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Keywords
Skin tribology, Surface texture, Interlocking, Tactile friction

Disciplines
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A parametric contact model to describe the interlocking of soft bodies with ridged surface textures used in haptic applications

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Abstract

Tactile interactions with product surfaces are essential to how such products are used and the value that users ascribe to them. It has been shown that contact mechanisms and frictional interactions are central to the haptic attributes perceived by the users. While there are established and well-studied models that describe the adhesive and deformation components of friction, interlocking behavior – while shown to be dominant in some tactile applications – has not been thoroughly studied as a frictional mechanism for soft materials such as skin, partly because of the complex contact mechanics involved. This investigation involved a computational parametric study of interlocking behavior between a soft material and a parallel-ridge surface texture, across a range of ridge widths, spacing and applied pressure. The goal of the work was to determine if a relatively simple contact model could be developed to predict the number of potential points of interlocking between the soft body and the ridge features. The results showed that a standard Hertzian approach predicted the number of ridge edge contacts (potential interlocking locations) with acceptable accuracy, so long as the ratio of ridge width to ridge spacing was large. However, a hybrid model that also incorporated the ridge width performed remarkably well across a wide range of ridge widths and spacing. This model may provide utility as an input into various proposed models of frictional interlocking to explain haptic perception of textured surfaces.

1. Introduction

Tactile interaction with the surfaces of engineered products is a nearly continuous occurrence and there is a need to better understand the tactile phenomenon to improve both functional and aesthetic qualities of surface textures. Tactile interaction helps us make judgements about materials [1]–[3], allows us to distinguish between materials [4]. While complex tactual attributes likely involve not only contact parameters but also such phenomena as viscoelasticity and transmission of vibrational energy during sliding, tactile optimization can also serve functional purposes such as the control of friction for product grip. One common means of imparting desired characteristics to a surface is the use of repeating textural elements such as dots, ridges or other simple geometries. Many surfaces are textured with parallel raised ridges to influence the frictional characteristics of the surface, either increasing or decreasing friction based on the geometry parameters of the ridges. Parallel ridged textures can be seen in products requiring grip for functionality such as power tools, razors, and bottle tops. In contrast, the presence of the resulting grooves between raised ridges can reduce the coefficient of friction due to a lower contact area. This approach is used in various products for tactually distinguishing among surfaces. A fair amount of work has been done to understand the impact of simple textures on skin friction with some evidence to suggest that it is adhesively driven and thus dependent to a large extent on actual contact area [5][6]. However, the frictional mechanism becomes more complex when the skin can deform and penetrate into the zones between ridges and thus mechanically interacts with the edges of these features. It should be noted however, that there can be a multitude of tactual goals in the design of surfaces and many – but, likely not all – depend to some extent on friction. Aside from very complex tactual attributes such as smoothness, prickle and heft, there are more functionally oriented goals such as the positive perception of surface grip or prevention of slip without aggressive skin penetration. These latter goals are often addressed by the use of texturing of soft materials that come into contact with the skin during product use.

The friction between a deformable body such as skin and a counter surface has been shown to be dependent on adhesion, deformation, and interlocking. In tactile friction, the adhesion component has been shown to contribute much of the frictional force [7], [8]. However, as surface roughness increases beyond a certain point, the deformation and interlocking components begin to strongly influence friction [9], though there do not yet exist good models to predict the interlocking of soft bodies against textured surfaces. The contact between cylindrical bodies and rigid planes has been extensively studied to serve as a model for many applications on the micro and macro scale of tribo-surfaces. Analytical solutions for contact area between two elastic bodies go back to Hertz and are used frequently for estimating real contact area and friction. Two- and three-dimensional finite element analysis (FEA) simulations have been employed for more complex surface interaction and material properties to address the complexity of modeling human skin-to-surface interactions. Jackson, et al. [10] simulated the contact area of elasto-plastic hemispherical contact against a rigid flat surface. Xydas, et al. [11] simulated the contact of a non-linear elastic hemispherical body against a rigid flat surface with friction. Locations of stress concentrations with respect to tactile sensors were simulated by Maeno, et al. [12] for flat surfaces and by Shao et al. [13] for grooved surfaces. Each of these uses of FEA provided much insight into tactile interaction that would have otherwise been very difficult to study analytically.

Both Lederman, et al. [14] and Smith, et al. [15] investigated parallel-rectangular ridged textures and reported a correlation between the perception of roughness and the groove width and pressing force. Grooves were also shown to be important for grip by Tomlinson et al., whose study showed that when the surfaces roughness of triangular-ridged textures increased beyond a certain threshold, friction increased significantly as a result of interlocking [9]. In a study by Taylor, et al. [16] involving a parallel rectangular ridged texture, they hypothesized that the amount of penetration of the human finger into the groove impacted the perception of surface roughness. It was hypothesized in this investigation that the number of ridges in contact plays an important role in friction and tactile perception for two primary reasons: it affects the true contact area and thus adhesive friction; and the number of zones where the skin penetrates in between ridges all count as locations of localized interlocking friction. The former concept has been studied, however, there lacks an analytical solution to accurately predict the number of ridges that would be in contact with a soft body under a given load and ridge geometry parameters. While the Hertzian model accurately predicts the contact distance between a soft cylinder and rigid plane, it is not formulated to address the complex problem of a non-uniform surface interrupted by the space between ridge surfaces. Hertzian contact distance can be used indirectly to predict the number of theoretical ridges in contact (based on groove and ridge width), but it has not been clear how much error this approach might be subject to, and whether it is a viable step to use in an overarching frictional model based on interlocking.

