Scaled Surrogate Hertzian Bearing Pairs for Contact and Wear Testing

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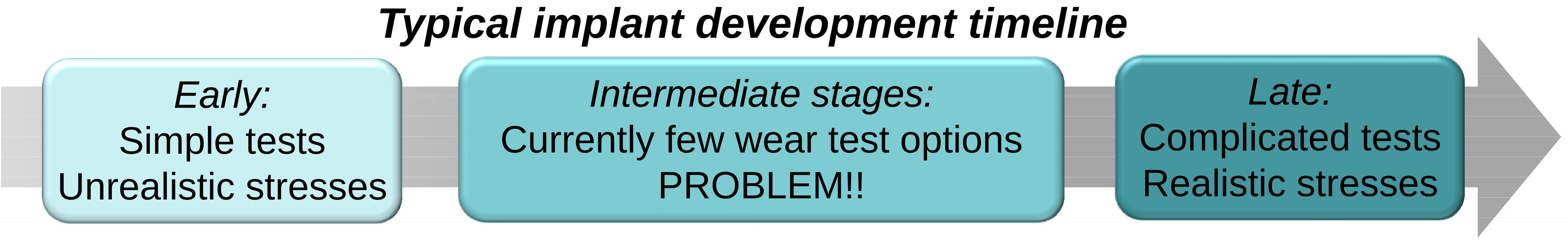
1 Introduction

Problem: Wear tests of orthopaedic implant materials and devices are typically performed either with very simple configurations, such as pin-on-disk wear tests, or in complicated configurations, such as joint simulator wear tests. The simple tests have advantages such as low-cost specimens, but they only crudely represent the contact stresses of full scale implants. The complicated tests have advantages such as better fidelity to service conditions, but they require final design components and are quite expensive. This dichotomy of testing approaches is a problem because the results of simple testing may be viewed as unsubstantial, and the results from complicated testing may not be available until very late in a product development cycle, typically just before submission of a design dossier for clearance by a regulatory authority.

Typical implant development timeline



Objective: The broad aim of this research is to span the gap between the simple and complicated wear testing approaches, particularly for knee implant bearings. We aim to develop a test method in which the contact mechanics of full-scale implants are accurately replicated using much simpler surrogate test specimens. Moreover, for practicality, the method is to be readily implemented on available test equipment heretofore used only for simple pin-on-disk wear testing. Since the load capacity of such equipment may be less than that required to replicate full-scale implant contact forces, it may be necessary to scale the testing forces downward. Accordingly, this particular research examined means to scale surrogate test specimens to yield a contact stress field that was spatially scaled yet faithful in magnitude and distribution to that of full-scale implants or their full-scale surrogate specimens.

2 Methods

Mathematical determination of surrogate test specimens

The notion behind surrogate contact and wear testing is outlined with the following problem statement:

1. Given: An original contact pair whose surfaces are subject to small displacements ... for instance, a condylar contact pair in a knee prosthesis (Fig A).
2. Find: A second contact pair (Fig B) comprised of the same materials but consisting of simpler shapes that, when pressed together under the same normal force, will generate contact stress and displacement fields that are approximately equivalent to those of the original pair.

The second contact pair should then be suitable as a surrogate for the original pair in contact and wear testing. Further, the notion of *scaled* surrogate testing is as follows:

3. Find: A third contact pair (Fig C), smaller than the second, that can be tested under a smaller force than either the original or second pairs, yet it will generate contact stresses that are equivalent in magnitude to those of the second pair.

