Experimental determination of the Young’s modulus for the fingers with application in prehension systems for small cylindrical objects

C Oprişan1, V Cârlescu1, A Barnea1, Gh Prisacaru1, D N Olaru1 and Gh Plesu2

1Mechanical Engineering, Mechatronics and Robotics Department, “Gheorghe Asachi” Technical University of Iasi, Iasi, Romania
2Machine-Tools Department, “Gheorghe Asachi” Technical University of Iasi, Iasi, Romania

E-mail: coprisan@gmail.com

Abstract. A new methodology to determine experimentally the Young’s modulus of the human fingers has been developed by the authors. The methodology consist in the experimental variation of the elastic deformation for the finger in contact with a steel cylinder normal loaded from zero to 10 N. The Hertzian model for elastic deformation specific to a point contact between a cylindrical object and the index finger has been used to curve fitting the experimental curve for elastic deformation of the finger in the vicinity of imposed forces from 0.5N to 10 N. Values between 0.07 MPa and 0.2 MPa for Young’s modulus of the finger have been obtained, in agreement with the values determined by the other authors using ball finger contacts or finger plane surface contacts.

1. Introduction
The prehension of the small objects with two fingers is depending both of the friction between finger’s skin and object’s surface and of the finger elastic deformation covering partially the object. The finger elastic deformation is depending of the prehension force, configuration of the object and of the visco-elastic behaviour of the finger’s skin.

As a result of the viscoelastic properties of the human skin, the friction and deformation behaviour of the human skin is a complex problem and in the literature, the skin friction coefficient varies within different anatomical skin (finger, forearm), human age, presence of the water or greases on the skin, the configuration of the objects balls, surfaces plane, surface roughness). Also, the mechanical properties of skin in the term of Young’s modulus has an important influence of the human skin friction [1].

Derler et al.[2] investigated the friction behaviour of human skin by using friction measurements with a tri-axial force plate in contact with the index finger and the edge of the hand in contact with a smooth and a rough glass surface under dry and wet conditions. Based on a lot of experiments Derler et al.[2] evidenced that the friction coefficients were generally higher than 1 and decreased until 0.15-0.3 by increasing the contact pressure up to about 100 kPa. By using the following dependence between friction coefficient $\mu$ and contact pressure $p$, $\mu(p) = k \cdot p^{(n-1)}$, the authors determined the values of the exponent (n-1). So, for finger on smooth glass in dry conditions the authors obtained for the exponent (n-1) values between $-0.15$ to $-0.96$. 
Derler and Rotaru [3] investigated the stick–slip behaviour of the index finger pad sliding on wet, smooth glass as a function of normal force and sliding velocity. The authors evidenced that the presence of the stick–slip leads to an increasing of the friction coefficient generally varied more than 25% about the mean values. By curve fitting of the experimental results a new dependence between friction coefficient and normal force in stationary conditions has been obtained. So, Derler and Rotaru [3] established for their experimental conditions that 

$$\mu(F_n) = 0.70 \cdot F_n^{-0.40}$$

Tomlinson [4] experimental investigated the tribological behaviour between human fingers and flat, rough or textured surfaces obtaining interesting dependences between friction force and normal force for a lot of materials (glass, steel, plastics, rubber). It was evidenced that the friction mechanisms of the finger on a flat surface are complex, due to a number of different aspects influencing the properties of the contact surfaces. So the total friction force between the finger and a flat surfaces is a sum of following forces: adhesive force, skin deformation force, capillary or viscous shear force caused by water or natural grease on the skin, and friction due to the deformation of finger ridges [4]. Other research realized by Tomlinson et al. [5] studied the friction between 17 different rectangular ridged surfaces and the human finger. The authors established that the main mechanisms of skin friction, when the finger sliding over rectangular ridges surfaces, are adhesion, deformation and relaxation energy dissipated in contact of the skin and the ridges. The elastic modulus of the skin is an important parameter both in friction problems and in visco elastic deformations of the skin in contact with different objects.

One of the most important problem in friction behaviour of the skin is to be obtained real values for the Young modulus of the skin.