The objective of this study was to investigate viable approaches for predicting the number of textural ridges in contact with a deformable body (such as a fingertip), so that this could be integrated into a higher-level interlocking-based friction model in particular applications. Furthermore, the authors sought to determine the error in applying low-complexity models, such as a Hertzian approach. Furthermore, it is important to estimate the number of grooves in which an elastomeric body penetrates for the development of an interlocking friction model. In this investigation, a plane strain finite element modeling approach was employed to examine the compression of an ideally elastic cylinder against rigid rectangular-ridged textures. This model was experimentally validated in a previous study [17], and thus served as a useful platform for the current work. This served as an investigative platform to determine the structure and performance of models for predicting the number of texture ridges in contact with the soft body. In this fully parameterized study, textured were defined by ridge and groove widths in relation to the radius and elastic modulus of the cylinder. The result of the work was a set of relationships that predicted, with high fidelity, the number of textural ridges in contact with the soft body based on applied load and the geometric parameters of the texture. Because of it parameterization, the authors show that the model could be applied to both the micro and macro scale.

2 Methods

2.1 Texture parameters and application to Hertzian contact

The textures used in this analysis are referred to as two dimensional ridges, meaning that they have a surface profile that remains constant laterally across the surface, and thus are fully defined by a projected cross section. The textural elements studied were parallel rectangular ridges, as indicated in Figure 1. In this paper, the term *groove* is used to indicate the space between two adjacent ridges. Furthermore, a *proximal edge* contact is defined as contact with the top corner of the ridge which is closest to the centerline of the soft body. It is theorized that proximal edges contribute the greatest amount to an interlocking mechanism as a soft body slides laterally against a parallel ridge texture. As shown in the figure, the texture's ridge width is referred to as a, while the groove width (i.e., distance between the ridges), is referred to as b. A cylinder was used to represent the elastomeric body because its geometry is seen in many applications and its simple nature confines its defining parameters to its radius, R, elastic modulus, E, and Poisson ratio, v. The applied load per unit area of the cylinder is referred to as p. The number of the proximal ridge edges which come into contact with the cylinder when loaded is referred to as Q. In order to non-dimensionalize this study for different scales and stiffnesses, parameters of similitude were defined using Buckingham Pi theorem as a/R, b/R, and p/E, respectively [18].

In order to examine if the Hertzian model was an adequate prediction for determining the number of proximal ridge edges in contact with the elastomeric cylinder, the Hertzian contact distance was reformulated to incorporate the geometry parameters used in this study. Generally, a formulation of the Hertzian contact distance between a cylinder and two rigid plates includes a loading term per unit depth. Adjusting this formulation to include *p*, and in terms of the radius yields the following

$$d = 4R\left(p\frac{2}{\pi}\frac{1-v^2}{E} \right)^{1/2} \qquad (1)$$

In order to use the Hertzian model to predict the number of proximal ridge edges in contact, this relation needed to be expressed in terms of number of proximal edges based on the ridge and groove widths. The number of proximal ridge edges is numerically equal to the number of ridges in contact. This is due to the fact that each ridge has two edges, one proximal and one distal, but the latter is disregarded for the purposes of frictional interlocking. The first step in reformulating the Hertzian model was to express contact length in terms of total number of ridges in contact, and to normalize this term so that it would scale with ridge size. Essentially, rather than expressing Hertzian contact length in a standard unit such as millimeters, it was useful to express the length using ridges as the fundamental unit of measure. This contact length in ridge units – denoted as *Q'* – is the predicted Hertzian contact length against a perfectly smooth surface, but divided by the number of ridges which would occupy that length of the surface. This yields a fully continuous form of the Hertzian model, with partial ridge contact producing a non-integer number. At the instant of initial contact between the cylinder and a proximal edge, *Q'* will be equal to the number of proximal edges in contact. Because the center of the cylinder was constrained to align with the centerline of the central groove, it was initially in contact with two ridge proximal edges when unloaded, and thus had an initial contact distance of *b* (groove width). The difference of the initial contact distance from the total contact distance is of interest because it determines the number of additional ridge edges in contact when divided by the ridge pitch (*a*+*b*). This relationship is described by

