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Imaging the 3-D Deformation of the Finger Pad When Interacting with Compliant Materials

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Abstract

We need to understand the physics of how the skin of the finger pad deforms, and their tie to perception, to accurately reproduce a sense of compliance, or ‘softness,’ in tactile displays. Contact interactions with compliant materials are distinct from those with rigid surfaces where the skin flattens completely. To capture unique patterns in skin deformation over a range of compliances, we developed a stereo imaging technique to visualize the skin through optically clear stimuli. Accompanying algorithms serve to locate and track points marked with ink on the skin, correct for light refraction through stimuli, and estimate aspects of contact between skin and stimulus surfaces. The method achieves a 3-D spatial resolution of 60-120 microns and temporal resolution of 30 frames per second. With human subjects, we measured the skin’s deformation over a range of compliances (61-266 kPa), displacements (0-4 mm), and velocities (1- 15 mm/s). The results indicate that the method can differentiate patterns of skin deformation between compliances, as defined by metrics including surface penetration depth, retention of geometric shape, and force per gross contact area. Observations of biomechanical cues of this sort are key to understanding the perceptual encoding of compliance.

I. Introduction

To replicate the feel of the hand of another, or of tissue in medical exams and procedures, touch interactive devices will need to relay a sense of compliance, or ‘softness.’ As of yet, such devices have not sufficiently replicated our everyday experiences with natural objects [1–4]. To increase their realism, we need to more closely examine the physics at the contact interaction between compliant stimuli and the bare finger. Biomechanical cues derived from the three-dimensional deformation of the skin – the distribution of surface pressure over the time course of an indentation – provide input vital to perceptual encoding [3, 5, 6].

As of now, however, instead of observing the skin’s deformation in a detailed way, most techniques measure more reductive, bulk compressive characteristics. These metrics include net force due to contact, displacement of the stimulus, and gross contact area measured indirectly. For example, the net force delivered to the finger is typically measured by a load cell affixed to the stimulus [2, 7–9], which does not account for the spatial distribution of pressure across the finger pad’s surface. Likewise, metrics of gross contact area – which are

not usually informed directly but estimated using either a rigid body resembling the finger [2, 10] or models of Hertzian contact [6] – generally omit the geometric shape and curvature of finger pad’s surface as well as micro-scale contact interactions [11]. Others have tracked beads or markers positioned within silicone-elastomer substrates, rather than at the finger pad surface itself, in order to back out the pressures distributed across their surface [12, 13].

In contrast, for the case of contacting rigid plates the skin’s deformation has been studied more often and in higher fidelity. For example, regions of skin movement and stretch have been measured during slip against a glass plate, at the level of resolving individual finger print lines and sweat ducts. In one case, the geometrical asymmetry of the contact region was found to be a potential cue for perceiving the direction of the moving stimulus [14]. Others have examined micro-scale contact within the gross contact region to better understand friction and grip [11, 15, 16]. Similarly, stress distributions across the skin surface have been measured by employing PDMS membranes overtop of a glass plate [17]. These efforts typically employ single-camera video imaging techniques, such as frustrated total internal reflection (FTIR) [11, 18]. Although such techniques ideally apply for compliant interactions as well, a constraint of single-camera imaging is that the measurement surface lies flat in a consistent imaging plane, which is problematic for highly compliant stimuli.

As an intermediate step between measures of bulk compressive characteristics and imaging techniques constrained by interactions with rigid bodies, our group previously developed a way to measure the flattened geometric shape and size of the contact region [8]. Ink marked on the stimulus surface was deposited on the skin after an indentation and imaged to generate stimulus- and indentation depth- specific contact areas. While this method directly measures the skin’s surface, the caveat is that resultant contact area is only captured for the peak indentation depth, ignoring the skin’s temporal dynamics. Furthermore, the contact area measured is a single “flattened” value, ignoring the 3-D shape and curvature of finger pad within the contact region.

In summary, to directly observe the finger pad skin in its interaction with compliant stimuli, an approach is required that can continuously measure its deformation in three dimensions as it presses into the stimulus. To address this gap, we developed a stereo imaging technique to visualize through optically clear, compliant stimuli. Over a range of stimulus compliances, this technique can differentiate spatial and temporal patterns in skin deformation.

