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Erratum

Erratum: "Effect of Fluid Boundary Conditions on Joint Contact Mechanics and Applications to the Modelling of Osteoarthritic Joints," J. Biomech. Eng., 126(2), pp. 220–225

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Erratum—Fluid Flow in the VRDP Model

In our recent paper, we studied the joint contact mechanics between two symmetric, spherical, cortical bones covered with biphasic, linearly elastic cartilage layers. We analyzed the effects of the fluid boundary conditions at the contacting surfaces (permeable or impermeable) on the fluid flow patterns using a finite element model.

The fluid flow predicted by the VRDP model (variable permeability surface model) was based on the condition of "drainage-only flow" (i.e., the fluid only flows from the interior to the exterior of the cartilage layer), stated in Eq. (9) (in the following, we use the same equation and figure numbers as in our paper, for ease of cross referencing):

$$w_n = \begin{cases} k_s p & \forall p \geqslant 0 \\ 0 & \forall p < 0, \end{cases} \tag{9}$$

where $w_n = w \cdot n = \phi^f (v^f - v^s) \cdot n$ is the component of the pore fluid velocity normal to the surface (n is the outward normal to the surface), and k_s is a seepage coefficient. This condition does not take into account the interaction between the two contacting layers, and resulted in an incorrect prediction of fluid flow by the VRDP model. The VRDP model, as presented in our paper, predicted fluid flow that was orthogonal to the articular surface. For reasons of symmetry, the fluid velocities pointing outward of the two cartilage layers had opposite axial components. This result contradicted the biphasic jump condition [Eq. (11), in our paper], which enforces the vanishing of the axial components of fluid velocity at the contacting surface.

The condition in Eq. (9) is correct only in regions where no contact occurs. In the contact region, fluid flow is controlled by the difference in fluid pressure between the contacting surfaces. This result agrees with earlier findings by Ateshian and Wang [1] and Kelkar and Ateshian [2], who showed that the biphasic jump condition [Eq. (11)] must be enforced in the region of contact, while free-draining conditions should be used anywhere else at the articular surface.

By designating the two contacting layers with the superscripts (1) and (2), Eq. (9) can be rewritten as

$$w_n^{(1)} = k_s (p^{(1)} - p^{(2)}) \quad \text{contact region,}$$

$$\left.\begin{array}{ll} w_n^{(1)} = k_s p^{(1)} & \forall p^{(1)} \geqslant 0 \\ w_n^{(1)} = 0 & \forall p^{(1)} < 0 \end{array}\right\} \quad \text{free-draining region,} \tag{9,\textit{corrected}}$$

for surface 1, and analogously for surface 2. This condition was implemented in ABAQUS by use of the ABAQUS subroutine FLOW.

The load sharing between elastic stress and fluid pressure in the VRDP model was recalculated using the corrected fluid boundary conditions [Eq. (9, corrected)] and were compared to the results obtained using the SEAL model which had impermeable surfaces (Fig. 3, corrected). The predictions from the VRDP model show a stress relaxation that is physically realistic, whereas those predicted by the SEAL model are not. The stress is carried mainly by the fluid phase in the VRDP model (which is in contrast with the results presented in our original manuscript).

Furthermore, we plotted the correct fluid flow at $t = 10$ s (end of the loading ramp; Fig. 4, corrected) and at $t = 300$ s (end of the simulation; Fig. 5, corrected).

At the end of the loading ramp (Fig. 4, corrected), the fluid flow in the VRDP model is qualitatively similar to that of the SEAL model.