$$Q' = 2 + \frac{d-b}{a+b} \qquad (2)$$

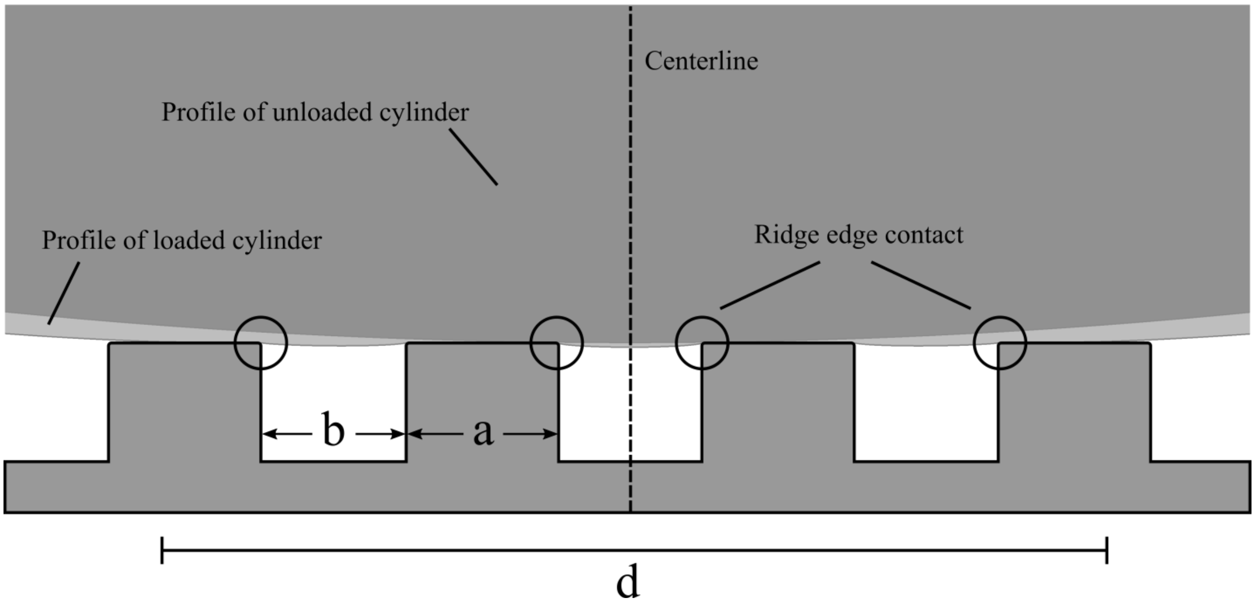

Figure 1. Illustration of the ridge geometry used in this study. 'd' is the overall contact distance, 'a' is the ridge width, and 'b' is the groove width. In this figure, the unloaded cylinder is in initial contact with 2 proximal ridges, (*Q* = 2). Under load, *Q* increases to 4 ridge edges in contact with the cylinder.

Substituting (1) into (2) and putting into the chosen dimensionless parameters, yields

$$Q' = 2 + \frac{-b/R + 4\sqrt{\frac{2}{\pi}}\left(1-\nu^2\right)^{1/2}\left(p/E\right)^{1/2}}{a/R + b/R} \tag{3}$$

As stated above, the ridge-based contact distance (*Q'*) is not directly useful as an indicator of edge interlocking unless it is expressed as an integer number of proximal ridge edges in contact, or *Q*. This was accomplished using a mathematical floor function. Because *Q* represents the number of proximal edges in contact, it must be an integer, and because the model is symmetric in the lateral direction, the number must be even. Thus, the floor function must round down to the nearest even integer. The mathematical representation used here for a floor function to the nearest integer is expressed by brackets "⌊ ⌋". In simple terms, Q is equal to the floor function applied to *Q'*. Assuming an incompressible material (ν = 0.5) and simplifying some of the terms in (3), the Hertzian model expressed as the number of proximal ridge edges in contact is:

$$Q = 2\left[1 + \frac{-\frac{1}{2}\,{}^{b}\!/\!_{R} + 1.382\left({}^{p}\!/\!_{E}\right)^{1/2}}{{}^{a}\!/\!_{R} + {}^{b}\!/\!_{R}}\right] \tag{4}$$

This is the finalized form of the Hertzian-based ridge prediction model and will hereafter be referred to as the *Classic* Hertzian model. This model was used as a benchmark to investigate the accuracy of the more complex regression-fitted models based on finite element analysis, described below.

2.2 Computational Model

Finite element Analysis (FEA) was used (Abaqus/CAE v6.12) to conduct this parametric investigation for contact model development. Due to the uniform profile of the texture ridges laterally across a surface, the study was able to be conducted using plane strain assumptions. The choice of using a soft-body cylinder – rather than a sphere – was informed by this decision with the goal of keeping the analysis computationally tractable yet realistic. The mesh of cylinder was constructed using linear elastic eight-node biquadratic quadrilateral elements with full integration. Quadratic elements assisted in simulating contact of curved surfaces to a higher degree and the use of full integration reduced the effect of hour-glassing of the elements. The experimental validation of this computational approach has been published previously by the authors [17]. In order to verify the simulation configurations as well as the classic Hertzian contact approximation, the first phase of the investigation involved loading the modeled cylinder between two flat rigid plates. The resulting contact distance was recorded as a function of load and converted to *Q'* values using (2). These values were then compared to the predictions from the classic Hertzian equation (4) to verify that the FEA approach was producing reasonable results and that the model was able to reach convergence without errors.

