAX4R) was used to discretise the domain. The FE mesh is shown in Fig. 1. A preliminary mesh sensitivity analysis was performed to ensure that the simulation results were insensitive to mesh size in the indenter tip region.

### 2.2. *Materials*

Following Mullins et al. (2009), isotropic linear elasticity was used in all simulations with elastic modulus $E = 13.56$ GPa and Poisson's ratio $\nu = 0.3$. Plasticity was incorporated using both von Mises ($\sigma_y = 0.301$ GPa, perfectly plastic) and Drucker–Prager ($\delta = 122$ MPa, $\beta = 46°$) yield surfaces.[1] The indenter was assumed rigid.

### 2.3. *Loads and boundary conditions*

The model was loaded in two steps. The indenter was firstly subjected to a ramped 5 mN compressive load, followed by unloading to zero indenter force, in order to observe the indentation left in the bone upon removal of the load. During these steps, the lower edge of the bone was constrained vertically. An axisymmetric boundary condition was used along the symmetry axis beneath the indenter tip. In order to explore the effect of interface friction, a range of friction coefficients were simulated between indenter and bone ($\mu = 0, 0.1, 0.2, 0.3$). A penalty friction algorithm was used, and a 'hard' contact formulation was used in the normal direction.

### 2.4. *Solution and post-processing*

The models were solved using ABAQUS/Explicit version 6.7-1 (Dassault Simulia Inc, RI, USA). All simulations included the ABAQUS non-linear geometry capability (*NLGEOM) for finite deformations. The dependent variables investigated were (i) the predicted indenter force–displacement profile, (ii) the predicted degree of pile-up, and (iii) the predicted normal and shear stress distribution at the interface between indenter and bone.

[1] $\sigma_y$ is the uniaxial yield stress, $\delta$ is the cohesion, and $\beta$ is the friction angle in the meridional plane.