Fig A:

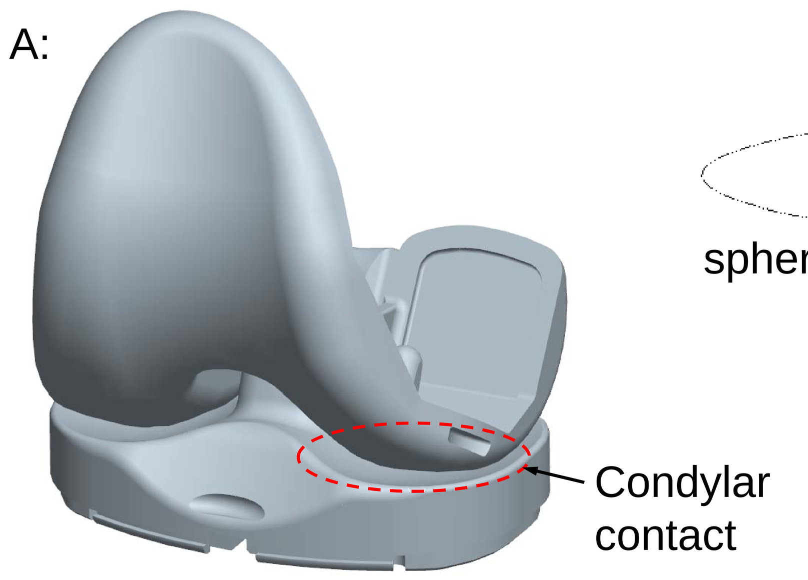


Fig B:

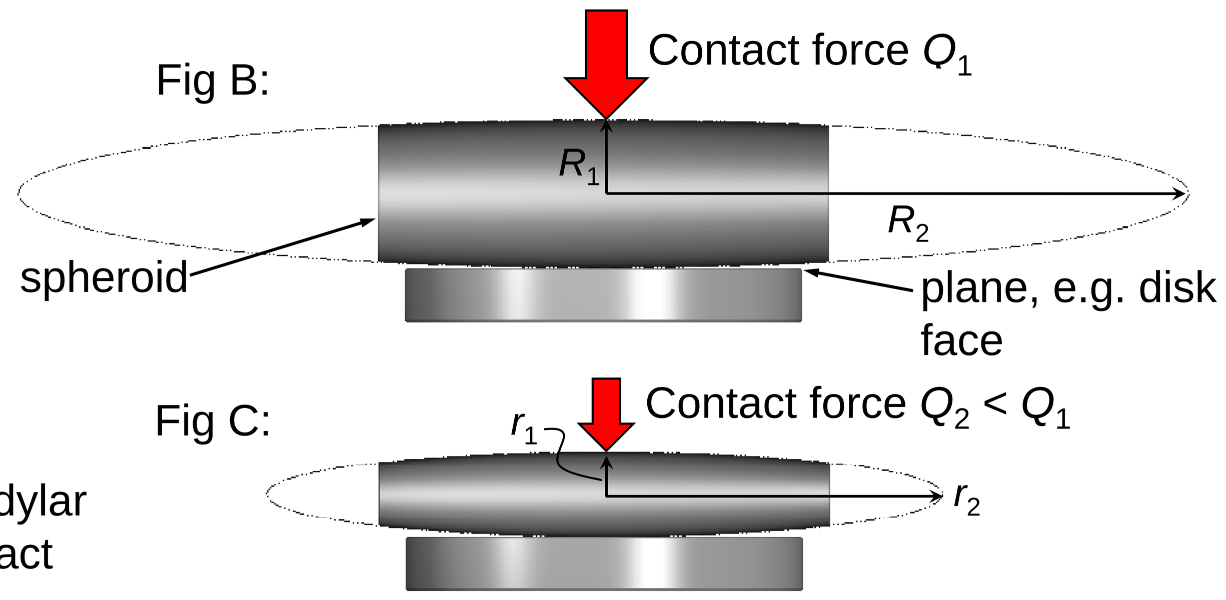


Fig C:

The means to determine the dimensions of the second pair (Full-Scale Surrogates, *FSS*) have been detailed [1]. The pair consists of a spheroid and a planar surface, and the dimensions of the spheroid (R_1 and R_2) are computed using Eqns. 1-4. In the third pair (Scaled Surrogates, *SS*), the dimensions of the spheroid are computed using Eqns. 5-6 (determined in this research).