Once the proper functioning of the computational model was validated, the second phase of the investigation involved the parametric study of the soft cylinder against a substrate covered with ridges. The textured surface was modeled as being perfectly rigid. The starting position for each test involved centering the cylinder laterally so that its center was vertically collinear with the centerline of a groove on the textured surface. A negligible normal load was applied in order to bring the cylinder in contact with the surface, which involved the establishment of contact between the cylinder radius and the first two proximal ridge edges (Q = 2), one on the left and one on the right of center, respectively. The mesh was highly refined in the area of contact as illustrated in Figure 2, in order to increase the accuracy at which the cylinder made contact with additional ridge edges. After initial contact, the load was gradually increased in the model such that large enough such that a growing number of ridges came into contact with the deforming cylinder. The exact load was noted when each ridge became in contact during the loading process. This process was repeated for all combinations of values of *a/R* (normalized ridge width) of 0.012, 0.022, and *b/R* (normalized groove width) of 0.01, 0.02, 0.03 and 0.032. These are values which are common in tactile experiments [19] when assuming a single radius of curvature to represent the finger. From the *p/E* values obtained when ridge edges became in contact, a model was developed using a least squares regression which incorporated the dimensionless geometric and loading parameters to predict *Q*.

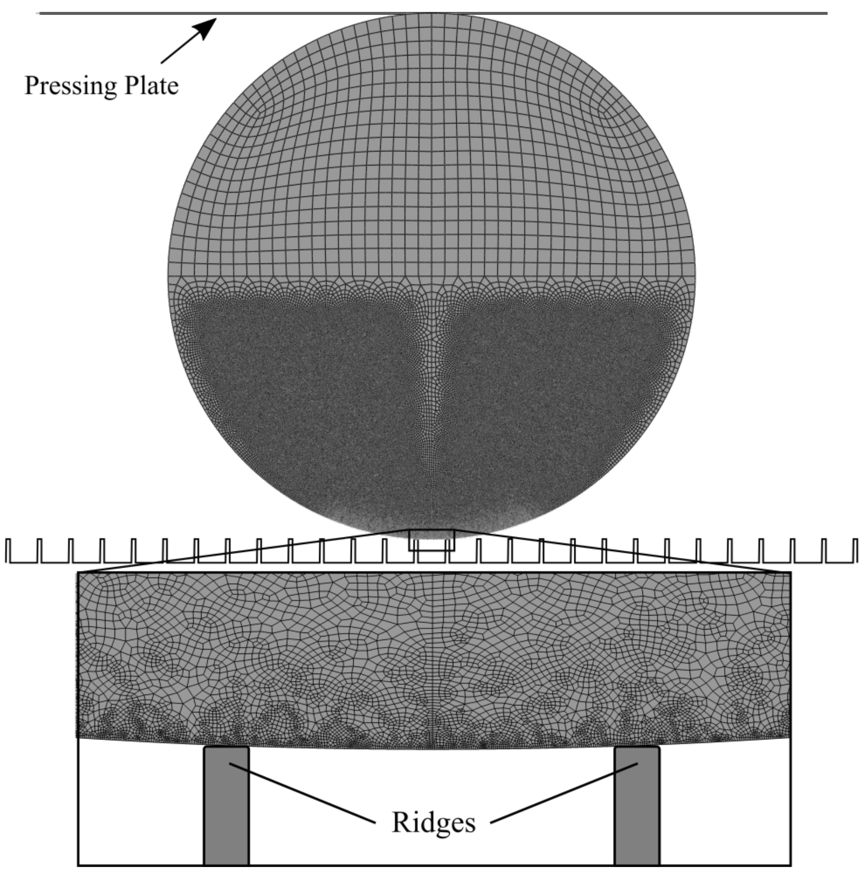

Figure 2. Illustration of the configuration used in the finite element model, with a large *b/R* of 0.09, and small *a/R* of 0.011. The mesh is highly refined at the area of contact. The lower part of the figure shows greater detail of the ridges.

3 Results and Discussion

3.1 Hertzian-Based Models

The computational simulation was first verified by comparing the simulated contact distance of a compressed cylinder between two rigid plates with the closed-form analytical Hertzian contact model. The FEA results matched the hand calculations with very high precision over the loads used in this study. Relation (2) – a reformulation of Hertz which essentially converts the fundamental unit of contact length from a true distance to number of ridges in contact – was also verified by comparing its results to the classic Hertzian contact described by (4). This comparison resulted in a near perfect correlation ($R^2 \approx 1$) for several of the load and geometry settings, and maximum error of 2% which can be seen by Figure 3. The primary concern regarding the error in using the simple Hertzian model is that by definition the cylinder is in contact with less area on the surface due to the spaces between the ridges. Thus, it was hypothesized that with less counterface area, the cylinder would experience less lateral deformation (i.e., contact length) because some of the zones of the cylinder would penetrate into the grooves rather than be forced to deform in the lateral direction. It was believed that this effect would be minimal with large ridge widths (*a*) coupled by narrow groove widths (*b*), because this would most closely resemble a flat uniform surface. The initial observations of very high correlation of contact length with Hertzian predictions suggested that this relatively simple relation could provide useful predictions to gauge the extent of potential interlocking.

