TRANSFERRING LOAD TO FLESH
PART IV. FLESH REACTION TO CONTACT CURVATURE[a]

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ABSTRACT

Flesh may be loaded through a member of small radius, such as a pebble underfoot. A similar type of loading is frequently observed in prosthetic work; for example, the above-knee socket brim is arranged to impinge directly on flesh and bear appreciable load.

The reactions within the flesh to this form of loading are given. Specifically, reaction pressure and circumferential shear loads are developed in the case of a rigid hemisphere pressed into flesh. It is shown that the reactions differ considerably from a hydrostatic model, especially when the flesh thickness is large.

INTRODUCTION

We are concerned with the stresses within flesh caused by mechanical loading. Our goal is the reduction of soft tissue trauma resulting from the wearing of prosthetic and orthotic devices. Our procedure is to analyze loading situations with the aid of modern theoretical solid mechanical tools, searching for optimum methods of assuming load.

Previous articles in this series (1, 2, 3) have presented the concepts explored in a qualitative fashion (1), the compressive stress in flesh under varied loading situations (2), and the shear stress developed as a function of loading conditions (3).

This work is concerned with the effect of a rounded rigid block pressing against flesh. As in prior articles, the work closely follows the assumptions and techniques of certain Russian applied mathematicians and civil engineers as given by Vlasov and Leontev (4). Thus, flesh is taken to be elastic, isotropic, and homogeneous; it is assumed to possess a fixed modulus of elasticity and Poisson's ratio. All visco-elastic and nonlinear properties of flesh are ignored with the single exception

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of limited plastic flow at discrete locations (sharp corners). Although we are specifically treating rounded corners in this work, the last proviso remains significant; small radii undoubtedly incur local plastic flow.

The case solved is that of a rigid hemisphere whose radius is a parameter, impinging on flesh whose thickness, Poisson's ratio, and other characteristics are all parameters. The flesh is assumed backed with a rigid bone that ultimately absorbs all load. See Figure 1 for a schematic drawing of the model employed. Note that the model is symmetrical about a vertical axis, i.e., truly a portion of a hemisphere; this is in contrast to prior articles which dealt entirely with two-dimensional slices of cylindrical shapes, wherein the shape was preserved along the Z axis. The axi-symmetrical model is less realistic than the two-dimensional model with respect to prosthetic application, and therefore is less desirable. It is introduced because of certain mathematical simplifications made possible by the assumed symmetry. Note that the radius of contact R_o (from a vertical axis of symmetry of the plug) is a completely different quantity from the hemisphere radius R. The total applied load P_o may consist of distributed or concentrated loads; as the button is taken to be rigid, the manner of load application to

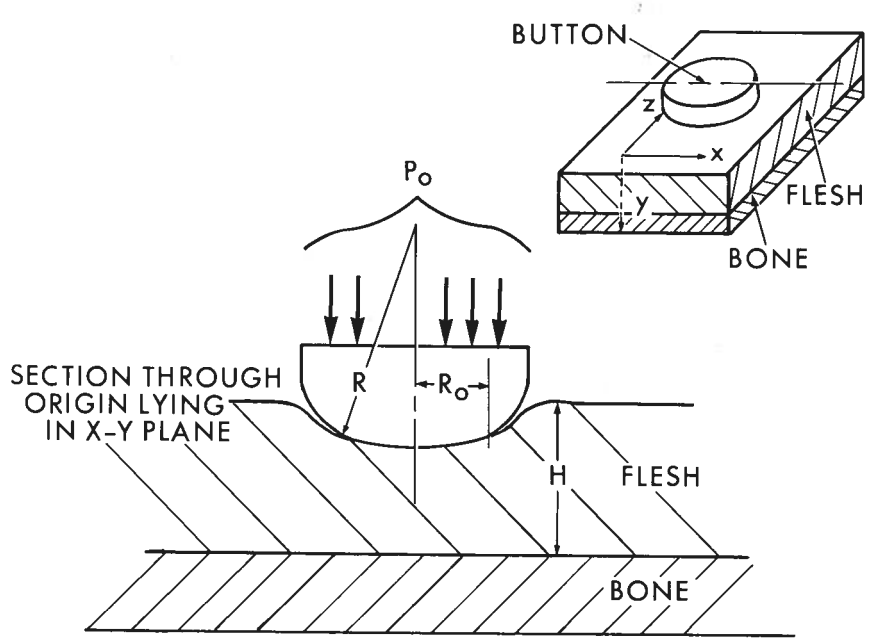

FIGURE 1.—Sketch of the model loading situation employed in this work. A rigid "button" of Radius, R, and contact radius, R_o, impinges on flesh of initial thickness, H, backed by rigid bone. The total applied load or force is P_o.

the button (discrete or uniform) is unimportant. However, the work does assume a zero applied bending moment; this in turn requires the loading pattern to be symmetrical. In addition, torsional and frictional loads are assumed negligible.

