Research Article

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The haptic and perceptual characteristics of an anthropomorphic curved soft finger structure

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Abstract: In recent decades, modeling of soft fingertips has fascinated a superior momentum in research initiatives concerned with development of an anthropomorphic soft finger tip. In design and development of soft fingertips, analysis of contact a characteristic plays a vital role on dexterous manipulation. This research work presents the results of the experimental investigation in relation to the formulations of contact area for soft fingertips pressed against assorted target profiles. A dimensionless parameter, curve factor Y (r/R) is introduced to derive a parametric relationship among the key parameters. It also addresses the growth of contact area of fingertips for five different combinations. From experimental observations, a modified power law equation with conversion factor (X) is proposed to interpolate the magnitude of contact area for different profiles.

Keywords: Soft finger contact; curved structure; Conformal contact; anthropomorphic finger modeling

Nomenclature

Y	Power law constant that varies from 0 to 1/3
a	Contact radius
C	Power law proportionality constant
N	Normal force
R	Radius of Target Profile
r	Radius of Fingertip
X	Conversion Factor
Y	Curve Factor

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1 Introduction

In the design of dexterous robotic manipulation, an in-depth knowledge of contact parameters needs high attention for developing a realistic model. When manipulating an object, the geometry of target objects plays a big role in change of contact area between the finger tip and the object. The theory developed by Hertz [1] in 1880 remains the foundation for most elastic contact problems. He proposed that the radius of contact is directly proportional to the applied normal force raised to the power of 1/3 based on the experiments using hemispherical glass pressed against planar glass plate. Timoshenko and Goodier [2] extended same contact theory for cylinders and came up with the conclusion that contact width is proportional to applied normal force raised to the power of 1/2. The contact characteristics of different kinds of soft materials were studied by Schallamach [3]. Cutkosky *et al.* [4] compared various nonlinear materials for the developing artificial robotic fingers. The progress of contact area as a function of the applied normal force for human finger was studied by Kinoshita *et al.* [5]. Tatara [6, 7] and Tatara *et al.* [8] analyzed various nonlinear elastic materials and validated that Hertz model is not applicable for soft materials undergoing large deformation. Cutkosky, M.R. and Wright, P.K [9] analyzed friction and stability characteristics of flat and curved fingertips for better design of soft fingers. Howe *et al.* [10] studied the effects sliding in robot finger under combined torsion and shear loading.

Kao I and Cutkosky MR [11] made analytical derivations for modeling of sliding fingers for dexterous manipulation and validated with experiments results. The effect of friction in modeling of soft finger was studied by Han *et al.* [12]. Xydas and Kao [13, 14] proposed a power law model as of extension of Hertz contact theory for nonlinear materials is given by

$$a = CN^Y \quad (1)$$

Where “ a ” is radius of contact, “ C ” is proportionality constant, “ N ” is Normal force, “ Y ” is constant varies from 0 to 1/3. Xydas *et al.* [15] also investigated the effects of material properties and fingertip size in power law theory.

Park *et al.* [16] investigated the relationship between geometry and force distribution for modeling soft fingertips using tactile sensors. Hubbard, G.S [17] discussed the importance of robotic grippers like human hand in space applications. Shimawaki and Sakai [18] analyzed numerically the mechanical deformation of human fingertip pressed against flat plate using three dimensional finite element models. The effects of deformation in soft fingers during power grasping were investigated by Elango and Marappan [19]. Shimoga and Goldenberg [20–22] investigated various soft materials experimentally for precision and power grasping and also discussed three common issues in modeling and impedance regulations of soft fingertips. Tiezzi and Gabriele [23] made experimental analysis of soft materials with inner rigid cores by application of normal and tangential load. Marco Picinini *et al.* [24] predicted the conformity of soft fingertips with different layered design. Yaralioglu *et al.* [25] evaluated contact stiffness of layered materials. Treesatayapun C [26] regulated grasping force of industrial parallel grippers using multi-input fuzzy rules emulated network. Venkatesh Raja and Malayalamurthi [27, 28] investigated numerically the contact characteristics fingertips with internal rigid core and compared experimentally with entirely soft fingertips. They have claimed power law model is invalid for fingertip with internal core. Elango N and Faudzi AAM [29] presented a detailed review on soft materials and soft manipulators for improved design and development of soft fingertips. Tiezzi and Kao [30] analyzed contact parameters of viscoelastic fingers.

