Deformations Experienced in the Human Skin, Adipose Tissue, and Fascia in Osteopathic Manipulative Medicine

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Context: Osteopathic manipulative medicine techniques involve compressive and tangential forces to target the fascia. These forces are transmitted to the skin and adipose tissue before the fascia is encountered. Knowing the extent of deformation of these 2 tissue layers relative to the fascia will assist osteopathic physicians in evaluating techniques for manual therapies and adjusting these therapies to reduce patient discomfort and improve results.

Objective: To determine the magnitude of the forces transmitted to the skin, adipose tissue, and fascia, and to determine the magnitude of deformation produced in the skin and adipose tissue relative to the fascia using a mathematical model.

Methods: The large deformation theory of elasticity, valid for 3-dimensional deformations, was used to evaluate the forces that need to be applied such that a specified deformation is produced in any region of the skin, adipose tissue, or fascia layers. Similarly, if the forces are specified, then the deformation produced can be determined.

Results: The normal and tangential forces required to produce a deformation of 9% compression and 4% shear for the skin were 50 N and 11 N, respectively. Normal and tangential forces of about 100 N and 22 N were found for a similar deformation of fascia. For adipose tissue, these forces were 36 N and 8 N, respectively. In addition, the skin experienced more compression and shear—about 1.5 times as much as the fascia, and the adipose tissue experienced about 2.5 to 3.5 times the deformation of the fascia and 50% more than the skin when a given force was applied to the skin.

Conclusion: The forces applied to the surface of the skin were transmitted through this layer and the adipose layer entirely to the fascia. Therefore, the skin and adipose tissue experienced the same magnitude of force as the fascia. However, the skin and adipose tissue experienced more compression and shear than the fascia.

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In osteopathic manipulative medicine (OMM), several forms of manual fascial therapies are practiced, such as friction, trigger-point therapy, neuromuscular therapy, fascial manipulation, and soft-tissue manipulation using the hands or a mechanical device.[1,2] Although the deep fascia layer is the target of therapy, each compression on the body is delivered through the more superficial layers, the skin and adipose tissue. Tunay et al[3] observed that information on how these techniques affect the adipose layer seems to be lacking. In this article, we examine the effect of OMM techniques on the deformation of all 3 layers: the skin, adipose tissue, and fascia.

Osteopathic researchers have reported local tissue release after the application of manual therapy.[2,4,5] In general, all manual therapy techniques involve compressive and tangential forces applied to the skin at a particular site of the body. Cherkin et al[6] noted that minor pain or discomfort was experienced by 13% of participants during or shortly after receiving massage. In more vigorous forms of manual therapies, intermittent discomfort may be reported in almost 100% of patients.[7]

Determining the exact amount of compression to apply to the skin in order to reach the deep fascia may allow fine tuning of these therapies to reduce discomfort. Another measure to consider is the magnitude of the forces received by the skin and adipose tissue before they reach the fascia. At present, osteopathic physicians do not have methods to compute these measures, and they must instead rely on their intuitive clinical judgment. Scientific evidence is needed to evaluate the magnitude of the forces on each of these tissues during manual therapies.

In biomechanics, deformations of less than 5% are considered small and therefore are subject to approximate analysis. Larger deformations must be analyzed by more complex equations, collectively termed *large deformation theory*. Human tissues are subjected to large deformations under the impact of manual therapy forces. Therefore, a large deformation theory needs to be applied to determine the magnitude of these forces absorbed by the skin, adipose tissue, and fascia. To meet this need, we developed a 3-dimensional mathematical model for deformation of human fascia in manual therapy,[8] in which only fascia was considered. The current article presents our revision of that model to include the skin and adipose tissue. To do this, we needed to know the stress-strain relationships for skin, adipose tissue, and fascia.[9-11]

Because the weight of the skin and that of the adipose tissue are negligibly small compared with the forces applied to them, the skin, adipose tissue, and fascia all experience the same magnitude of forces applied regardless of the thickness of the individual layers. The deformations of each layer depend on their stiffness.

