A Tribometric Device for the Rolling Contact of Soft Elastomers

Brodie Hoyer (✉ brodie.hoyer@colorado.edu)

University of Colorado Boulder College of Engineering and Applied Science <https://orcid.org/0000-0001-7878-1458>

Rong Long

University of Colorado Boulder College of Engineering and Applied Science

Mark E. Rentschler

University of Colorado Boulder College of Engineering and Applied Science

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A Tribometric Device for the Rolling Contact of Soft Elastomers

Brodie K. Hoyer^{1*}, Rong Long¹ and Mark E. Rentschler¹

^{1*}Department of Mechanical Engineering, University of Colorado,
Boulder, CO 80309, United States.

*Corresponding author(s). E-mail(s): brodie.hoyer@colorado.edu;
Contributing authors: rong.long@colorado.edu;
mark.rentschler@colorado.edu;

Abstract

Rolling contact experimentation is a viable and instructive method for exploring the adhesive contact between surfaces. When applied to soft elastomeric or engineered surfaces, the results of such experiments can provide insights relevant to medical robotics, soft gripping applications, and reversible dry adhesives for bandages or wearable devices. We have designed and built a tribometric device to capture normal and tangential forces between a rolling indenter and substrate correlated with contact area imaging. The device was validated using an experimental setup involving a rigid, nominally smooth acrylic cylinder rolling against a flat polydimethylsiloxane (PDMS) substrate, the results of which matched favorably with accepted contact mechanics theories. The second test involved an indenter with a rigid core and thin (3 mm) smooth shell of a highly deformable, viscoelastic polyvinyl chloride (PVC) rolling on the same PDMS substrate. This test deviated significantly from analytical predictions, highlighting the effects of finite-thickness effects, viscoelasticity, and interfacial slip. This device will facilitate experimental investigations of the rolling contact mechanics between textured surfaces and soft tissue-like materials, which is an important fundamental problem in medical robotics.

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1 Introduction

With roots dating back over a century, contact mechanics remains a dynamic field of study with practical and theoretical relevance to myriad engineering applications. As modern contact theories more effectively incorporate complex surface geometries, interactions, and material properties, they are better able to predict and explain interactions ranging from nano- to macroscopic length scales. This predictive ability has been applied successfully to modeling and design efforts in fields as disparate as biological locomotion [1], microelectromechanical systems [2], medical robotics [3], and automotive design [4].

The modern treatment of contact mechanics began with Hertz' analytical solution for the contact of spherical bodies [5]. Building upon Hertz theory, several independent contact theories were developed to incorporate adhesion [6–9]. The theory of Johnson, Kendall, and Roberts captures the effect of adhesion by following a fracture mechanics approach and gained further relevance with the application of cohesive zone models [10–14] which regulate the stress singularity at the contact edge, making adhesion computationally tractable for finite element methods and opening the field to the investigation of almost any arbitrary geometry.

Recent advancements in adhesive contact theories have focused on surface texture and novel materials. Surface texture, in most general terms, includes inherent roughness [4, 15–18] and engineered surfaces [19–21]. Regarding the materials, recent interests in friction, wear, and adhesion of materials with moduli in the sub- to single-MPa range has led to an emerging field known as soft tribology [22]. In addition to large deformation, these materials also tend to show high rate-dependency, either through visco- or poroelasticity, and may respond differently to surface texture due to their inherent deformability.

Because of their relevance to biological tissue, advances in soft tribology can contribute to advances in the design of medical robotics, reversible adhesives for bandages and wearable devices, and soft grippers.

Soft materials pose several challenges for investigations on frictional or adhesive contact. In the case of indentation experiments, the high deformability of soft materials implies that material or geometrical nonlinearity may prevail even under relatively low force, which is beyond the regime of applicability of analytical contact theories. In the case of peel experiments, soft materials are often difficult to be gripped firmly and often must be affixed to an inextensible backing layer to ensure the measured extension reflects only the interface crack progression and not the stretch of the material itself.

