Assessment of contact characteristics of soft fingertip applied for multi-profile grasping

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Abstract. This paper presents experimental study of contact parameters for soft hemispherical fingertip pressed against target profiles. In design and development of soft robotic fingertips, in-depth knowledge of realistic contact parameter is required. Soft fingers are easily conformed to the geometry of the target profiles like human finger. In this work, fingertip is pressed against convex, concave and flat profiles experimentally with numerical validation. The magnitude of contact radius is calculated and compared for different profiles. From close observation it is observed that contact radius is higher for curved profiles when compared with a flat profile for a particular combination.

Keywords: Soft finger; Contact mechanics; Grasping; Conformal contact

1. Introduction
In design and development of soft fingertips an in-depth knowledge of realistic contact characteristics is required. One of the most considerable characteristics of soft fingertips is softness which is the difference between anthropomorphic robotic fingertips and humanoid fingertips. Soft fingers plays a major role in grasping condition and also safety handling. When grasping object, soft fingers easily conform to the geometry of an object. Soft hemispherical fingertip model provides realistic results in grasping conditions; estimation of grasping forces needs contact parameters on different target
profiles. Contact parameters are also required for handling an object. These factors are considered as an essential for dexterous manipulation.

More than a century ago, [1] Herts initiated famous contact theory and still this theory is base of major problems involving contact. They investigated results through the experiments of two elastic hemispherical glass and they concluded that radius of contact is directly proportional to the applied normal force raised to the power of 1/3. Timoshenko and goodier [2] developed a same concept for cylinder made up of elastic materials. And they revealed that the contact width is directly proportional to the applied normal force raised to the power of 0.5. Schallamach [3] tested different kind of rubber materials to estimate their contact parameters. Tatara and Tatara et al [4, 5, 6] proposed that hertz model is not suitable for the nonlinear materials. They also revealed that anthropomorphic fingertips cannot be employed as a non-linear material and nonlinear materials shown large deformation for small loads. Meanwhile, Han et al [7] analysing friction impact in designing a fingertip.

Kinoshito et al [8] studied the relationship between contact area and applied normal force of human fingers. Galin [9] found that there is an indentation problem in the presence of partial friction on the surface. By extending the hertz theory, Xydas and Kao [10-12] proposed new theory (Power Law Model) for nonlinear materials. They also studied that the influence of fingertip size and material properties on the power law model equation. This theory suitable for elastic nonlinear material under small deformations. Howe at al [13] and kao et al [14] conducted experimental study and analytical studies on artificial fingertips. Kao and yang [15] developed power law model to estimating a nonlinear stiffness of soft fingers. And also, the gave relationship between vertical deformation and applied normal force.

Hendricks et al [16, 17] developed FE model for characterising nonlinear material properties. Quati static deformation of the human fingertip on a flat surface using three-dimensional finite element model are analysed by [18] Shimawaki and Sakai. Venkatesh raja and Malayalmurthi [19, 20] conducted experiments on soft hemispherical fingertips. They studied the influence of the internal rigid core on the contact parameters. They concluded that the power theory was invalid for soft fingertips with inner rigid core. S.Yuvaraj [21] conducted experiments on flat and curved profiles. They found that for grasping of curvilinear objects less force is required as the grasping stability of the fingertip is increased by the geometric profile restriction.

Most of the researchers are tried to investigate the effects of contact parameters against flat surface profiles and very few investigated on curved profiles. Since large vacuum of space created. This research objective is to fulfil this space. Our paper presents experimental validation and FEM.

2. Experimental approach and setup
The soft fingertips shown in figure 1 are made up of neoprene rubber with a hardness of 40. The external diameter of fingertip is 25 mm. The schematic diagram of experimental setup is illustrated in figure 2. Target profiles were presented in figure 3. The artificial soft fingertip is attached to the rod. The rod is then mounted on a loading unit. Electronic measuring device is placed under the fingertip. Mild steel target profiles are located above the electronic measuring device. Recording paper when fingertip is loaded against target profiles. The purpose of using recording paper is to tracking the changes in contact area with an accuracy. All experiments were conducted on a flat, concave and convex profiles. The range of normal force was varied from 0 to 1000 N. To get the accurate recorded imprints, fine toner was applied every time to the fingertip. Also, experiments were repeated again for few trials and mean value of contact area taken into account. Finally, contact radius calculated by using digital image processing technique.
Figure 1. Soft fingertip with rod.

Figure 2. Experimental setup.
3. Soft finger model with flat and curved surface

The two-dimensional model of soft hemispherical fingertip contact with flat and curved surfaces are illustrated in figure 4a and 4b. A perpendicular coupled load in the UY direction is applied on finger, which is in contact with flat and curved surface. ANSYS® a commercial finite element package is used for solving this nonlinear contact problem.