The equations employed in the solution and all nomenclature are given in the Appendix. Three terms important in understanding the results are introduced here (see Fig. 2).

The applied pressure, p, is equal to the applied load, P_o, over the projected contact area, πR_o^2. Thus p is precisely equal to a Brinell number, with the exception of differing units (Brinell is metric; ours is English). To us, the value of p is partly one of a simple index to the severity of loading and partly one of sidestepping the issue of deflection. In reality, the contact area will be influenced by flesh thickness and stiffness; that is, the contact area is a function of the deflection characteristics of flesh. However, so long as we confine our attention to given values of p without concern over how these values arise, we circumvent the issue of deflection and simplify the presentation.

The basic reaction pressure, q, is that uniform pressure experienced under the button. A second form of reaction is a running vertical shear load, Q, appearing roughly at the perimeter, R_o, or outboard of R_o. Additional comments on the location of Q appear under Results. A running shear load is a form of continuous shear load applied to a load line, in this case a circle. The effect of the running shear load, Q, is to attempt to punch through the flesh near R_o.

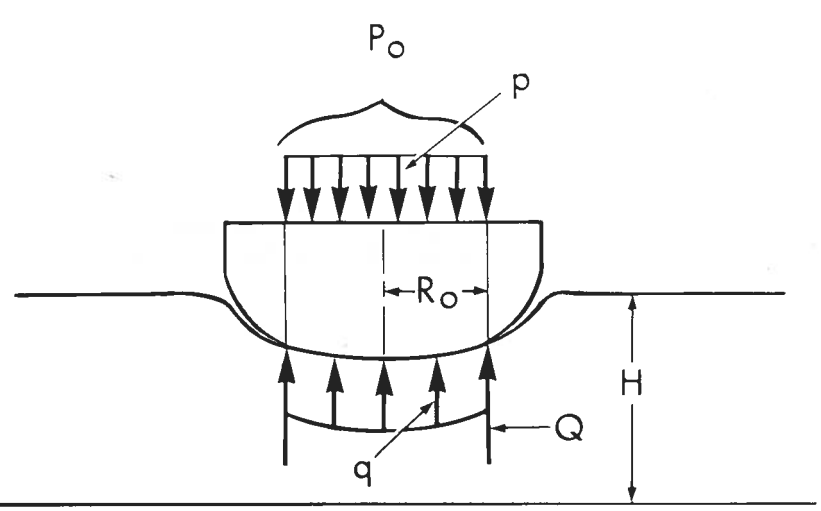

FIGURE 2.—Sketch of loading parameters. The effective applied pressure p is countered by a uniform flesh pressure q and a running vertical shear Q.

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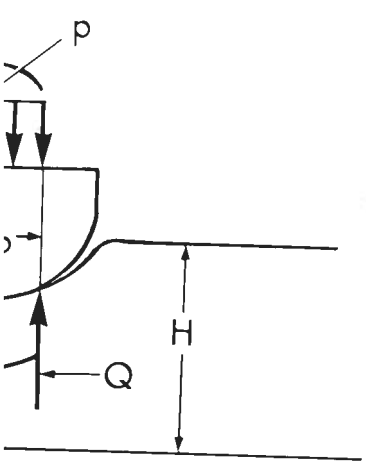

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METHOD OF PROCEDURE

The method of procedure is taken verbatim from Vlasov and Leontev (4) Chapter V; the reader is referred to this source for details of derivation. In briefest outline, the displacement procedure is utilized, and a homogeneous differential equation describing strain as a function of loading and material characteristics is evolved. Key assumptions are that the loading member is rigid and symmetrical, and that the loaded material (in that case, flesh) is everywhere continuous (failure has not occurred). The solution takes the form of a modified Bessel function. A practical numerical solution incorporating flesh values was performed with standard Bessel function and hyperbolic function tables, to slide rule accuracy.