A particularly relevant contact mode in medical robotics is rolling contact [3, 23] (Figure 1b), in which a cylindrical roller is brought into contact with a deformable substrate and translated across, either by means of a tangential drawbar force or imposed torque. If the indenter and substrate are stiff, it is sufficient to describe the kinetics of rolling in terms of a frictional force imposed at a small contact area or even a point. In soft materials, however, adhesion contributes significantly to both contact area and forces. By measuring the forces and contact area during rolling contact, the adhesive properties of surfaces can thus be characterized. In particular, Kendall's rolling contact theory suggests that the separation of surfaces at the trailing edge of contact is analogous to a peel experiment [24]. In this way, rolling contact experiments provide many advantages over peel experiments in that the soft material can be affixed to either the roller or base to prevent extension, preload force or displacement can be easily controlled, and imaging of the contact area is comparatively simple provided that one material is optically clear or translucent. Additionally, in the case of engineered surfaces, rolling contact experiments allow the

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study of surfaces with directional anisotropy that would be indistinguishable in indentation and retraction experiments [25].

Fig. 1 Schematic representations of (a) the tribometer and (b) adhesive rolling contact. (a) The functional subsystems of the tribometer include: (1) positioning control comprised of (1a) velocity controlled horizontal stage and (1b) fixed indentation vertical stage, (2a) normal force sensors and (2b) free rolling indenter, (3) frictionless stage for the substrate mount and tangential force sensing, and (4) camera. (b) In adhesive rolling contact, the leading and trailing edges of contact act as crack fronts. Because the work of adhesion is typically higher for separation, the contact area is pulled towards the trailing edge by distance d . Rolling contact geometry is defined in terms of the indenter radius R , contact half-width b , and off-center distance d

Foundational studies on soft rolling contact focused on soft-to-rigid contact, with either a rigid cylinder rolling on a rubber surface [26] or a rubber-coated cylinder rolling on a rigid surface [27]. Recently, tribometric studies have been conducted for rolling of a periodically-structured indenter on a rigid surface [28] as well as a micropatterned wheel with imposed slip rate rolling on a viscoelastic substrate [3]. In this work, we have chosen to investigate the rolling contact of a finite-thickness, highly deformable, and viscoelastic elastomer. To do so, we designed and built a benchtop tribometric device (Figure 1a and Figure 2) capable of collecting relevant forces and contact area images in real time, and validated that device against comparatively rate-independent elastomer such that the results could be compared with analytical solutions. Section 2 presents a brief theoretical background for adhesive rolling contact mechanics. Section 3 details design of the device and experimental test setup. Section

4 presents results from the two experimental test configurations. Finally, the conclusions of this work are presented in Section 5.

Fig. 2 As-built picture of the tribometer with major components (1) horizontal stage, (2) vertical stage, (3) frictionless air bearings, (4) Motor and lead screw, (5) tangential force load cells, (6) substrate mount, and (Inset) normal force plate with (7) normal force load cells and (8) rolling indenter

2 Theory

As stated in the introduction, formalized contact theory begins with Hertz, who observed that when two elliptical bodies (i.e., smooth bodies whose surface profiles could be described analytically as ellipses with two characteristic axes) were brought into contact, a finite and similarly elliptical contact area was formed [29]. Under the simplifying assumptions that the contact area was significantly smaller than the characteristic lengths of the bodies, that no adhesion was present between the bodies, and that the surface interface was frictionless, Hertz developed an analytical solution relating surface tractions and stress distributions to the imposed deformations, ultimately relating compressive force to the dimensions of the contact area. The geometric case of Hertz theory relevant to rolling contact is that of cylindrical contact, in which

one principal curvature of each body is zero. This is achieved practically by compressing two cylinders aligned axially or compressing a cylinder against a flat substrate. The subsequent Hertz relationship for this type of contact is [29]

$$P = \frac{\pi E^* b^2}{4R}, \quad (1)$$

in which P represents the normal load per unit length, b is the contact half-width, R is the radius of the cylinder, and E^* represents the plane-strain modulus $E^* = E/(1 - \nu^2)$, with E and ν representing Young's Modulus and Poisson's ratio respectively.