(1) $\Sigma = \eta_1 + \eta_2 + \varepsilon_1 + \varepsilon_2$

(2) $\Delta = \left[(\eta_1 - \eta_2)^2 + (\varepsilon_1 - \varepsilon_2)^2 + 2(\eta_1 - \eta_2)(\varepsilon_1 - \varepsilon_2)\cos(2\alpha) \right]^{1/2}$

(3) $\kappa_1 = \frac{1}{2}(\Sigma - \Delta),\ \kappa_2 = \frac{1}{2}(\Sigma + \Delta)$ (4) $R_1 = 1/\kappa_2,\ R_2 = \sqrt{1/\kappa_1\kappa_2}$

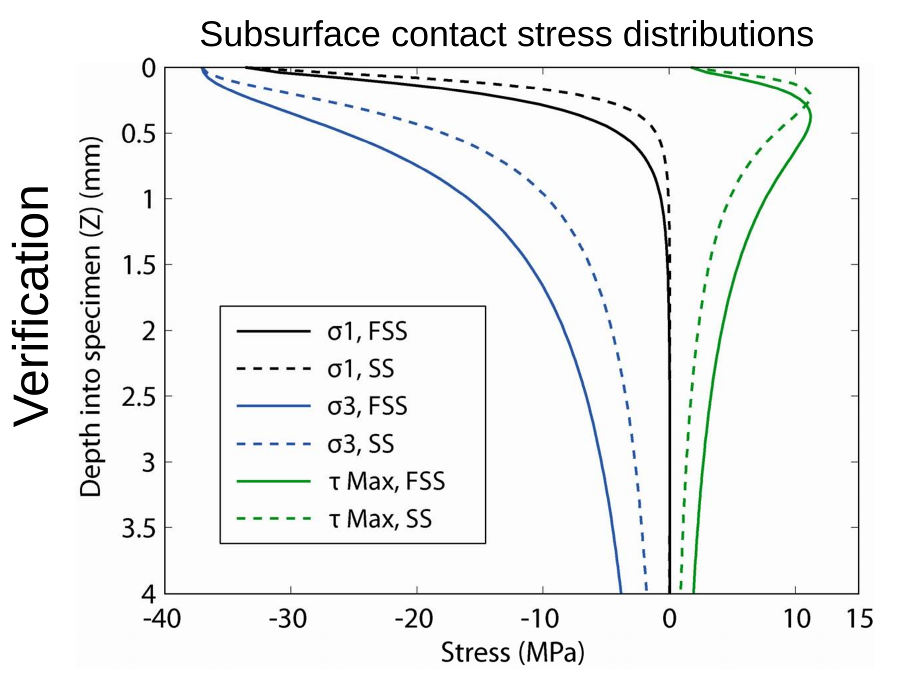
(5) $\rho_1 = \kappa_1\sqrt{Q_1/Q_2},\ \rho_2 = \kappa_2\sqrt{Q_1/Q_2}$ (6) $r_1 = 1/\rho_2,\ r_2 = \sqrt{1/\rho_1\rho_2}$

η_1, η_2	Principal curvatures of femur at contact point
$\varepsilon_1, \varepsilon_2$	Principal curvatures of tibia at contact point
κ_1, κ_2	Principal curvatures of FSS spheroid
R_1, R_2	Dimensions of FSS spheroid
ρ_1, ρ_2	Principal curvatures of SS spheroid
r_1, r_2	Dimensions of SS spheroid
Q_1, Q_2	Normal contact force of FSS, SS