Kwiatkowska et al.[6] experimentally determined the friction and deformation behaviour of human skin in vivo by using steel balls having 2 mm and 5 mm reciprocating-sliding against the nominally dry inner forearm skin of a healthy 32 year-old woman under the normal load between 0.19 and 0.5 N with sliding speed of 16 mm/s. The authors obtained in these experiments the development of a “bow-wave” in front of the probe when the ball is compressed and sliding on the skin. The two components of the friction force between a ball and the skin consisting in an adherence force $F_{ad}$ and elastic deformation force $F_{def}$ has been evidenced by skin deformation – relaxation diagrams. Also, Kwiatkowska et al. determined the Young modulus of the skin as a function of the balls diameter and obtained values between 0.2 MPa and 0.05 MPa, with a decreasing of the Young modulus by increasing of the ball diameter.

Liu[1] in his Ph.D thesis investigated experimentally the mechanical properties of the finger skin by using some experiments. So, by using the penetration of the finger skin with a small ball Liu obtained the stiffness of the skin $S_{skin}$ as ratio between variation of applied load $dF_n$ and variation of elastic deformation $d\delta$, $S_{skin} = \frac{dF_n}{d\delta}$. By knowledge of the stiffness it can be use the Oliver & Pharr [7] model to obtain the global Young’s modulus of skin by the following equation:

$$E_{skin} = S_{skin} \cdot \frac{\sqrt{\pi}}{2 \cdot \sqrt{A}}$$

where $A$ is the projected contact area. To evaluate the contact area between a human skin finger and a plane surface it can be use the equation proposed by Han et al. [8]:

$$A = k \cdot F_n^b$$

where $k$ and $b$ are constants which must be determined by experiments.

Barnea et al. [9,10] developed a new methodology to determine the friction coefficient by using a rigid cylinder in contact with human skin, sliding motion being in the axial direction of the cylinder. By this method is avoiding the elastic deformation in the front of the cylinder, the contact deformation of the skin having the same configuration during the sliding process. Were determined the friction
coefficient between a steel roller and a human finger for normal load between 1 N and 4 N with linear sliding speed of 1 mm/s.

In the present paper the authors propose a new methodology to determine the Young’s modulus of the human fingers in the normal compression by using indentation with a cylindrical steel roller.

2. Experimental investigations

2.1 Experimental procedure

A lot of experiments presented in the Introduction were focused to obtain informations about the Young modulus of the human skin by using indentation with balls or plane surfaces. The new methodology propose by the authors is based on the indentation of the human finger with a cylindrical surface and monitoring the variation of the elastic deformation of the finger as function of the normal applied force. The indentation experiments were realized with Tribometer CETR UMT-2 from the Tribology laboratory as is presented in figure 1 and detail of the finger’s indentation is presented in figure 2.

Figure 1. General view of the experimental equipments.

Figure 2. General view of the contact between cylinder and finger (a). Detail of the contacts between finger and steel cylinder (b).
A steel cylinder having the diameter of 7 mm, length of 14 mm and a surface roughness Ra = 0.06 μm is attached on the pin which is fixed in the DFM-2 force sensor of the Tribometer. A finger support is fixed on the linear table of the Tribometer. The finger is fixed on the support and the cylinder is pressed on the finger with normal forces Fz (in the vertical direction corresponding to Z axis of the Tribometer) between 0 N and 10 N as is presented in figure 2.

The indentation of the finger is realized with a speed of 0.1 mm/s. The variation of the finger’s elastic deformation δ with the applied force Fz for the index finger is presented in figure 3.

Figure 3. Variation of the index finger’s elastic deformation δ as function of the applied force Fz: experimental values and approximated equation.

2.2. Hertzian model between cylinder and finger

The contact between cylinder and index finger is presented in figure 4 as a Hertzian point contact between two elastic elements.

The index finger was assimilate as an elastic element having in the contact point with the cylinder a transversal radius R_{2x} = 8 mm and a longitudinal radius R_{2y} = 30 mm. The cylinder has a diameter of 7 mm.