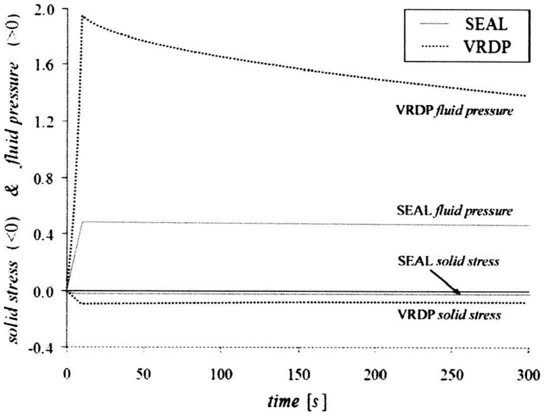

Fig. 3 corrected

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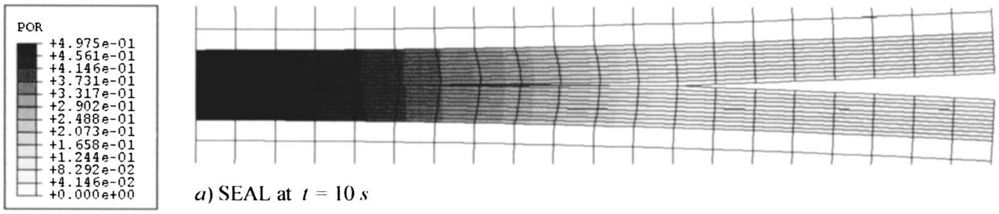
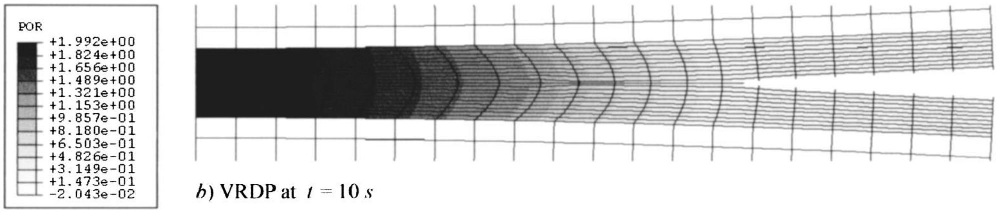
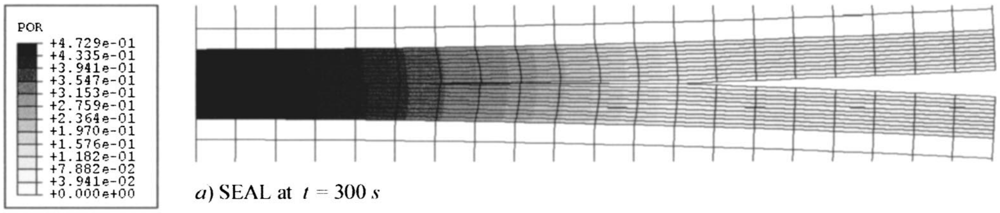


a) SEAL at $t = 10\ s$

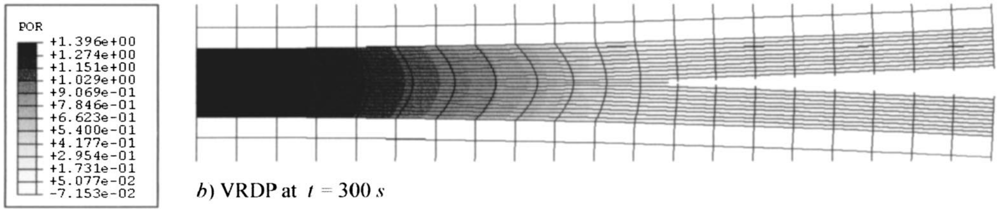


b) VRDP at $t = 10\ s$

Fig. 4 corrected



a) SEAL at $t = 300\ s$



b) VRDP at $t = 300\ s$

Fig. 5 corrected

At the end of the simulation $(t = 300\ \mathrm{s})$, the fluid flow predicted by the VRDP model is one-dimensional in the contact region [Fig. 5(*b*), corrected]. Therefore, the biphasic jump condition is preserved. Outside the contact region, the fluid flow is two-dimensional, with an outward component.

The corrected solution presented here confirms conceptually the results in our original paper. The permeable surface model (VRDP) predicts the stress relaxation behavior of the tissue properly, whereas the impermeable surface model (SEAL) does not. Moreover, the fluid flow predicted by the VRDP model is two-dimensional, and the fluid velocity at the free surface has outward components, which is consistent with the experimental observations on fluid exudation.

Earlier Studies

In the Introduction section of our original paper, third paragraph, we stated that: "There has been no published research addressing the effects of fluid boundary conditions in contact problems." However, McCutchen [3,4] studied such effects, and the corresponding references are given below.

Acknowledgment

Dr. Gerard A. Ateshian, for the technical suggestions and the references provided.

Appendix

There was a typing error in Eq. (8)

$$k = \left(\frac{e}{e_0}\right)^{\kappa} \exp\circ\left(\frac{M}{2}\left[\left(\frac{1+e}{1+e_0}\right)^2 - 1\right]\right). \tag{8}$$

It should be

$$k = k_0\left(\frac{e}{e_0}\right)^{\kappa} \exp\circ\left(\frac{M}{2}\left[\left(\frac{1+e}{1+e_0}\right)^2 - 1\right]\right), \tag{8,\textit{corrected}}$$

where k_0 is the initial permeability.

References

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