Because Hertz Theory assumes only compressive tractions within the contact area, it tends to underestimate the observed contact length for a given compressive force, and is unable to account for the pull-off force due to adhesion. To account for adhesion, Johnson, Kendall, and Roberts (JKR) developed a contact theory in which attractive tensile tractions cause additional surface deformation, extending the contact length [7]. JKR uses an adhesive contact solution based on the minimization of total energy comprised of elastic energy due to material deformation and surface energy due to adhesion. The relevant JKR relationship for cylindrical contact is [30, 31]

$$P = \frac{\pi E^* b^2}{4R} - \sqrt{2\pi E^* b w}, \quad (2)$$

with w representing either the work of adhesion for bodies being brought into contact or work of separation for bodies being separated.

The equations developed above are based on indentation and retraction, with contact characterized by two crack fronts, equidistant from the center of the indenter, opening or closing with equal work of adhesion. Rolling contact,

by contrast, involves a crack closing at the leading edge of contact and a crack opening at the trailing edge (Figure 1b). Because the work of adhesion during separation is typically much larger than for indentation in most materials [32, 33], the contact area will tend to lengthen towards the trailing edge and shorten at the leading edge. For such asymmetric contact, the normal surface traction within the contact area is [26]

$$\sigma(r) = \frac{-P/\pi + (E^*/2R)(r^2 - rd - b^2/2)}{(b^2 - r^2)^{1/2}}, \quad (3)$$

with d representing tangential distance from the center of the indenter to the center of the contact area (Figure 1b) and r representing the distance of a point from the center of contact. Because the work of adhesion and separation are not equal, the crack tips must be evaluated independently. Using the leading edge of contact as an example, it is necessary to first solve for the Mode-I stress intensity factor [33]

$$K_{I,lead} = \lim_{r \rightarrow b} \sigma(r)[2\pi(b - r)]^{1/2}. \quad (4)$$

Because the crack tip is in equilibrium, the stress intensity factor can be related to the strain energy release rate G and work of adhesion as

$$w_{adh} = G = K_{I,lead}^2/2E^*. \quad (5)$$

By solving the two equations above and relating the the torque on the indenter to the contact asymmetry through the integral of the surface traction, the resulting relationship is [33, 34]

$$P = \frac{\pi E^* b^2}{4R} - \sqrt{2\pi E^* b w_{adh}} - \frac{\pi E^* b d}{2R}, \quad (6)$$

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with F representing the tractive force on the indenter. In a similar fashion, the work of separation at the trail edge is equal to

$$P = \frac{\pi E^* b^2}{4R} - \sqrt{2\pi E^* b w_{sep}} + \frac{\pi E^* b d}{2R}. \quad (7)$$

Additionally, by considering the equilibrium of forces acting on the indenter, a relation between the external forces and characteristic lengths of contact can be derived [26]:

$$P = \frac{\pi E^* b^2}{4R} - \frac{FR}{d} \quad (8)$$

Using Equations 6, 7, and 8, we can derive an expression for the difference between the work of separation and work of adhesion:

$$w_{sep} - w_{adh} = F \quad (9)$$

which is in agreement with Kendall's theory [24].

3 Material and Methods

3.1 Tribometer Design

This section will outline the key physical and electrical systems of the tribometer, as well as data synchronization, collection, and processing.

3.1.1 Motion Control

The tribometer (shown schematically in Figure 1a and as-built in Figure 2) is a 3-Degree-of-Freedom (DOF) system. Constant vertical displacement (indentation) is achieved with a vertical positioning stage (THORLABS MVS-005) actuated via a dial micrometer with 0.001" gradation. Horizontal translation takes place via a sliding stage (THORLABS PT101) actuated by a DC Servo

Motor and lead screw combination (THORLABS PT1-Z8R). The translational velocity is PID-controlled using a motor controller (THORLABS KDC101), with the velocity set by the user via a MATLAB Graphical User Interface (GUI). The third degree of freedom is the unconstrained rotation of the rolling indenter.