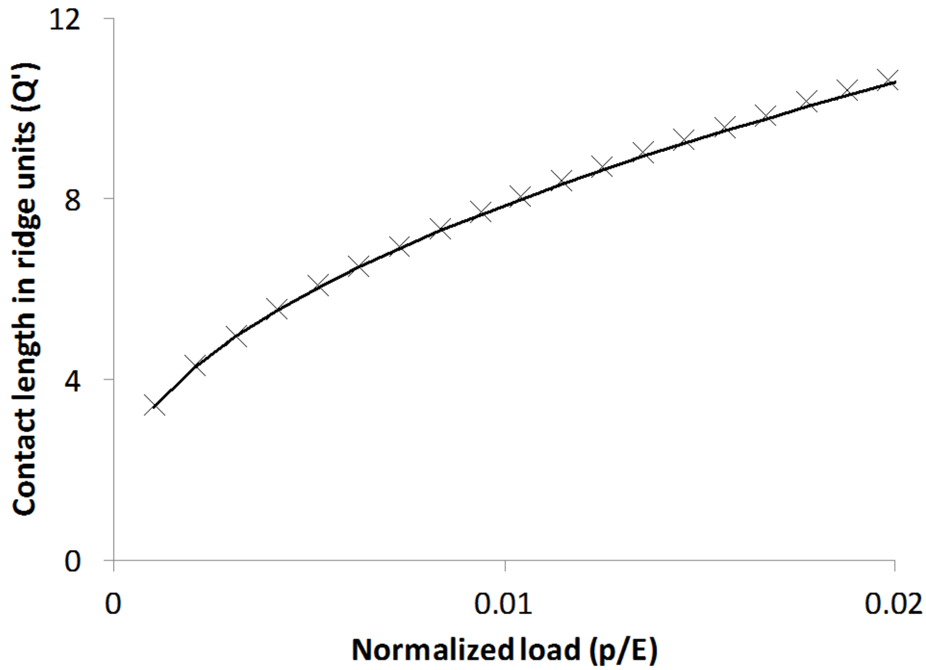

Figure 3. The points represent the computational model's contact length between a cylinder and two rigid planes expressed as total ridge units in contact (*Q'*) using (2) at values *a/R = 0.022* and *b/R* = 0.03. The simulated results are predicted with high accuracy ($R^2 \approx 1$) by the classic Hertzian contact (solid line).

As previously stated, the computational cylinder model was then loaded against a rigid grooved surface for all combinations of normalized groove and ridge width, respectively (*b/R* values of 0.01, 0.02, 0.03 and *a/R* values of 0.012, 0.022, and 0.032), and across two orders of magnitude of normalized pressure (p/E). As normal load was increased during the simulations, the load at which a new pair of proximal ridge edges came in contact with the deformed cylinder was recorded. Figure 4 shows the observed number of ridge edges in contact (*Q*) with respect to non-dimensional pressure and ridge width, with a fixed value of normalized groove width. Because proximal ridge edge contacts can only take on even integer values, those are the points plotted in the figure. The minimum value of *Q* is 2 and thus there is no change in the value at low loads until the next set of proximal ridge edges (Q = 4) makes contact.

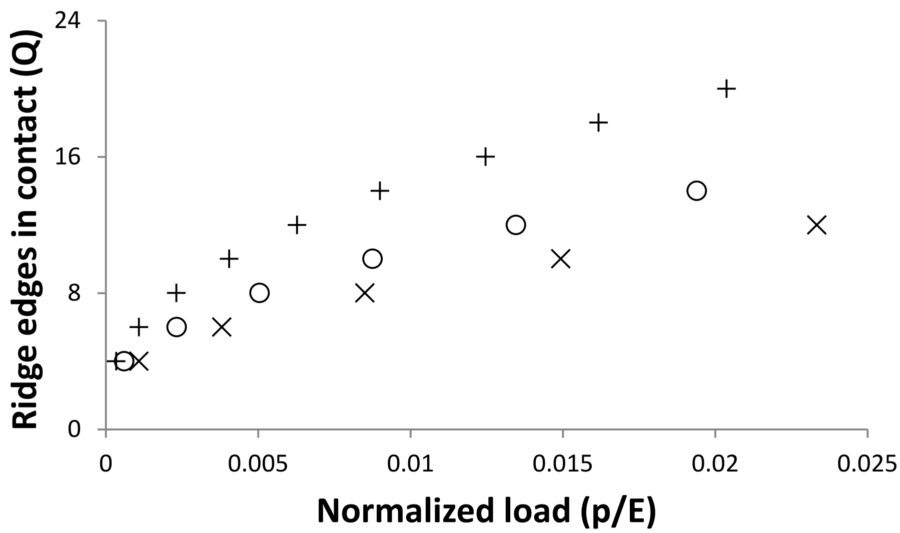

Figure 4. Number of proximal ridge edges in contact as a function of load, with *b/R* = 0.01 and *a/R* ranging from 0.032 (X), to 0.022 (O), and 0.012 (+). This plot is representative of the behavior of the other test combinations.