RESULTS

The results (see Fig. 3) are presented in the form of pressure and shear response for a given load as a function of radius of contact. The ordinate represents both the applied pressure, p, and the basic reaction pressure, q, for a unit load as well as the running shear load per unit load. The units of the pressure terms are p.s.i. per pound of load; that of the running shear is lb./in. of circumference per pound of load. An additional parameter considered is the effect of flesh thickness on the loading relationship; varied values of flesh thickness including 0.1, 0.5, and 1.0 in. are analysed. Note that the applied pressure, p, is independent of flesh thickness, H. To achieve this condition in reality, it would be necessary to vary applied load, P_o, with H. However, as noted previously, so long as we confine our attention to p and draw no conclusions about the factors entering into p, such a process is legitimate.

The reaction pressure, q, is everywhere smaller than the applied pressure, p. As flesh thickness decreases, reaction pressure approaches the applied pressure. All pressures decrease with increasing radius. However, the asymptotic form of the pressure-radius relationship suggests diminishing returns as radii are increased in value above, e.g., 1 in. In other words, increasing the radius of contact with flesh so as to lower the pressure experienced is generally a sound concept until the radius becomes so large (at about 1 in.) that further gains by extending this process are minimal.

A continuous decrease in radius produces an ever greater reaction pressure. Small contact areas—even a large number of small contact areas—are an unsatisfactory way of transmitting load.

The running shear load may be viewed as the load created by stressing flesh beyond the button. The running shear load is equal to the summed shear stresses outside the button; there is no significant