3.1.2 Normal Force Sensing and Rolling Indenter

Fixed atop the vertical stage is a machined force plate (Inset, Figure 2) designed to provide adequate clearance for four 500 g Load Cells (Sparkfun TAL221). The displacement of the four load cells is coupled by a rigid aluminum plate, which also serves as a mounting platform for the rolling indenter. The rolling indenter is mounted above the aluminum platform by two high-precision roller bearings. The experimental configuration can be easily switched from position- to force-control by replacing the fixed indenter housing with a fulcrum-mounted housing. The current device configuration can accommodate indenters up to 35 mm in length and 25 mm in diameter.

3.1.3 Force Isolation and Tangential Force Sensing

A key design consideration for this system was the elimination of spurious strains in the tangential load cells due to axial loading from the normal force. To achieve this end, the substrate is affixed below a rigid acrylic plate which travels on two horizontal rails by means of frictionless air bearings (NewWay S301201). The air bearings serve two purposes: they prevent the transfer of normal loads to the tangential load cells and eliminate friction which would negatively impact the tractive force readings.

There are four thin-beam load cells (Omega LCL-113G, 100 g capacity) affixed to the sliding plate assembly, two on each side. The opposing ends of the load cells are affixed rigidly to the tribometer frame. Thus, any tangential

translation of the sliding plate is conferred to bending moments in the load cells, correlating to tangential force on the substrate.

3.1.4 Contact Area Imaging

A key characteristic of adhesive cylindrical contact is the width of the contact area formed between the two solids. An HD camera (ArduCam B0280, 12MP) is mounted above the substrate window to collect real-time images of the contact for each experiment.

3.1.5 Data Collection and Synchronization

The load cell signal processing flow described in this paragraph (shown schematically in Figure 3a) is identical for both directions, normal and tangential. Unless stated specifically, the following description applies to both channels. From the measurement base, each of the four load cells emits a voltage signal proportional to the strain to which it is subjected. These four signals are then combined through a passive averaging circuit in a junction box (ANYLOAD J04-SA). The output signal from the junction box, still in the millivolt range, passes to a Signal Conditioner/Amplifier (Tacuna Systems EMBSGB200) with a two-stage low-pass filter and selectable gain amplifier. The amplified signal is then passed to a DAQ (National Instruments myDAQ). Each DAQ Channel has 16-bit resolution, resulting in maximum force resolution of 0.78 mN for normal force and 0.027 mN for tangential force (based on load cell signal range and amplification).

Overall data collection and synchronization is conducted by a MATLAB script. Based on user inputs regarding test velocity and direction of travel, test length, and number of test iterations, the MATLAB script will run the test protocol and collect the data. The data collected for each test iteration includes the time and channel voltages from the DAQ, which are subsequently

Fig. 3 (a) Schematic of the data flow for the tribometer: for each force direction, voltage data from four load cells is combined in a summing junction and the single signal is filtered and amplified before passing to the DAQ. The digital signal is then converted to a force and stored via a MATLAB GUI. Examples of filtered data for multiple test iterations of a nominal indentation depth and translational velocity: (b) tractive force and (c) normal force. (d) Images of the contact area workflow: raw images are flattened and contrast-adjusted to heighten the contact area, and the lead and trail edges are delineated in order to determine the mean contact width.

converted to force measurements, video and timestamps for each frame capture from the camera, and position data from the motor controller.

3.2 Data Processing

For each test iteration, the normal and tractive data is smoothed using a moving mean filter with a window equivalent to 0.05 seconds. The data is then truncated to represent only the equilibrium portion of the rolling contact. Based on experimental observation, and to remain consistent, this is defined as the range 60-95% of overall execution time. From this data, mean values of tractive and normal forces are calculated.