Methods

Development of Mathematical Model

Because the skin, adipose tissue, and fascia are known to experience large strains when subjected to longitudinal forces,[11] a large deformation theory[12] was used to determine the magnitude of the mechanical forces applied to the surface of the skin that results in a specified deformation. We followed the development of the large deformation theory equations from our previous study[8] and used a 3-dimensional element comprising the skin, adipose tissue, and fascia (*Figure 1*). We assumed that these tissues are composed of incompressible material[11] (ie, the volume before and after deformation remains the same). We also included the basic kinematics and kinetics equations of Green and Zerna[12] for evaluating the stresses under specified deformations for any such tissue.

The stresses are required to satisfy differential equations of equilibrium and boundary conditions to determine the magnitude of the mechanical forces needed to produce the specified deformations.

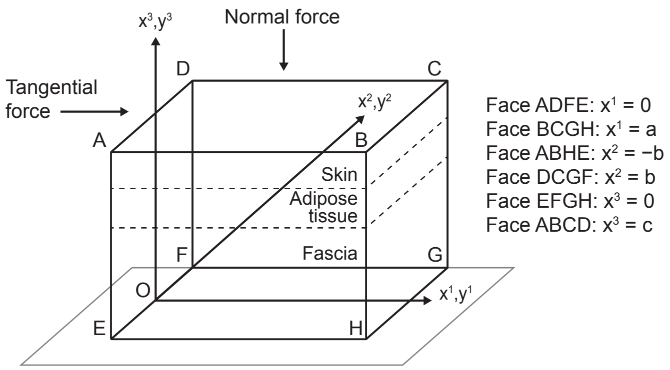

Figure 1.
Three-dimensional model of skin, adipose, and fascial layers subjected to normal and tangential forces in the undeformed state. The axes (x^1, x^2, x^3) in the undeformed state coincide with the axes (y^1, y^2, y^3) in the deformed state. The symbols represent the coordinate values of the faces along the x^1, x^2, and x^3 axes.

The metric tensors g_{ij}, g^{ij} (needed to evaluate stresses) in the Cartesian coordinates x^i in the undeformed state are determined by:

$$(1)\quad g_{ij} = \frac{\partial x^r}{\partial x^i}\frac{\partial x^r}{\partial x^j},\quad g^{ij} = \frac{\partial x^i}{\partial x^r}\frac{\partial x^j}{\partial x^r},\ (r = 1,2,3;\quad i,j = 1,2,3)$$

The repeated index means summation over r. Similarly, the metric tensors G_{ij}, G^{ij} in the deformed Cartesian coordinates y^r ($r = 1,2,3$) are determined by

$$(2)\quad G_{ij} = \frac{\partial y^r}{\partial x^i}\frac{\partial y^r}{\partial x^j},\quad G^{ij} = \frac{\partial y^i}{\partial x^r}\frac{\partial y^j}{\partial x^r},\ (r = 1,2,3;\quad i,j = 1,2,3)$$

From equation (1) we find that

$$(3)\quad g_{ij} = g^{ij} = \delta_{ij}(\text{kronecker } delta),\quad g = |g_{ij}|$$

Where $|g_{ij}|$ is the determinant of the matrix g_{ij}. Thus, $g = 1$. The metric tensors defined above are the measures of deformations in 3 dimensions. Their physical meaning can be understood by their relationship to the strains E^{ij} through the equation:

$$(4)\quad E^{ij} = \frac{G^{ij} - g^{ij}}{2}$$

Deformation

We assumed that the deformation produced by the manual therapy techniques of shear along the x^1 axis, and compression along the negative x^3 axis (*Figure 1*), would be determined by the following equation:

$$(5)\quad y^1 = x^1 + k_1 x^3,\quad y^2 = k_2 x^2,\quad y^3 = k_3 x^3,\quad (k_3 < 1, k_1, k_2 > 0)$$

where the y^i axes in the deformed state coincide with the x^i axes in the undeformed state.