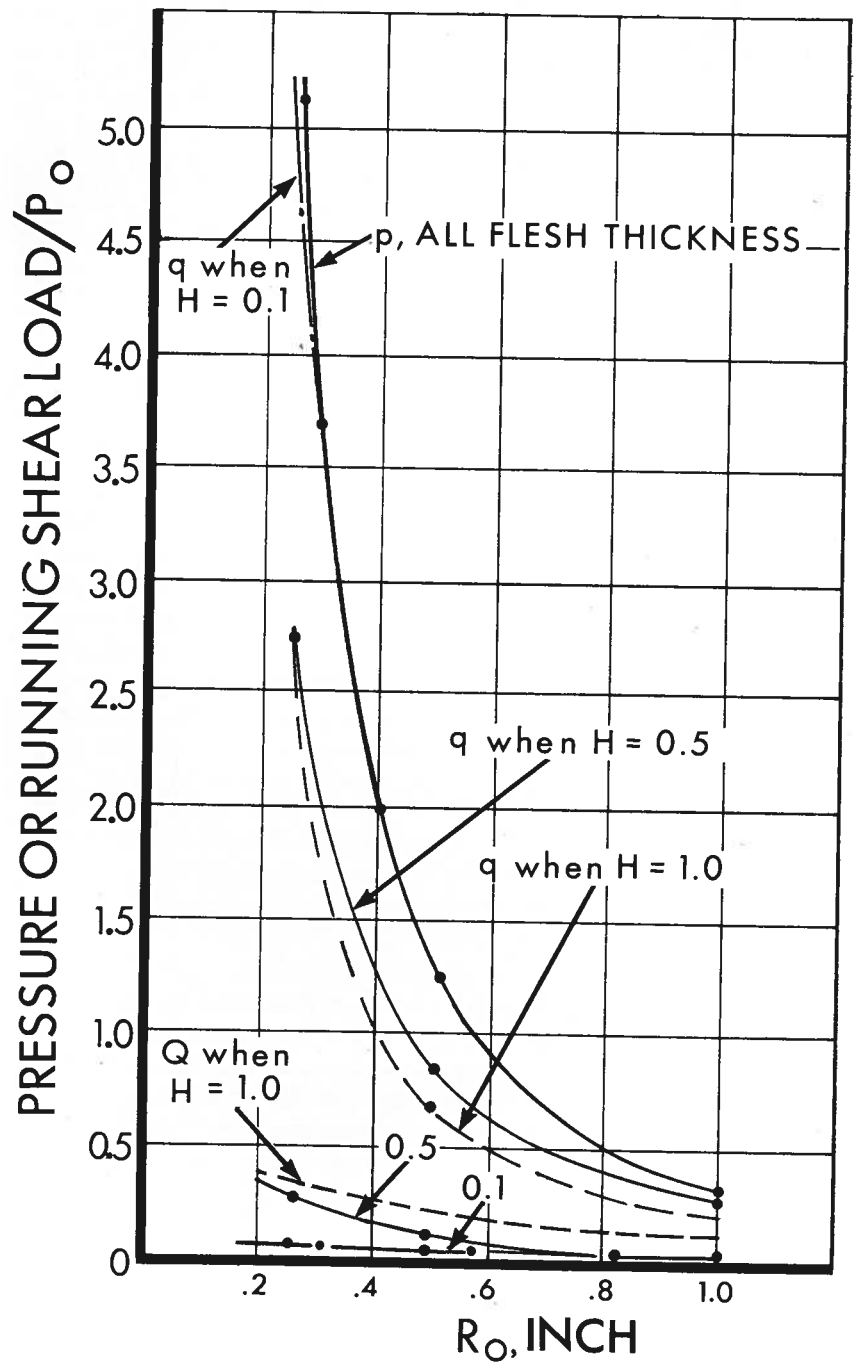
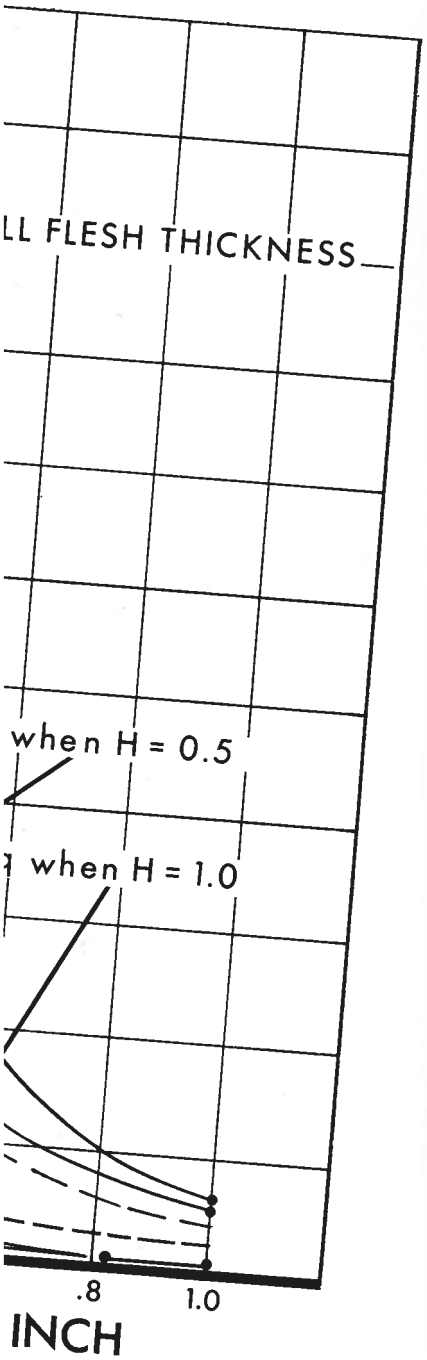


FIGURE 3.—Computed applied and reaction pressures and running shear loads as a function of contact radius and flesh thickness.



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shear stress under the button by the arguments previously presented in Reference 3, page 40. To help picture this form of load, it might be viewed as the punching load or tendency for the button to cut through the flesh around the button perimeter. Viewed rigorously, this load does not exist at a clear-cut point in space, but in an annular zone adjacent to the button edge. The uncertainty in location follows partly from mathematical difficulties associated with the button boundary and partly from practical uncertainties, such as the extent of plastic flow, if any, likely to occur at the boundary. While the location is thus unsure, the magnitude follows directly from simple equilibrium relationships, which are well-proven. It may be said, in summary, that a running shear load exists for all button-type loadings and that its scalar value is readily determined. To a high degree of probability, it will peak sharply at a point between the contact radius and at a distance of 1 centimeter outwards from the contact radius. Under no circumstances will the peak value of shear occur near the center of the loaded flesh area. As the running shear will ultimately be absorbed in a gradient fashion, some shear stress will be experienced in the directly loaded area. Such stresses will be small.