Next, a representative sample of video frames captured during the equilibrium time bounds are randomly selected to be processed. Each frame is flattened based on calibration data specific to the camera, lens, camera resolution and zoom, and contrast adjusted to accentuate the limits of the contact

area (Figure 3d). The lead and trail edges are then identified and a mean contact width is measured. The associated timestamp of the frame capture is used to determine the indenter's center of rotation, as well as the instantaneous normal and tractive forces corresponding to the contact width.

3.3 Experimental Test Cases

We conducted two separate experiments. The first, intended for device validation, involved a rigid acrylic indenter rolling along a flat, comparatively rigid elastomer substrate, which could be readily compared to JKR contact theories and experimental results from previous studies. The second, designed for testing the contact with tissue-like materials, used an indenter comprised of a thin shell of a highly-deformable, viscoelastic elastomer affixed to a rigid core rolling along the same substrate.

3.3.1 Device Validation

When dealing with highly deformable materials, there is a potential for interfacial slip, even at low loads. To minimize the likelihood of slip, the device validation test case involved the indentation and rolling of a rigid, nominally-smooth acrylic cylinder, radius 9.5 mm and length 28.6 mm along a nominally flat silicone substrate of polydimethylsiloxane (PDMS) (Dow Corning Sylgard 184 at 10:1 base/curing agent ratio by weight) of dimensions 31.8 mm W x 50.8 mm L x 3.2 mm D. Based on extension tests conducted using an Material Testing System (Instron Corp., Norwood, MA), PDMS can be modeled as an incompressible hyperelastic material with a Young's modulus E of 2.9 MPa. Because of the comparative rigidity of the indenter and substrate, a force-controlled experiment was conducted to minimize the effects of indenter or substrate irregularities. Four normal force values of 3.22, 9.34, 19.54, and 23.62 mN were imposed on the indenter by means of a counterweight. Because the

equations by which we were to validate our data are based on the assumption of elastic materials, the validation experiments were conducted quasi-statically, at a translational velocity of 0.06 mm/s. Relevant results from this test case are presented in Figure 4.

3.3.2 Tissue-Like Test Case

For the tissue-like test case, the rigid indenter was replaced with an indenter comprised of a rigid acrylic cylindrical core (radius 6 mm) with a 3 mm-thick smooth outer layer of poly(vinyl chloride) (PVC) (M-F Manufacturing Co, Fort Worth, TX), thermally bonded to the acrylic core. Previous studies on this material determined that it could be modeled using a Standard Linear Solid (SLS) viscoelastic material with $E_1 = 16.4$ kPa, $E_2 = 0.467$ kPa, and $\eta = 20.3$ kPa-s [3, 35]. Using a PVC outer layer on the rolling indenter provided the opportunity to investigate the effects of both viscoelasticity and finite-thickness effects. The more rigid material (PDMS) was selected as the substrate because it is optically clear and could be molded to a more reliably flat surface. Because the PVC is highly deformable, a displacement-controlled experiment was used to better control contact width. Three relative indentations¹ of 0.902 mm, 1.02 mm, and 1.12 mm were used. Additionally, the indenter was subjected to a range of translational velocities from 0.06 mm/s to 1.0 mm/s in order to observe viscoelastic effects from the PVC. Relevant results from the this test case are presented in Figure 6.

¹Because of the difficulty of establishing a zero point of indentation for adhesive cylindrical contact, values are relative to a zero point at which a defined contact area was no longer observed across the extent of the indenter.

4 Results and Discussion

4.1 Device Validation

The analytical solutions outlined in Section 2 are based on the assumption that surface tractions are only in the normal direction. Therefore, the materials in the device validation case were chosen such that interfacial slip was minimal, ensuring that the measured tractive force was due primarily to the disparity between adhesive interaction at the leading and trailing edge, unaffected by friction.