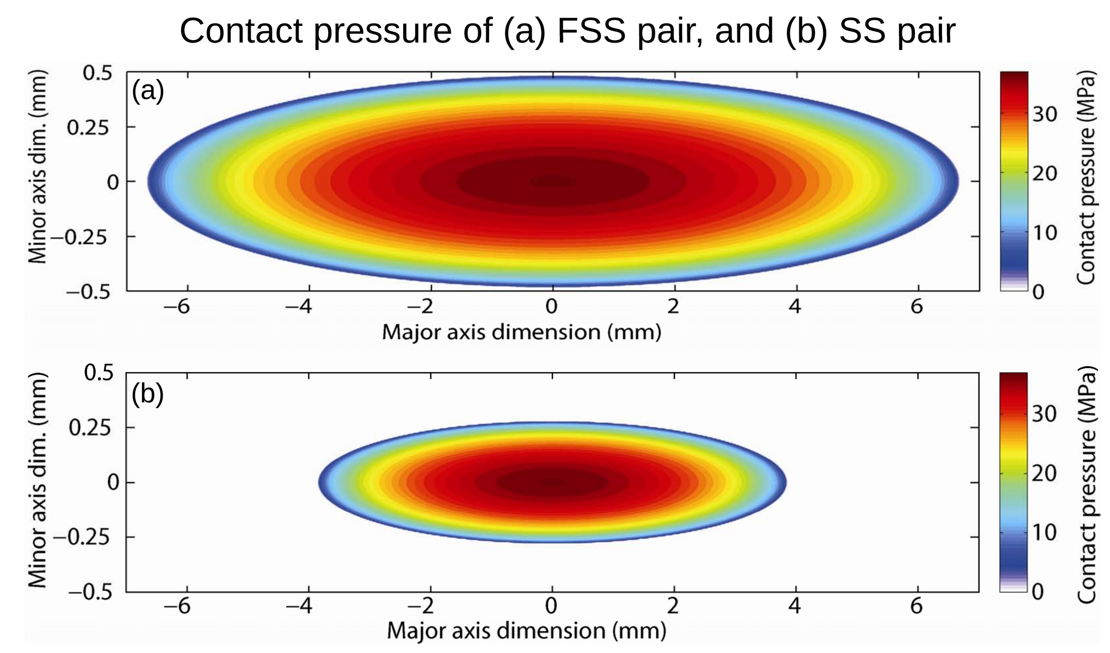
Verification and **Validation** were performed to test the relationship of the FSS pair to the SS pair. Verification consisted of a Hertzian contact analysis to predict the contact areas, pressures, and subsurface stresses in each pair. The spheroids were represented as steel with Young's modulus E=200 GPa and Poisson's ratio v=0.3, and the planar members as UHMWPE with E=1 GPa and v=0.45 (both materials assumed as linear elastic). The normal forces were Q_1= 250 N and Q_2= 83 N such that Q_1/Q_2 =3. The principal curvatures at the contact point of all analyzed members were as follows (all in mm^{-1}): (η_1, η_2)=(0.0345, 0.1335); (ε_1, ε_2)=(-0.0111, -0.0325); (κ_1, κ_2)=(0.0020, 0.1223); (ρ_1, ρ_2)= (0.0034, 0.2119). In the planar member of the surrogate pairs, both principal curvatures were zero. Validation consisted of contact tests between specimens of the same materials and dimensions wherein the contact patch was recorded using a "fingerprinting" technique [2] and measured with a measuring microscope. Tests were performed with (1) rapid loading to negate UHWMPE's viscoelastic properties, and (2) static loading for 500 s to include viscoelastic creep.