The results indicated that as pressure was increased, the cylinder exhibited two forms of deformation. The first type involved penetration of the soft body vertically into the grooves. This mechanism was described at length in a previous publication by the authors [17]. The second type of deformation was dominant and involved the mode of lateral spreading which is the concern of the Hertzian model. Initially, the unloaded cylinder was in contact with the proximal edges of the two innermost ridges. As pressure was increased, the cylinder deformed laterally along the top surfaces of these two ridges, however the proximal ridge count remained at 2 because no additional ridges had yet come into contact. With further increase in pressure, the limits of the contact zone eventually surpassed the distal edges of the innermost ridges (but still only two proximal edges in contact) as the soft body exhibited a limited amount of penetration in the grooves. At yet higher pressure, the cylinder eventually deformed laterally enough to reach the proximal edges of the next set of ridges at which Q became equal to 4 and the process continued anew across the new ridge tops. Thus, the number of proximal ridge edges in contact was always equal to the largest whole integer less than the ridge-based contact length (*Q'*). Consequently, the two parameters were identically equal at even integers. All combinations of ridge and groove width showed similar trends. Inspection of each data series suggested a relationship between loading and proximal ridge edge contacts that can be well modeled using the following form:

$$Q = 2 + K\left(p/E\right)^{1/2} \qquad (5)$$

Where K is a fit coefficient. Apply such a model to each combination of ridge and groove width produced a very high correlation for each series ($R^2 > 0.999$). It was thus hypothesized that K must be directly dependent upon the texture parameters, b/R and a/R.

The classic Hertzian model (4) takes a similar form to (5), however the former tended to over-predict the amount of load necessary to obtain contact with a chosen number of ridge edges. A likely reason for this is the fact that the Hertzian does not account for the fact that the central segment of the cylinder is never in direct contact with a ridge top because of the groove width, b. When the Hertzian contact distance described by (1) included an initial contact distance of b, the first term on the numerator of (4) vanishes yielding:

$$Q = 2\left\lfloor 1 + \frac{1.38}{a/R + b/R}\left(p/E\right)^{1/2} \right\rfloor \qquad (6)$$

This model also fits the data remarkably well ($R^2 = 0.999$) and will hereafter be referred to as the *Modified* Hertzian Model. Inspection of its form and comparison with (5) clearly shows the dependence of the coefficient K on the normalized ridge and groove widths. Interestingly, this relation indicates that the specific values of groove width and ridge width have a minimal effect on deformation. Rather, the model predicts that the number of proximal ridge edges in contact depends only on the sum of a/R and b/R, otherwise known as the pitch. Essentially, this further suggests that for the range of ridge parameters used in this study, cylinder penetration between ridges caused very little deviation from smooth surface behavior. The fact that this best fit model is nearly identical to the classic Hertzian model supports the use of the latter in haptic studies involving textured surfaces.

One type of behavior that was observed under unique circumstances was that the Hertzian model under-predicted the necessary load to initiate contact with 4 ridge edges at relatively small groove widths (b/R). Upon further examination of the computational solution process, it was discovered that this was due of the inherent error in the FEA simulation due to the size of the calculation increment. Because contact with four ridge edges required very little applied load, the simulation added more load than necessary to obtain the contact. However, the increment was small enough that it did not significantly impact the results for contact with six or more ridge edges at low *b/R* ratios.

3.2 Hybrid Model

While the Modified Hertzian model performed very well at all of the settings used in this investigation, its error did increase with larger groove widths (*b*) and narrower ridges (*a*). At the lowest *b/R* to *a/R* ratio, 0.01 and 0.032 respectively, the error of the modified model was between 1% and 2%, while at the highest *b/R* to *a/R* ratio, 0.03 and 0.012 respectively, the error climbed to between 3% and 5%. This can be attributed to a deviation from classic Hertzian contact as vertical penetration into the grooves became more pronounces. With a normalized groove width (*b/R*) much larger than normalized ridge width (*a/R*), (values of 0.09 and 0.012 respectively) the error in the model's predicted load of grew as high as 15% when compared to the FEA results. Thus, it was decided to consider an additional term in the model to address this issue. Because it was observed that ridge width had a greater impact on error than groove width, an additional term dependent on normalized ridge width (*a/R*) was added to the Modified Hertizan model to account for this effect. Using a least squares best-fit regression, the empirically modified model became

$$Q = 2\left[1 + \left\{\frac{1.348}{a/R + b/R} + \frac{0.01583}{a/R}\right\}\left(p/E\right)^{1/2}\right] \tag{7}$$

This is hereafter referred to as the *Hybrid* Model. There are two terms in the coefficient to the load. It is heavily influenced by the first term, which is effectively the normalized pitch of the texture. As the pitch increases, the number of ridge edges in contact decreases. The second term, which is only dependent on *a/R*, represents the resistance to deformation caused by the width of the ridges. In contrast to groove width, ridge width increases both the pitch and resistance to compression, thus having a more profound effect on limiting *Q*. Essentially, wider ridges serve two functions. Firstly, for a given pitch, they lead to more spacing between proximal ridge edges.