Using the measured values of normal force P (N/mm), contact half-width b (mm), and contact asymmetry d (mm), along with a Young's modulus of 2.9 MPa and a Poisson's ratio of 0.5, the expected values for work of adhesion and work of separation were calculated using Equations 6 and 7 respectively. The difference between the values was compared to the measured tractive force as per Equation 9. The results are shown in Figure 4a, with the blue circles representing the measured values of tractive force and purple triangles representing the theoretical values. The blue dashed line and shaded area represent the mean and standard deviation of the measured tractive force. Both the experimental and measured values agree, within an order of magnitude, to those observed by Barquins and Charmet at similar velocities [26]. It is also notable that both the measured value of tractive force and analytical value of the difference between the work of separation and adhesion, remain independent of the normal force as would be expected if adhesion were the relevant predictor of contact forces.

To validate the normal force measurements, the measured tractive force F (N/mm), contact half-width b (mm), and contact asymmetry d (mm), along with Young's modulus and Poisson's ratio from above, were used in Equation 8 to calculate the expected normal force. The results, shown in Figure 4b, show

good agreement between experimental and theoretical values. The Hertzian component of normal force, that which would be expected in the absence of adhesion, is also shown (yellow squares) to highlight the prevalence of adhesion between the indenter and substrate. In particular, the Hertz contact force (i.e., adhesionless) required to achieve a given contact half-width is much larger than the measured normal force, thereby highlighting the the strong effects of adhesion in our experimental system.

Fig. 4 Experimental results from the Rigid Acrylic Indenter with PDMS Substrate. (a) tractive force versus normal force: blue circles represent the experimentally measured values, with the blue dashed line and shaded area representing the mean and standard deviation thereof, while purple triangles represent the expected values from Equation 9; red diamonds and yellow squares indicate expected values of work of separation and adhesion respectively as per Equations 6 and 7. Good agreement is found between the measured and theoretical values, and work of separation is consistently higher than work of adhesion, as is predicted. (b) Normal force versus contact width, showing good agreement between measured values (blue diamonds) and theoretical (red circles) as per Equation 8. The normal force prediction absent adhesive interactions (Hertzian – yellow squares) is included to highlight the prevalence of adhesive forces in this experimental configuration.

4.2 Tissue-Like Elastomer

The first observed difference between the validation case and the tissue-like PVC is the relation between normal force and contact half-width (Figure 6a). In contrast to Fig.4b, with the PVC layer, the normal force required to achieve

a given contact half-width is much larger than that predicted by the Hertz solution. This is due to the fact that the PVC is a thin layer (3mm) adhered to a rigid acrylic core. As described by Shull [36] and expounded on in later work for curved spherical shells [37], contact deviates from Hertzian predictions when the relevant contact length grows proportionally closer to the depth of the substrate because the material can no longer be accurately modeled as a half-space, and correction factors must be applied. The experimental results were thus compared to a numerical model. A two-dimensional plane strain model of the indenter and substrate geometries was built using ABAQUS (Dassault Systemes Americas Corp, Waltham, MA), with each material modeled using incompressible, Neo-Hookean hyperelastic materials. The modulus of the PVC was tuned to best match the experimental data resulting in a predicted modulus of 21 kPa, which closely matches the expected value for the material, again considering that the experimental data is taken from the equilibrium rolling portion of the test. A comparison of the Hertz prediction, numerical model, and experimental results is shown in Figure 5.

Fig. 5 A comparison of the relationship between contact half-width and normal force. As shown, when the half-width approaches and exceeds the thickness of the deformable layer on the wheel (3 mm), there is significant deviation from the contact predicted by Hertz (dashed blue line). The FEM simulation results (solid red line) match much more closely to the experimental results (squares).

Because of the viscoelasticity of the PVC, the relations between contact half-width and normal force with relative indentation were affected by translational velocity. Relating normal force P to relative indentation $\hat{\delta}$ (Figure 6b), the relational exponents ($P = k\hat{\delta}^n$) ranged from 1.796 to 2.948. The relational exponents for contact half-width b to relative indentation ($b = k\hat{\delta}^n$) were similarly varied (Figure 6c), ranging from 0.160 to 0.516. This further illustrates the need to consider both finite-thickness effects and viscoelasticity in similar test configurations.