Values of the running shear load, Q, are given in Figure 3. Such values are normalized for both contact perimeter and applied load. Multiplying by perimeter and applied load will convert any ordinate value Q to pounds force.

Q values decrease as the contact radius increases. Q increases with flesh thickness. However, both these effects are subject to diminishing returns; at flesh values greater than 0.5 in. thickness, effects of further increases in thickness are small. In practice flesh thicknesses greater than 0.5 in. thick are found relatively rarely in heavily loaded "flare" areas, given soft untensed flesh.

DISCUSSION

Many of the results appear to confirm intuition and require no comment. For example, the larger the contact radius for a given load, the smaller the reaction pressure. Similarly, for a given load the deeper the button sinks, the lower the reaction pressure. Certain of the results, however, are not self-evident; we shall consider these.

Reaction pressure is insensitive to button radius and quite sensitive to contact radius. Referring to Figure 1, R may be unimportant; R_o is critical. This means that even though a designer may supply a generous radius to a rigid member impinging on a bony prominence—where R_o is clearly small—the generous radius accomplishes nothing. Also, when the flesh is very thin or very stiff (high muscle content), a generous radius is of limited value in reducing flesh stress.

The existence of the running shear load, under all conditions of flesh

thickness, attests to the departure of the loading situation from that of a hydrostatic model. If the reactions were truly hydrostatic in nature, p would equal q and Q would equal zero. Such is not the case. Indeed the difference between p and q *increases* as the flesh thickness increases; this behavior is opposite to one's expectations of a hydrostatic model. The essential difference between the model employed in this work (which hopefully is a superior depiction of the characteristics of flesh) and a hydrostatic model is that we permit the spread of load through cohesion. This allows shear reactions to appear outside the region of load application: a useful improvement in view of the known existence of certain dermatological problems proximal to the brim of a prosthetic socket. The spread of shear through cohesion also lowers peak values of local pressure as compared to a "nonspreading" model.

To the appliance designer, the following "rule of thumb" is offered. When a button presses on flesh, the reaction pressure is about half of the applied pressure. The net difference appears as a shear around the edge, opposing a tendency of the button to punch through the flesh. A good radius to specify on any object pressing into flesh is about ½ in. A larger radius is better, subject to diminishing returns.

One suspects, without proof, that the shearing tendency may be the more significant clinically of the two reactions. The ratio of shearing stress to compressive pressure grows larger as the flesh thickness increases and as the button radius increases. Finally the horizontal shear (parallel to the undisturbed flesh surface and roughly equal to the Q-induced stress) may also be important clinically.

ACKNOWLEDGMENTS

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APPENDIX

This Appendix contains the nomenclature and equations used in generating the preceding results. Both nomenclature and equations are largely drawn from Reference 4, Chapter V; the reader is referred there for derivation of procedure and details.

$$q=\frac{P_o}{\pi R_o^2\left[1+\frac{2K_1(\alpha R_o)}{K_o(\alpha R_o)\alpha R_o}\right]}$$

where $\alpha=\frac{\psi\alpha}{H}\sqrt{\frac{6}{1-\nu_o}}$

and $\psi\alpha=\frac{\gamma H}{R_o}\sqrt{\frac{\frac{1}{3}\,\mathrm{sh}\frac{\gamma H}{R_o}\,\mathrm{ch}\frac{\gamma H}{R_o}+\frac{\gamma H}{R_o}}{\mathrm{sh}\frac{\gamma H}{R_o}\,\mathrm{ch}\frac{\gamma H}{R_o}-\frac{\gamma H}{R_o}}}$

$$Q=(p-q)\frac{R_o}{2}$$

where $p=\frac{P_o}{\pi R_o^2}$

P_o = Sum of applied load
R_o = Contact radius
$\psi\alpha,\alpha$ = Parameter, given above
H = Flesh thickness
ν_o = Poisson's Ratio parameter $=\frac{\nu_s}{1-\nu_s}$
ν_s = Poisson's Ratio flesh, taken as 1/3
γ = Vertical attenuation coefficient, taken as 1
$K_1(\alpha R_o)$, $K_o(\alpha R_o)$ = Modified Bessel functions of the second kind
q = Reaction pressure
Q = Running shear load in the plane of the load along a circle of radius greater than R_o
p = Loading pressure