## VALIDATION AND APPLICATION OF ITERATIVE COUPLING TO POROELASTIC PROBLEMS IN BONE FLUID FLOW

G. C. Goulet[1], D. Coombe[2], R. J. Martinuzzi[1], R. F. Zernicke[1,3]
[1]Schulich School of Engineering, Dept of Mechanical and Manufacturing Engineering, University of Calgary, Calgary, Canada
[2]Computer Modelling Group, Ltd., Calgary, AB, Canada
[3]Departments of Orthopaedic Surgery and Biomedical Engineering, and School of Kinesiology, University of Michigan, Ann Arbor, MI, USA

### INTRODUCTION

The ability of exogenous mechanical loading to elicit an adaptation response has received much attention with the aim to develop non-pharmacological interventions to mitigate bone structure deterioration related to aging, osteoporosis, long-term bed rest, and spaceflight.

Although it is agreed that interstitial bone fluid serves as a coupling medium through which external mechanical signals can be transduced into a cellular response, the precise stimulatory signal, or combination thereof, remains incompletely understood.

It is inherently difficult to study *in situ* bone fluid flow; the mineralized nature of bone and the small scale of the pore spaces preclude direct measurement of intrinsic fluid characteristics. As an alternative, investigators have employed the theory of poroelasticity to gain an enhanced understanding extracellular fluid flow and its role in functional adaptation.

In this study a computational method for coupling fluid flow and mechanical deformation in porous media is presented. The numerical coupling scheme is applied to three example problems, firstly, to validate the coupling method, and secondly, to demonstrate its utility as a sophisticated tool for the study of bone fluid flow.

### METHODS

Through iterative coupling, information is exchanged between a fluid flow simulator and a mechanics module. The mechanics module obtains pressure from the fluid flow simulator and treats this information as an external load in the calculation of displacements. When displacements are computed, strains and stresses are determined through the strain-displacement and stress-strain relations, respectively. After the mechanics solution is obtained, compressibility factors for a specialized porosity function are calculated and sent to the coupling driver. Based on the updated porosity function, the pressure is computed in the fluid flow simulator and sent back to the mechanics module. The process of coupling is repeated until convergence is achieved (i.e., when the norm of pressure or stress change between two consecutive coupling iterations is below a given tolerance). The process of iterative coupling is illustrated in Fig. 1.

A poroelastic prismatic solid was modeled in STARS – a coupled finite difference fluid flow[1,2] and finite element mechanics simulator (Computer Modeling Group, Ltd., Calgary, AB) – and boundary conditions were imposed to create three example problems: firstly, a geomechanical phenomenon well-known as the Mandel-Cryer effect was recreated; secondly, the prismatic solid was modeled as a bone specimen under cyclical loading; and lastly, a dual-material example was elaborated to illustrate the potential for modeling the multiple levels of porosity in bone.

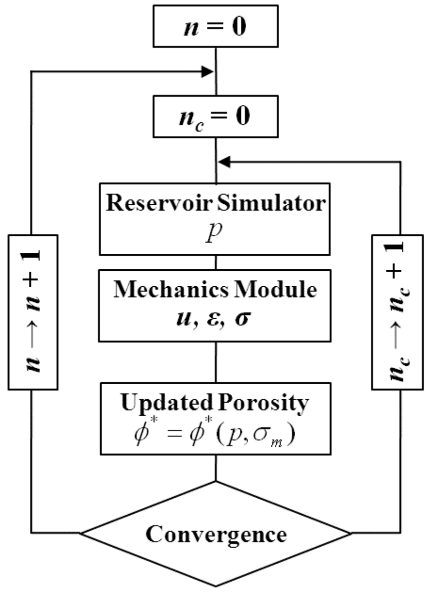


**Figure 1. Schematic of iterative coupling scheme. Number of time steps: *n*. Number of mechanical coupling iterations: $n_c$.**

### RESULTS

The iterative coupling scheme was successfully validated against the analytical solutions for the Mandel-Cryer effect (e.g., Fig. 2), and the cyclical loading example, and a dual-continuum example demonstrated the use of poroelastic models to simulate physiologically relevant bone fluid flow.

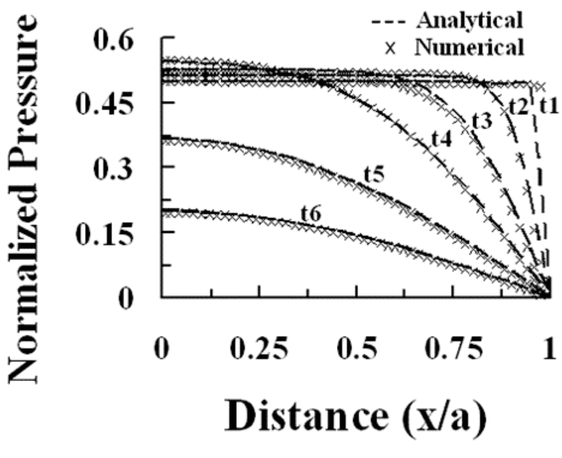


**Figure 2. Comparison of numerical and analytical solutions for fluid pressure for Mandel-Cryer problem at selected time steps.**

### CONCLUSION

Advanced theoretical studies based on the coupling scheme and models developed here will provide an enhanced understanding of the role of extracellular fluid flow in functional adaptation of bone, as well as offer insights into potential experimental techniques.

### REFERENCES

[1] Oballa et al. (1993). *Journal of Canadian Petroleum Tech.* 32: 31-42.
[2] Darche et al. (2005). *SPE Reservoir Simulation Symposium*