Here, k_1 denotes the shear ratio from the application of the tangential force. The maximum shear occurs at the surface of the fascia where the thickness is maximum, and is 0 at the bottom of the fascia where the thickness is 0. In equation (5), k_3 denotes the compression ratio from the applied normal pressure, and k_2 is the extension ratio resulting from compression on the surface of the fascia. Often in manual therapy, compression and shear are applied simultaneously. Values of k_3 less than 1 indicate compression. For example, $k_3 = 0.90$ indicates 10% compression. In this equation, k_2 is determined in terms of k_3 using the incompressibility condition as described below.

Using equations (2) and (5) we get

$$(6)\quad G_{ij} = \begin{bmatrix} 1 & 0 & k_1 \\ 0 & k_2^2 & 0 \\ k_1 & 0 & k_1^2 + k_3^2 \end{bmatrix}$$

$$(7)\quad G^{ij} = \begin{bmatrix} \frac{(k_3^2 + k_1^2)}{k_3^2} & 0 & \frac{-k_1}{k_3^2} \\ 0 & \frac{1}{k_2^2} & 0 \\ \frac{-k_1}{k_3^2} & 0 & \frac{1}{k_3^2} \end{bmatrix}$$

The strain invariants I_1, I_2, I_3 (needed to evaluate stresses) are determined by

$$(8)\quad I_1 = g^{rs}G_{rs},\quad I_2 = g_{rs}G^{rs},\quad I_3 = \frac{G}{g}$$

where G is the determinant of the matrix G_{ij}, and G from (6) is k_2^2 [k_3^2]. The strain invariants in equation (8) do not vary with the coordinate system.

Using (3) and (6) through (8), we find

$$(9)\quad I_1 = k_1^2 + k_3^2 + k_2^2 + 1; I_2 = \frac{\left(k_3^2 + k_1^2\right)}{k_3^2} + \frac{1}{k_2^2} + \frac{1}{k_3^2};$$
$$I_3 = \frac{G}{g} = k_2^2 k_3^2$$

Because the fasciae are assumed to be incompressible,

$$I_3 = 1, i.e. \quad k_2 = \frac{1}{k_3}$$

To determine the tensor B^{ij} used to evaluate stresses, we used the following equation:

$$(10)\quad B^{ij} = I_1 g^{ij} - g^{ir} g^{js} G_{rs}$$

Therefore, using (3), (7), and (10), we obtained

$$(11)\quad B^{ij} = \begin{bmatrix} k_1^2 + k_2^2 + k_3^2 & 0 & -k_1 \\ 0 & k_1^2 + k_3^2 + 1 & 0 \\ -k_1 & 0 & k_2^2 + 1 \end{bmatrix}$$

Evaluation of Stress

The stresses can be evaluated from formula (11) as follows:

$$(12)\quad \tau^{ij} = \varphi g^{ij} + \psi B^{ij} + p G^{ij}$$

$$(13)\quad \text{Here } \varphi = 2\frac{\partial W}{\partial I_1}, \psi = 2\frac{\partial W}{\partial I_2}, p = 2\frac{\partial W}{\partial I_3}$$

where W is the strain energy function.

We used the form of the strain energy function for soft tissues described by Demiray.[13] This function is given by

$$(14)\quad W = C_1\left[e^{C_2(I_1-3)} - 1\right]$$

where C_1 and C_2 are mechanical parameters to be determined. These parameters are analogous to the elastic parameters in the small deformation theory of elasticity. Their values are determined by curve fitting as explained in the Evaluation of Mechanical Parameters section.

After applying the equilibrium equations and the boundary conditions, we arrived at the following equations for evaluating the normal and tangential stresses, N and T, respectively. The details are provided in Chaudhry et al.[8]