Secondly, because the ridge tops are wider they provide additional surface length in contact with the soft body. The predictions from the Hybrid Model were compared to that of the Modified Hertzian Model for all simulation settings. The Hybrid Model performed better than the Modified Hertzian Model at the lowest *b/R* to *a/R* ratio as shown by Figure 5. The parameter settings for the results shown in the figure are for a surface with relatively wide ridges and narrow grooves. It could be argued that this type of surface is most like a smooth flat surface of any of the parameter settings used in this study. In theory, this scenario is most similar to the straightforward Hertzian contact model for a cylinder on a plane. Therefore, this combination of parameters provided a good way to determine the impact of relatively narrow grooves on lateral deformation. The difference in performance among the three models can be ascertained from the figure. For moderate numbers of proximal ridge contacts, both the Modified Hertzian and the Hybrid models show considerable improvement over the Classic Hertzian model, with the Hybrid performing much better than the other two. However, the advantage of the Hybrid model seems to be most apparent at moderate numbers of ridge contacts, because the Modified Hertzian and Hybrid models perform similarly at higher numbers of contacts. The disparity between these two and the Classic model become especially large at higher numbers of contacts. Overall, the error of all models tended to decrease with larger numbers of ridge contacts.

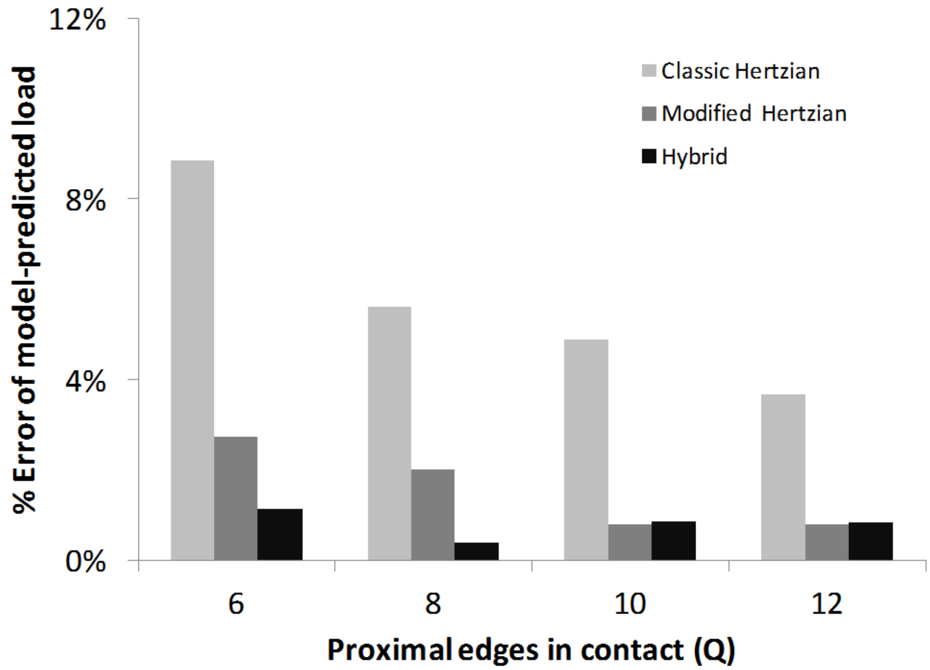

Figure 5. Percent error of model-predicted load for a specific number of proximal ridge edges in contact, for small groove width (*b*/*R*=0.01) and large ridge width (*a*/*R*=0.032). While the Classic and Modified Hertzian models performed well, they were outperformed by the Hybrid Model.

In contrast to a surface with wide ridges and narrow grooves, the results from a surface with very narrow ridges and wide grooves are illustrated in Figure 6. Qualitatively, this surface resembled a flat plane with numerous narrow spikes that made contact with the cylinder, similar to the surface illustrated in Figure 1. It was surmised that this type of surface would produce the greatest error for any of the models with respect to the pressure required to attain a chosen number of edge contacts. As the *b/R* to *a/R* ratio increased, the Hybrid model remained within 2% error while the Modified Hertzian model became less accurate. Furthermore, while the error of the Modified Hertzian model grew to 15% for the highest *b/R* to *a/R* ratio tested, the Hybrid model remained below 2% in error. Unlike the results shown in Figure 5, however, not all of the models showed a uniform decrease in error with greater numbers of edge contacts. The accuracy of the Classic Hertzian model improves but is never low enough to be acceptable. The Modified and Hybrid models have the highest error at 8 ridge contacts and then do a better job of prediction at larger numbers. It would have been useful to determine if this trend continued at higher numbers of ridge contacts, but a limitation of this study at large *b/R* values was that the finite element models had difficulty in converging at higher loads and thus the simulation results were not reliable. A future study that employs controlled displacement rather than controlled load may increase the likeliness of convergence.