The intricate coupling between the finite thickness effect and viscoelasticity is further reflected in Figure 6d, where the contact width is plotted as a function of the tangential velocity at three different indentation depths. The different scaling exponents between contact width and velocity (i.e., 0.05, 0.04, and 0.02 for shallow, intermediate and deep indentations, respectively) shows that the finite thickness effect can reduce the rate-dependence of contact width by increasing the contact stiffness (Figure 5). In contrast, the tractive force exhibits a remarkably consistent scaling relation with the velocity at a mean exponent n of 0.316 ± 0.01 for all three indentation depths (Figure 6e). This can be understood by recognizing that a majority of the energy is dissipated as viscoelastic losses locally at the leading and trailing edge cracks. Such viscoelastic losses can be merged into the work of adhesion w_{adh} and work of separation w_{sep} , leading to increases in these two values. Under this physical picture, w_{adh} and w_{sep} are functions of the respective crack tip velocity and should be interpreted as the effective work of adhesion and separation. Since the data is collected during steady state rolling such that crack tip velocity matches the tangential velocity, it is expected that Kendall's steady state argument still holds, which implies that Equation 9 is valid and hence the tractive force solely depends on the tangential velocity regardless of the contact

width. This feature allows one to decouple the tractive force from the complex viscoelastic contact mechanics and use it as a reliable measurement for the adhesion between the tissue-like material and the PDMS substrate.

Fig. 6 Experimental results from PDMS/PVC experiment: **(a)** contact half-width versus normal force; **(b)** normal force versus relative indentation; and **(c)** contact half-width versus relative indentation. Although best fit lines are shown (dashed lines), they were not found to match with conventional contact theories due to the need for finite-thickness correction as the contact half-width approaches the thicknesses for the indenter geometry. The PVC showed substantially more rate-dependence for **(d)** contact half-width, increasing at a power n of 0.4, 0.5, and 0.2 for the shallow, intermediate, and deep indentations respectively; and **(e)** tractive force with a mean power n of 0.316 across all three indentations.

5 Conclusion

Rolling contact remains an interesting and instructive means of exploring the adhesive interaction of natural and synthetic materials, whether nominally smooth, intrinsically rough, or with engineered features. We have described the design and realization of a 3-DOF rolling contact tribometer and presented the experimental results of two test cases: a validation test case involving a rigid acrylic indenter and rate-independent silicone elastomer (PDMS), and a

tissue-mimic case involving a finite-thickness viscoelastic (PVC) shell indenter rolling across the same PDMS substrate.

The validation test case was chosen since it has been extensively studied in the literature. As a rigid indenter rolling on a smooth elastomeric surface, it presented the simplest means to validate the data output from the device against established contact mechanics theories. The strong correlation between experimental and theoretical values provides confidence in the device itself.

The tissue-like test case, chosen for its novelty, highlights several interrelated aspects of soft tribology. First, the effects of finite-thickness materials was shown through the deviation of compressive behavior from analytical predictions. Second, the contribution of viscoelasticity is shown through the reliance of tractive force on crack-tip velocity at the trailing edge. Although no analytical or empirical models are presented, the data can serve as a relevant input for modeling applications involving the adhesion of PDMS with tissue or tissue-like substrates. In particular, our data demonstrate that the tractive force can provide a reliable measurement of the rate-dependent $w_{sep} - w_{adh}$ (or w_{sep} if w_{adh} is much smaller than w_{sep}), despite the intricate viscoelastic contact mechanics involved.

Declarations

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Competing Interests

Brodie Hoyer and Rong Long declare that they have no financial interests. Mark Rentschler is a co-founder of Aspero Medical, Inc., a start-up company that is focused on commercializing balloon overtube products for use in enteroscopy.

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