Using equations (13) and (14), we have

$$(15)\quad \varphi = 2C_1C_2e^{C_2(I_1-3)} \text{ and } \psi = 0$$

Then the normal pressure (N) is given by

$$(16)\quad N = 2\left(k_3^2 - 1\right)C_1C_2e^{C_2(I_1-3)}$$

The tangential stress (T) along CD in *Figure 1* becomes

$$(17)\quad T = 2k_1k_3C_1C_2e^{C_2(I_1-3)}$$

We assumed that the forces applied to the surface of the skin are transmitted entirely to the underlying fat and fascia, independent of the thickness of these tissues. We tested this hypothesis by placing various materials as proxies for skin, fat, and fascia on a pressure mat and applying forces of 10 kg, which was within the range of forces applied in manual therapies.[8] The forces were applied through these layers to the pressure mat in several configurations, and in all cases the forces were transmitted entirely through the layers, with measurements varying from 5% to 7%, which is within the sensitivity range of this device. This hypothesis does not conflict with the results in authoritative articles by others who have studied the transmission of forces through tissue.[14-16] Bereznick et al[14] studied frictional properties at the thoracic skin-fascia interface during spinal manipulative therapy. In their introduction, the authors stated that in the absence of friction, the normal component of the applied forces is directly transmitted to the underlying vertebrae, which is what we assumed. Kawchuk and Perle[15] studied the relationship between the application angle of spinal manipulative therapy and the resultant vertical acceleration produced. According to their findings (presented in Table 1 of their article), the experimentally measured transmitted force can be slightly more or less than the predicted force, and the average difference between the predicted force (based on the applied force) and the transmitted force to the underlying vertebral layer is –0.59%, with an SD of more than 6%. This finding indicates that any difference between the applied force and the measured transmitted force is well within the measurement capabilities of the experiment. That is, within experimental measurement error, the applied force is totally transmitted to the underlying layer. It should be noted that Perle and Kawchuk[16] studied the distribution of pressure generated on a single rigid surface during hand manipulation and its relationship with the location and magnitude of hand configurations; thus, their findings are not directly relevant to the work in the current article.

Evaluation of Mechanical Parameters

To estimate the values of C_1 and C_2 in the formulas for fascia, skin, and adipose tissue, we needed experimental data for the stress, σ, vs the extension. Then we found the values for C_1 and C_2 that minimize (in the least squares sense[17,18]) the difference between the experimental values and the form given in equation (18). The values of C_1 and C_2 for superficial nasal fascia were estimated in our 2008 study.[8]

We now needed to estimate C_1 and C_2 for skin and adipose tissue. To compute the theoretical stress-strain relationship, we used the longitudinal stress-stretch relationship for incompressible material[12(p80)] for our setting. This relationship is shown by

$$(18)\quad \sigma = 2C_1C_2(\lambda^2 - \frac{1}{\lambda})e^{C_2(I_1-3)}\text{, with } \psi=0,\ I_1 = \lambda^2 + \frac{2}{\lambda}\ (\text{using } \lambda_1^2=\lambda^2, \lambda_2^2=\lambda_3^2=\frac{1}{\lambda})$$

where λ is the stretch ratio.

For experimental values along the curve, we used the plot described in Lapeer et al[9] for human skin and the plot described in Finocchietti et al[10] for human adipose tissue. We assumed, as in our previous model,[8] that the strain energy function constants, C_1 and C_2, derived from experimental data from stretch experiments, were valid for compression.

As in our previous model,[8] we used the least squares method to find the values of C_1 and C_2 that minimize the difference between the experimental values given in Lapeer et al[9] and in Finocchietti et al[10] and the theoretical values from the form in equation (18) (*Figure 2*, *Figure 3*, and *Figure 4*). The values of mechanical constants C_1 and C_2 are presented in *Table 1* for the 3 types of tissue considered.

Table 1.
Mechanical Constants for Human Fascia, Skin, and Adipose Tissues

	Mechanical Constants	
Tissue Type	**C1, MPa**	**C2, no units**
Superficial nasal fascia	0.033	8.436
Skin	0.021	6.565
Adipose	0.347	0.371

Results

We used the methods from our previous work[8] to compute the forces on the skin, adipose tissue, and fascia. In our 2008 study,[8] during manual therapy on the nasal fascia (surface area, 8.18 cm^2), we observed a normal force of 950 N and a tangential force of 20 N at 7.25 seconds; a normal force of 70 N and a tangential force of 28 N at 4 seconds; and a normal force of 75 N and a tangential force of 7 N at 12 seconds for a 16-second treatment. We calculated these to correspond to a fascial deformation of 9% compression and 4% shear at 7.25

seconds, 7% compression and 6% shear at 4 seconds, and 8% compression and about 1.5% shear at 12 seconds of this 16-second treatment.