Summarizing the performance of the model for all ridge and groove width combinations showed clearly that relatively simple contact models based on Hertzian assumptions do a reasonable job of predicting the number of potential interlocking ridge contacts; however, the addition of the ridge width term in the Hybrid model yielded a profound improvement in model accuracy across all parameter combinations.

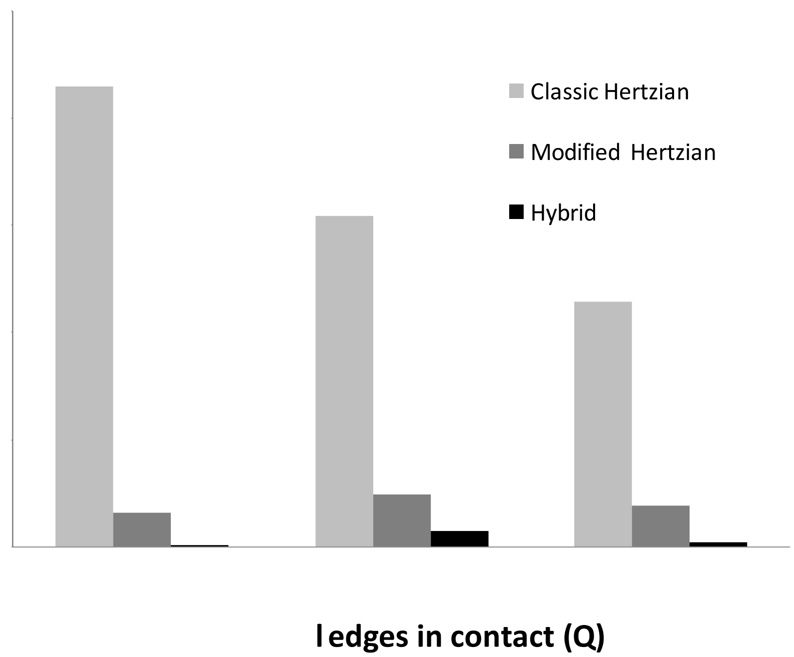

Figure 6. Percent error of required load for number of ridge edges in contact for large groove width (*b/R*=0.03) and small ridge width (*a/R* = 0.012). At these higher ratios of *b/R* to *a/R*, the Classic Hertzian prediction become extremely inaccurate. The Modified model is also challenged, but the Hybrid model remains highly accurate.

The effect of the groove width on the compression of the cylinder and theoretical contact distance was contrary to the authors' original expectations. It was hypothesized by the authors before this study that the presence of grooves would inhibit the lateral increase of contact length, because of the volume of the cylinder that would penetrate into the grooves would provide the necessary reaction force to support the applied load and thus a longer contact zone on the ridge tops would not be required. However, these results showed largely the opposite behavior. The presence of the grooves and the allowance for penetration resulted in a reduction in resistance to compression (i.e., larger accumulated contact length along the ridge tops). Contact length in the presence of grooves was greater than for a smooth surface because the grooves essentially lead to a vertical shift of the center of the cylinder superimposed on the elastic compression exhibited. Put another way, if the surface topology is imagined as a collection of asperities with a binary choice of heights – groove or ridge – then an average starting distance between the cylinder center and the surface can be calculated before loading. This average distance is greater than the distance between the ridge tops and the cylinder center and so there is some amount of downward vertical displacement of the cylinder center that is not accompanied by elastic deformation. This manifests itself as a larger contact length because more of the unloaded volume of the cylinder is engaged with the surface at all times during deformation, than if the surface had no grooves. This observed effect was more prominent for *b/R* values over 0.3, above which the Hertzian contact begins to greatly over predict the amount of load necessary to obtain contact with a certain number of ridge edges.

The Hybrid model was shown to be useful in predicting the number of proximal ridge edges in contact between a cylindrical elastomeric body loaded against a parallel ridge texture. Knowledge of the number of contact locations has many potential uses from determination of stresses to friction mechanisms encountered in tactile interaction with surfaces. As previously mentioned, interlocking has been shown to be a dominant component of friction with some textures of high surface roughness. Previous investigations have also shown that groove widths and pressure are linked to the perception of roughness. Therefore, the perception of roughness may be related to the number of interlocking surface features under a particular load. The Hybrid model presented here thus shows utility for use in the potential development of haptic applications employing textured surfaces.

4 Conclusions

The following conclusions have been drawn from the results of this study:

- The number of proximal ridge edges in contact with an elastomer cylinder is well modeled using standard Hertzian theory, when the cylinder is loaded against a parallel-rectangular-ridge texture and the ratio of ridge width is groove width is sufficiently large. However, the model exhibits considerable error when this ratio is small.

- A Modified Hertzian model, which takes into account the pitch of the texture ridges, greatly improved the accuracy of prediction of number of edge contacts for a given applied pressure. This model became less accurate as groove widths became large.
- A Hybrid model was developed which introduced empirical fit into the Modified Hertzian model as well as a term to include ridge width, exhibited excellent accuracy in predicting the number of edge contacts under load. The simple analytical form of the model lends itself to incorporation into potential frictional interlocking models for haptic applications.

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