3.1. Finite element analysis

The finite element model of soft finger contact with flat and curved surfaces is shown in figure 4a and 4b. PLANE 183 element was considered, for meshing fingertip, flat and curved surface because it is a higher order eight node two-dimension element which support hyper- elasticity as well as axis-symmetry [22]. Due to its nature, the element can conform to curved edge easily, so that it can give better results for soft fingertip which is in contact with a curved surface. The top nodes of the fingertip as coupled in the UY direction which facilitates uniform distribution of normal load on fingertip as shown in figure 4a. surface to surface contact was considered between fingertip using CONTACT 172 and TARGET 169 elements. Only half of the fingertip was modeled using the advantage of symmetry of problem. The Ogden model [23, 24] is used for the analysis of the soft finger contact problem [25]. The material properties of the soft fingertip and curved object were considered in this study is given in Table 1.

![Figure 4a](image1.png)  **Figure 4a.** FEA model of fingertip with flat surface.

![Figure 4b](image2.png)  **Figure 4b.** FEA model with curved surface.
3.2. Validation of finite analysis experiments
For validating the proposed experimental data’s was tested for nonlinear model [13]. From the results in table 2 it is very clear that the experiment results well in line with the FEM model results. The maximum variance evidenced in the model was 6%. Therefore, a similar methodology was extended for analysing the fingertip pressed against a curved surface.

4. Results and discussion
The significant outcomes of FEM modeling, experimental investigations and their comparisons are presented in detail. The magnitude of force applied on the fingertip was varied from the range of 0 to 1000 N for numerical validation. Weighted least square algorithm was used for fitting results of experimental and numerical validation and for obtaining realistic relationship between normal force applied and contact area developed. And also mean values were calculated using weighted least square algorithm. The final equation is presented in table 2.

| Table 1. Material properties of fingertip and surfaces [19] |
|-------------|-----------------|-----------------|
| Soft material | Neoprene | Constants |
| | | \( \mu_1 = 8.983 \times 10^{-8} \text{ MPa} \) |
| | | \( \mu_2 = 0.21 \text{ MPa} \) |
| | | \( \alpha_1 = 32.375 \text{ MPa} \) |
| | | \( \alpha_2 = 6.139 \text{ MPa} \) |
| | | \( d_1 = 0 \) \( d_2 = 0 \) |
| Object | Mild steel | Constants |
| | | \( E_1 = 2 \times 10^5 \text{ MPa} \) |
| | | \( \Upsilon_1 = 0.3 \) |

“\( \mu \)” is initial shear modulus of the material, “\( d \)” is Incompressibility parameter, “\( E \)” is Young’s modulus of elasticity and “\( \Upsilon \)” is Poisson’s ratio.

| Table 2. Fitted equations of contact parameters for curved and flat surfaces. Diameter of fingertip = 25 mm. |
|---|---|---|
| S.No | Target profiles | Experimental results | FEM results |
| | | | |
| 1 | Convex | 55.1863 \( N^{0.2606} \) | 54.3972 \( N^{0.2365} \) |
| 2 | Concave | 55.546 \( N^{0.2656} \) | 54.4326 \( N^{0.2455} \) |
| 3 | Flat | 27.187 \( N^{0.279} \) | 26.372 \( N^{0.2687} \) |
4.1 Contact area
The contact radii found for different magnitude of normal forces were obtained based on experimental and numerical investigations. The experimental and FEM mean value are illustrated in table 3. The following observations are drawn from results:

- Higher contact area is achieved due to higher softness of fingertip.
- The results reveal that under same finger size and soft grades neoprene gives higher contact area when compare with hard fingertip.
- Both the experiment and FEM results were matched with negligible deviations of 6%.

![Graph showing contact area vs. applied normal force for different profiles](image)

**Figure 5.** Comparison between applied normal force and contact area for flat and non-flat profiles.

5. Conclusion
To analysing soft fingertips on various profiles play a vital role in a modelling of anthropomorphic robotic fingertip. This proposed work presented experimental investigation followed by numerical analysis validated for characteristics of fingertip on three different surface profiles. The weighted least square fitted algorithm was used to analyse relationship between applied normal force and contact area developed. The experimental and numerical results are in-line with small interference.

(I) From the results it was observed that curved profiles like concave and convex, the force required for grasping is very less compare with flat surface for same contact area.

(II) It was found that grasping stability of fingertip increased for curved profiles due to geometric characteristics restrictions by surface profiles. Hence, these kind of analysis on different profiles will lead to better design and development of anthropomorphic robotic fingertips.

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