According to the Hertzian point contact model the elastic deformation δ can be determined by equation [11]:

\[
\delta = \sigma^* \left[ \frac{3 \cdot F_z}{2 \sum \rho} \left[ \frac{1 - \nu_c^2}{E_c} + \frac{1 - \nu_f^2}{E_f} \right] \right]^{\frac{2}{3}} \cdot \sum \rho
\]

where \( E_c \), \( E_f \) are the Young’s modulus for cylinder and for finger, respectively and \( \nu_1 \), \( \nu_2 \) are the Poisson coefficients for cylinder and for finger, respectively.
Curvature sum is calculated with equation:

\[ \sum \rho = \frac{1}{R_{1,x}} + \frac{1}{R_{1,y}} + \frac{1}{R_{2,x}} + \frac{1}{R_{2,y}} \]  \hspace{1cm} (4)

Dimensionless parameter \( \delta^* \) is given by equation [11]:

\[ \delta^* = \frac{2 \cdot F}{\pi} \left( \frac{\pi}{2 \cdot k^2 \cdot E} \right)^{1/3} \]  \hspace{1cm} (5)

where \( F \) and \( E \) are the complete elliptic integrals of the first and second kind, respectively, approximate by following equations [11]:

\[ E \approx 1.0003 + \frac{0.5968}{R_y / R_x} \]  \hspace{1cm} (6)

\[ F \approx 1.5277 + 0.6023 \cdot \ln \left( \frac{R_y}{R_x} \right) \]  \hspace{1cm} (7)

The elliptical eccentricity parameter \( k \) is approximated by equation [11]:

\[ k \approx 1.0339 \left( \frac{R_y}{R_x} \right)^{0.636} \]  \hspace{1cm} (8)

The equivalent radius \( R_y \) and \( R_x \) are obtained by relations [11]:

\[ \frac{1}{R_x} = \frac{1}{R_{1,x}} + \frac{1}{R_{2,x}} ; \quad \frac{1}{R_y} = \frac{1}{R_{1,y}} + \frac{1}{R_{2,y}} \]  \hspace{1cm} (9)

Because the Young’s modulus of the steel is about \( 2.1 \cdot 10^5 \text{MPa} \) and Young’s modulus of the human skin is less than \( 1 \text{MPa} \), equation (3) can be expressed only as function of Young’s modulus of finger:
\[
\delta = \delta^* \left( \frac{3}{2} \sum \rho \left[ \frac{1 - \nu^2}{E_f} \right]^{2/3} \frac{F_z}{E_f} \rho \right)^{2/3}
\]

By including the radius of the two contact elements in mm \((R_{i,x} = \infty)\) and imposing \(\nu = 0.5\) \([1]\), equation (10) becomes:

\[
\delta = 0.308 \left( \frac{F_z}{E_f} \right)^{2/3} \quad \text{(mm)}
\]

where \(F_z\) is included in N and \(E_f\) is included in MPa.

2.3 Determination of the Young’s modulus for the finger

To determine the Young’s modulus of the finger the experimental variation of the finger’s elastic deformation \(\delta\) as function of the applied force \(F_z\) was fitted in the vicinity of the various applied forces \(F_z\) from 0.2 N to 10 N by using equation (11). In fig. 5 is presented the curve fitting procedure in the vicinity of \(F_z = 1.5\) N. By imposing the value of 0.07 MPa for \(E_f\) the experimental data are approximated with the numerical data obtained from equation (11).

![Figure 5](image)

**Figure 5.** Variation of the elastic deformation of the finger in the vicinity of the applied force \(F_z = 1.5\) N both for the experimental data and analytical data obtained with equation (11) for \(E_f = 0.07\) MPa.

In figure 6 is presented the curve fitting procedure in the vicinity of \(F_z = 8\) N. By imposing the value of 0.2 MPa for \(E_f\) the experimental data are approximated with the numerical data obtained from equation (11).
Figure 6. Variation of the elastic deformation of the finger in the vicinity of the applied force $F_z = 8\,\text{N}$ both for the experimental data and analytical data obtained with equation (11) for $E_f = 0.2\,\text{MPa}$.

Starting the curve fitting of the experimental values for elastic deformation $\delta$ in the vicinity of the applied force $F_z = 0.2\,\text{N}$, the Young’s modulus of the finger has a value of $0.04\,\text{MPa}$ and increases to $0.2\,\text{MPa}$ in the vicinity of $F_z = 10\,\text{N}$.