In the current work, we determined the magnitude of normal and tangential forces required to achieve a specific deformation at each tissue level by using the formulas given in equations (16) and (17) for $k_3 = 0.91$ and $k_1 = 0.04$ for compression and shear, respectively, and equation (9) for the value I_1. *Table 2* presents the forces required to achieve the same percentage deformation in fascia, skin, and adipose tissue at these 3 time points. *Table 3* presents the percentage of deformations experienced in each layer for the given force at the same 3 time points.

We observed that the skin and adipose tissue experienced 9% compression and 4% shear when subjected to 50 N and 36 N compressive forces and 11 N and 8 N tangential forces, respectively. These tissues were actually subjected to much greater forces (*Table 2*). Although 950 N of compressive force and 20 N of tangential force resulted in 9% compression and 4% shear in the fascia, our analysis shows that these forces resulted in 14% compression and 6% shear in the skin, and the adipose tissue experienced 24% compression and 12% shear. We considered the normal and tangential forces applied in the experiment at 2 other times and computed the compression and shear for all 3 layers of tissue (*Table 3*).

Discussion

The skin, adipose tissue, and fascia are not isolated; rather, they form 1 block of layered tissue on a base of muscle and bone (*Figure 1*). The forces applied to the surface of the skin were transmitted entirely to the fascia, independent of the thickness of the tissues. As expected, the skin experienced more compression and shear, about 1.5 times as much as the fascia, and the adipose tissue experienced about 2.5 to 3.5 times the deformation of the fascia when subjected to a specified force. However, because these tissues are incompressible, they must deform

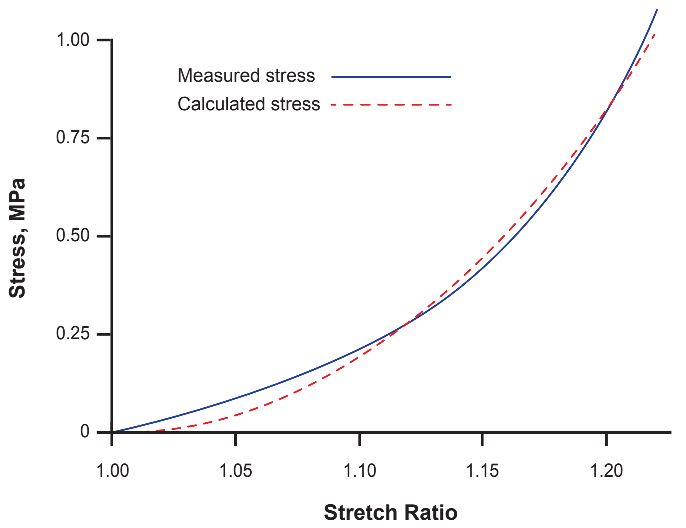

Figure 2.
Experimental (measured) and theoretical (calculated) stress-stretch ratio curves for superficial nasal fascia.[8]

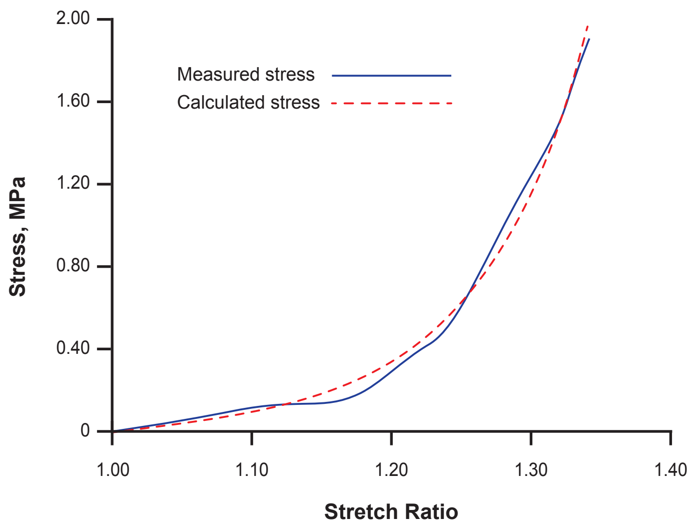

Figure 3.
Experimental (measured) and theoretical (calculated) stress-stretch ratio for skin.