3 Results

Verification

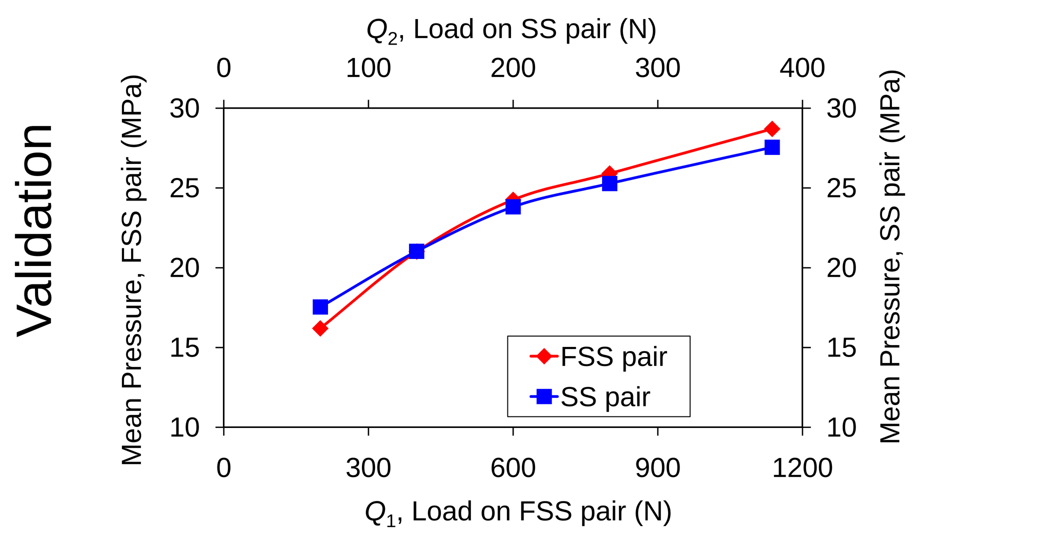


The stresses of the SS pair are spatially scaled with respect to those of the FSS pair. For example, at depth Z=1 mm, for each stress measure in the FSS pair, the equivalent value of stress in the SS pair occurs at depth Z=0.58 mm.

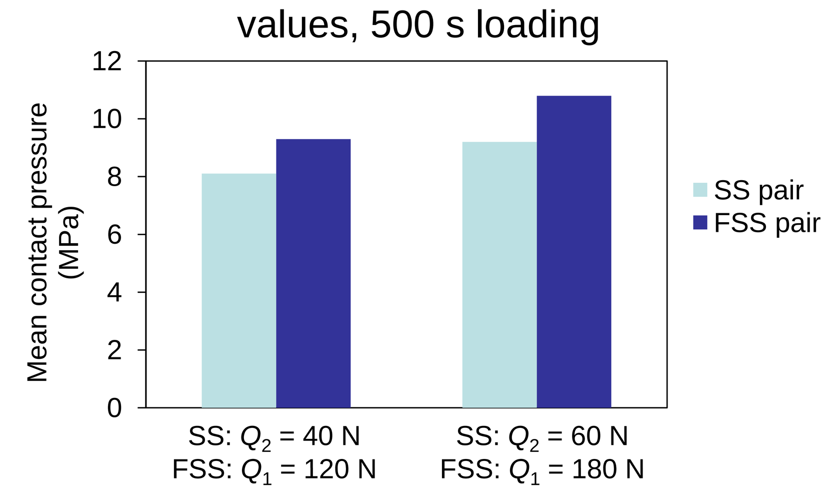


The contact pressure distribution of the SS pair mimics that of the FSS pair, with equivalent stresses that are distributed over a smaller area.

Validation



At comparable loads according to Q_1/Q_2 = 3, the FSS and SS pairs yield closely comparable contact pressures.



When the loads are held statically for 500 s, the SS pair experiences relatively more creep; hence, it has lower contact pressure.

Conclusions

- Hertzian analysis showed that compared to the FSS pair, the SS pair exhibits contact stresses of equal magnitude, though distributed over a smaller region.
- Laboratory tests showed that the SS pair provides nearly equivalent (1-10% difference) contact pressure to the FSS pair under rapid loading. Under long duration static loading, there was a more substantial difference (12-16%).
- Further research is needed to examine the ability of the SS pair to provide equivalent yet spatially scaled contact stresses in an articulating bearing pair.

Significance: This research will increase the utility of screening wear tests for prototype materials by showing means to implement realistic contact stresses using simple specimens. The knowledge will accelerate improvements in implant durability.

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References: [1] Sanders and Brannon, *Journal of Tribology*, 133(2), p. 024502-6, 2011. [2] Sanders and Brannon *Journal of Biomechanics,* 44(16), p. 2802-8, 2011.