Variation of the Young’s modulus for finger as function of the applied force $F_z$ determined by the above presented methodology is presented in figure 7.

Figure 7. Variation of the experimental Young’s modulus for the index finger as function of applied load.
A polynomial curve fitting equation for the variation of the Young’s modulus of the finger $E_f$ as function of normal load $F_z$ has been obtained by following equation:

$$E_f (F_z) = -10^{-3} \cdot F_z + 2.77 \cdot 10^{-2} \cdot F_z + 3.09 \cdot 10^{-2} \text{ [MPa]}$$  \hspace{1cm} (12)$$

where $F_z$ is expressed in N.

By including Young’s elastic modulus of the finger determined by equation (12) in the Hertzian equation (11) it can be observed in figure (8) a very good correlation between experimental values (red curve) and the values determined by equations (11) and (12).

![Figure 8. Variation of the elastic deformation of the finger both experimentally determined and analytically calculated by using equations (11) and (12).](image)

3. Conclusions
A new methodology to determine experimentally the Young’s modulus of the human fingers has been developed by the authors.

The methodology start from the experimentally variation of the elastic deformation of the finger in contact with a steel cylinder normal loaded from zero to 10 N.

The Hertzian model for elastic deformation specific to a point contact between a cylindrical object and the index finger has been used to curve fitting the experimental curve for elastic deformation of the finger in the vicinity of imposed forces from 0.5N to 10 N.

To be realized the best curve fitting was imposed the values for Young’s modulus of the finger as a variable function depending of the normal load. Values between 0.07 MPa and 0.2 MPa for Young’s modulus of the finger have been obtained, in agreement with the values determined by the other authors using ball finger contacts and finger plane surface contacts.

For the variation of the Young’s modulus of the finger as function of normal load a polynomial equation has been obtained. The polynomial variation of the Young’s modulus of the finger was
included in the Hetzian model for elastic deformation between the cylinder and index finger and very good correlation with experiments has been obtained.

4. References

[1] Liu X 2013 *Understanding the effect of skin mechanical properties on the friction of human finger-pads Ph.D. Thesis* (Sheffield: Department of Mechanical Engineering University of Sheffield)

[2] Derler S, Gerhardt L C, Lenz A, Bertaux E and Hadad M 2009 Friction of human skin against smooth and rough glass as a function of the contact pressure *Tribology International* 42 pp 1565–1574

[3] Derler S and Rotaru G M 2013 Stick–slip phenomena in the friction of human skin *Wear* 301 pp 324–329

[4] Tomlinson S E 2009 *Understanding the friction between human fingers and contacting surfaces PhD Thesis* (Sheffield: The University of Sheffield)

[5] Tomlinson S E, Lewis R, Carre M J and Franklin S E 2013 Human finger friction in contacts with ridged surfaces *Wear* 301 pp 330–337

[6] Kwiatkowska M, Franklin S E, Hendriks C P and Kwiatkowski K 2009 Friction and deformation behaviour of human skin *Wear* 267 pp 1264–1273

[7] Oliver W C and Pharr G M 1992 An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments *J. Mater. Res* 7(6) pp 1564–1583

[8] Han H Y, Shimada A and Kawamura S 1996 Analysis of friction on human fingers and design of artificial fingers *IEEE International Conference on Robotics and Automation, Minneapolis, Minnesota* pp 3061–3066

[9] Barnea A, Oprisan C and Olaru D 2014 Prehension of the Small Cylindrical Objects by the Human Fingers. Friction and Adherence Processes *Applied Mechanics and Materials* 658 pp 721-727

[10] Barnea A, Rusu A M, Oprisan C, Carlescu V, Prisacaru Gh and Olaru D 2015 Friction between cylindrical objects and Prehension elastomer fingers *The Romanian Review Precision Mechanics, Optics &Mechatronics* 48 pp 219-223

[11] Harris T A and Kotzalas M N 2006 *Rolling Bearing Analysis. Essential Concepts of Bearing Technology* (CRC Press)