Chen J and Zribi M [31] made an analysis and proposed a control law for multifingered robot hand with rolling and sliding contacts with the surface of target objects. Cherif M and Gupta KK [32] studied the quasi – static reorientation of convex object with four finger grasp. Heyneman B and Cutkosky MR [33] have classified different types of slips while grasping objects and they are also made an attempt to control of slippage using tactile array sensors. Seo, J *et al.* [34] made a theoretical study on grasping of curved surface objects for development of multi – fingers grippers. Deimel, R. and Brock, O [35] developed a novel type compliant and under actuated robotic hand by conduction of many experimental tests for dexterous manipulation. Khansari, M *et al.* [36] studied surface – surface contact analysis on different surfaces for better design and development of robotic hands. Tavakoli M *et al.* [37] developed a soft finger of 3D printed endoskeleton covered by soft matter and analyzed its characteristics for better grasping. Feng N *et al.* [38] developed soft robot with a combination of soft hand and Electromyographic (EMG) signal

for correct rate of recognition and reproduction of human grasping gestures.

Most researches attempted to model the soft fingertip but only few researchers have investigated the contact characteristics of fingertip pressed against various profiles. Yuvaraj *et al.* [39–42] made a numerical attempt to assess the contact characteristics of soft fingertips on curved profile grasping. This experimental work is proposed to address the effects of contact area growth and to modify the power law model [13, 14] when fingertips are pressed against non-flat profiles.

2 Experimental Approach and Setup

Figure 1 shows the geometrical profile soft fingertips made up of neoprene rubber with shore hardness of 40 units. Five different radiuses of fingertips with two various geometries (Hemispherical and Cylindrical) were made by compression molding process. The experimental setup was used to assess the contact area of different fingertips was shown in Figure 2. A hydraulic loading unit was used to press the fingertip against various non flat profiles as shown in Figure 3. The soft fingertip is fixed in a mild steel rod and mounted on the loading unit perpendicular to the target surface. The applied normal force was measured using electronic weighing scale with an accuracy of $\pm 0.1\text{N}$. The impressions of contact area were recorded using special sheets which are placed on non flat profiles.

2.1 Vectorization of Raster Image

The scanned raster images of contact area imprints are converted into vector form using AutoCAD® Raster Design 2014 Software [41]. To achieve true coordinate transforms requires preparing tasks such as cropping unwanted region and merging multiple images and files have to saved in JPEG formats. Reduction of file size is required by cleaning unwanted colors in the raster image. By using VTools and standard commands the dimensions of converted vector images can be predicted with good accuracy.

Figure 1: Fingertips with different radii.

Figure 2: Experimental Setup.

Figure 3: Fingertip pressed against various profiles.

3 Validation of Experimental results with Finite Element Analysis (FEA) Results

Table 1 shows the validation of experimental results with FEA results for flat and concave profile. From comparison it is clear that the results extracted from weighted least square fit algorithm of experimental results are well in line with FEA computations. The maximum error variance evidenced in the model is 6%.

Figure 4: Sample imprints of fingertips on various profile.

Table 1: Comparison and Validation of Experimental Results

Profile	Radius of Fingertip in mm	FEA [25]		Experimental	
		C	Y	C	Y
Flat	21	2.5358	0.2671	2.542	0.256
	22	2.5723	0.2674	2.591	0.263
	23	2.6110	0.2678	2.622	0.263
	24	2.6204	0.2678	2.628	0.263
	25	2.6372	0.2687	2.643	0.263
Concave	21	5.1223	0.2427	5.242	0.252
	22	5.2217	0.2437	5.285	0.258
	23	5.3264	0.2442	5.340	0.258
	24	5.3718	0.2448	5.380	0.258
	25	5.4326	0.2453	5.450	0.258

4 Results and Discussion

The noteworthy outcomes of experimental assessment and their critical comparisons are presented in the following sub-sections for five different combinations of fingertip with two geometries. To ensure wide range of application, the normal force applied on the fingertip was varied from 0 to 1000 N. The radius of non flat profile (R) was fixed as 30 mm and the radius of fingertips is varied from 21 to 25 mm in steps of 1 mm. The dimensionless parameter, curve factor 'Y' (r/R) is considered for further discussion. The curves are plotted between area of contact (a) and applied normal

force (N) for better clarity and analysis. The weighted least square curve fitting algorithm is used to process the raw data into a parametric relationship and the results are depicted in Table 2.