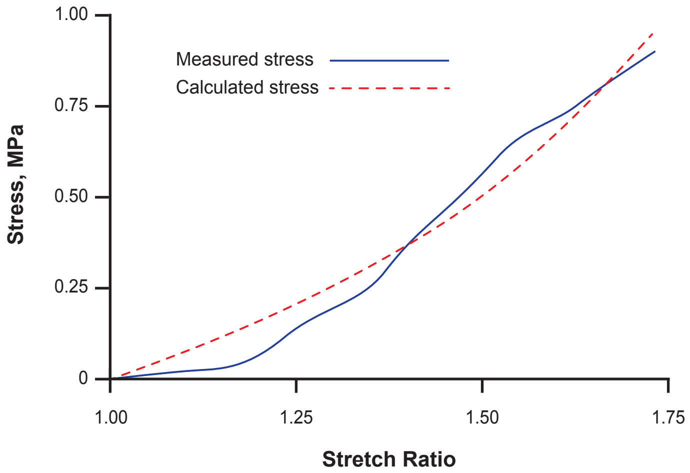

Figure 4.
Experimental (measured) and theoretical (calculated) stress-stretch ratio for adipose tissue.

differently in the lateral direction, but in reverse, to maintain constant volume. This information is important for osteopathic physicians and manual therapists to consider, as it implies that the tissue impact in the lateral direction is quite different from that in the longitudinal direction and perpendicular to the skin. Therefore, the direction and pressure of the tissue stroke by the practitioners of OMM may be important in achieving a desired clinical outcome. Although experienced practitioners of OMM may intuitively vary the direction of their tissue stroke, our study provides a quantitative basis for exploring this measurement. A cellular model of pressure and shear has been developed to study the effects of OMM.[19,20] Our study suggests that this cellular model needs to take into consideration the specific properties of the different layers overlying the fascia, as pressure and shear will be different for individual cells in each of the different layers.

Our fascia calculations in this paper are based on properties of the nasal fascia, which is an example of the softer fascial tissues in the body. The fascia lata and plantar fascia require much greater forces for deformation, which are greater than what can be applied in usual OMM treatments. Specific calculations for other fascial tissues of the body will further assist the refinement of OMM techniques.

Conclusion

In the present study, we applied forces that transmitted through the skin and adipose tissue to the fascia. Although all 3 layers had the same magnitude of force, the skin and adipose tissue had more compression and shear than the fascia. Because the current study focused on nasal fascia, additional calculations are needed for other body tissues.

Table 2.
Force (N) Required to Produce Compression and Shear in 3 Types of Human Tissue at Various Times

	9% Compression, 4% Shear, 7.25 s		7% Compression, 6% Shear, 4 s		8.6% Compression, 2% Shear, 12 s	
Tissue Type	Normal	Tangential	Normal	Tangential	Normal	Tangential
Superficial nasal fascia	105	22	75	31	98	11
Skin	50	11	53	15	47	5
Adipose	36	8	28	12	35	4

Table 3.
Compression and Shear (%) Evaluated for 3 Tissue Types When Subjected to Normal and Tangential Force (N)

	Normal Force (105 N), Tangential Force (22 N), 7.25 s		Normal Force (75 N), Tangential Force (31 N), 4.0 s		Normal Force (98 N), Tangential Force (11 N), 12.0 s	
Tissue Type	Compression	Shear	Compression	Shear	Compression	Shear
Superficial nasal fascia	9	4	7	6	9	2
Skin	14	6	11	12	13	4
Adipose	24	12	18	20	24	7

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