4.1 Discussion on the Constants of Power Law Equation

- The theory developed by Xydas and Kao predicted that, the constant of the power law equation 'Y' is only material dependant. However, a contrast result

Table 2: Fitted Power Law Equations for Flat and Non Flat Profiles

Geometry of Fingertip	Radius of Fingertip in mm, r	Curve Factor, $Y(r/R)$	Fitted Power Law Equations		
			Concave Profile	Convex Profile	Flat Profile
Hemispherical	21	0.700	$5.242N^{0.2520}$	$4.932N^{0.2591}$	$2.542N^{0.2560}$
	22	0.733	$5.285N^{0.2580}$	$4.983N^{0.2613}$	$2.591N^{0.2630}$
	23	0.767	$5.340N^{0.2580}$	$5.138N^{0.2620}$	$2.622N^{0.2630}$
	24	0.800	$5.380N^{0.2580}$	$5.189N^{0.2620}$	$2.628N^{0.2630}$
	25	0.833	$5.450N^{0.2580}$	$5.203N^{0.2620}$	$2.643N^{0.2630}$
Cylindrical	21	0.700	$7.363N^{0.2864}$	$6.928N^{0.2911}$	$3.670N^{0.2936}$
	22	0.733	$7.563N^{0.2874}$	$7.131N^{0.2956}$	$3.708N^{0.3014}$
	23	0.767	$7.667N^{0.2882}$	$7.320N^{0.2988}$	$3.745N^{0.3089}$
	24	0.800	$7.792N^{0.2882}$	$7.497N^{0.2988}$	$3.779N^{0.3089}$
	25	0.833	$7.856N^{0.2882}$	$7.577N^{0.2988}$	$3.810N^{0.3089}$

Figure 5: Comparison of area of contact versus applied normal force for hemispherical fingertips **Figure 6:** Comparison of area of contact versus applied normal force for cylindrical fingertips

is derived from the current research work. The constant 'Y' doesn't vary with the size of fingertip. However, it deviates upon the change in the profile of target surface.

- From close observation, it may be noted that convex target profile fetches a higher 'Y' value followed by flat profile and concave profile. This observation seems to be valid only for hemispherical fingertips.
- For cylindrical fingertips, the major of 'Y' is higher for flat profile followed by convex and concave one. These results are so significant hence a slight variation in the value of 'Y' may lead to wrong predictions.
- The constant 'C' varies progressively with the increased in radii of fingertip for both the cases.
- From the above facts, it may be concluded that, there is a need in modifying the terms of power law model [13, 14] while assessing the characteristics of non-flat profile grasping.

4.2 Discussion on Contact Area

- From the Table 2 and Figure 5 and Figure 6, it is very clear that cylindrical fingertip develops a bigger area of contact while compared with hemispherical ones under identical conditions.
- Also, owing to higher conforming nature of concave profile, full possible area of contact is established at relatively lower magnitudes of applied normal force.
- While compared with flat profile, the constant 'C' of the power law model is increased by a factor of ~2.04 and ~1.97 respectively for concave and convex profile for both geometric cases of fingertips. This magnitude factor gradually increases with the increase in radii of fingertip.

Figure 7: Contact area progress of hemispherical fingertip on various profiles

Table 3: Conversion Factor (X)

Geometry of Fingertip	Conversion Factor X		
	Concave to Flat	Convex to Flat	Concave to Convex
Hemispherical	0.489	0.512	0.953
Cylindrical	0.489	0.514	0.953

4.3 Discussion on contact area progress

Figure 7 and Figure 8 represents the progress of developed contact area for hemispherical and cylindrical fingertips pressed against three different profiles.

- From the Figure 6, it can be seen that the contact area of hemispherical fingertip developed on a flat profile target surface is circular at all loads with increasing fashion. However, Non-flat profiles developed an elliptical profile. Moreover, the final resulting shape is a circular one for all the cases.
- For cylindrical fingertips, the area of contact developed results in a rectangular profile. Since the length of the cylinder is fixed, the width of the rectangular contact area remains constant for all the cases. The breadth varies at a rapid rate for concave profile. The rate of change is high at lower magnitude of applied normal force and gradually saturated at higher levels.

4.4 Proposed Modified Power Law Theory

The proposed modified power law theory is based on average variations noted in the contact area for different profiles as shown in Table 3.

Figure 8: Contact area progress of cylindrical fingertip on various profiles

- From the Table 3, it is observed that the conversion factor X is almost similar for both hemispherical and cylindrical fingertip pressed on various profiles.
- The modified power law is suggested as below,

$$a = XCN^Y \quad (2)$$

5 Conclusion

In this study we have conducted experimental study of two geometrical soft fingertips pressed against flat, concave and convex target profiles and compared with numerical solutions. From the experimental results the following conclusions are drawn,

- The contact area developed by the fingertips while grasping non flat profiles is higher when compared to flat one under the same magnitude of applied normal force. This phenomenon happens due to the change in conforming characteristics of geometric profiles.
- Contact area pattern of concave and convex are inverse to each other.
- It is further, suggested that cylindrical fingertips can be utilized for power grasping and hemispherical one for precision grasping since the former one maintains higher line of contact at identical conditions.
- Also, the constant of power law equation 'Y' is not only dependant on material. It varies slightly with respect to the change in the profile of target surface.

Conflict of Interests: The authors declare that there are no conflicts of interest regarding the publication of this article.

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