II. Methods

In this work, we developed a stereo imaging technique to visualize the deformation of the skin surface in interacting with compliant stimuli. We validated its measurement capability against a rigid cylinder of known geometry, and tested its spatial and temporal capabilities with human subjects. In particular, first, a hardware apparatus positions a pair of cameras to image through optically clear silicone-elastomer substrates. Second, computer vision algorithms assist in point co-location, correct for distortion caused by imaging through silicone-elastomer, and estimate aspects of contact between finger pad and stimulus. Then,

to validate the accuracy of the measurements and distortion corrections, we indented into a rigid cylinder over a range of compliances and indentation depths. Finally, with human subjects, we measured the deformation of the skin surface over a range of compliances, displacements, and velocities. In attempting to differentiate patterns of spatial deformation between compliances, we defined new metrics including surface penetration depth, retention of geometric shape, and force per gross contact area.

A. Apparatus Setup

The elements of the apparatus tied to visual observation consisted of a 3-D printed fixture attached via a load cell (LCFD-5, Omegadyne, Sunbury, OH) to a cantilever of a vertically-moving indenter (ILS-100 MVTP, Newport, Irvine, CA). The load cell recorded force at approximately 150 Hz, with a resolution of ± 0.05 N. At the top of the fixture was space for two cameras facing downwards. At the bottom of the fixture was space for a disk of silicone-elastomer. The fixture was designed such that both cameras had an unobstructed, perpendicularly oriented views of the back of the disk (Figure 1). Two webcams (Papalook PA150, Shenzhen Aoni Electronic Industry Co., Guangdong, China) were used in a parallel, coaxial stereo configuration, spaced 30 mm center-to-center. Their maximum resolution is 1280×720 pixels at 30 frames per second, and they can maintain a manual focus.

B. Stimuli

The stimuli were constructed from Cell Guard Solar Cell Encapsulation (ML Solar LLC, Campbell, CA) and poured into 60 mm diameter by 15 mm tall polystyrene petri dishes in varied mix ratios with Silicone oil V50 (Modulor, Berlin, Germany) to create three compliances (61, 126, and 266 kPa). These modulus values are referred to as “soft,” “medium,” and “hard,” respectively, and approximately span a range softer and harder than human skin, which ranges from 42–130 kPa [19, 20]. Elastic moduli were measured via unconstrained, uniaxial compression of a plate into cylindrical punches of the substrates 10 mm tall by 10 mm diameter. As this material is perfectly transparent, the cameras were able to image through each stimulus. Note that while Cell Guard is advertised as being similar to Sylgard 184 (Dow Corning, Midland, MI), we have found their moduli to be distinct.

C. 3-D Surface Reconstruction Algorithms and Procedures

The Computer Vision System Toolbox of MATLAB 2017a (Mathworks Inc., Natick, MA) was used for stereo camera calibration, image correction, and 3-D scene reconstruction. For point co-location, we used two different methods:

Checkerboard Method: With this approach, the finger pad was first marked with ink in a checkerboard pattern, using a 3-D printed stamp with boxes of 1.75 by 1.75 mm. The stamp was pressed into blue ink and then rolled onto the finger pad of the distal digit of the index finger, typically marking 100–150 boxes. A custom checkerboard detection algorithm was created to identify the checkerboard corners in the left and right images (Figure 2, A-C). The use of these checkerboard points sought to avoid inconsistencies and ambiguities that might arise from a feature-matching algorithm. Furthermore, consistent points on the skin’s surface from image-to-image affords the examination of skin stretch and related cues such as

friction in the future. On the other hand, however, this method's spatial resolution is rather low, triangulating only about 100–150 points on the finger pad.

Disparity-Mapping Method: With this approach, the *disparity()* image correlation function included in the MATLAB Computer Vision System Toolbox co-located points by identifying similar pixel brightness values between left and right images (Figure 2, D-F). This method afforded much higher spatial resolution than the checkerboard method, with 70 to 90 thousand points on the finger pad (at a spatial resolution of about 60–120 microns per pixel), but does not readily afford the tracking of a specific point on the finger pad from image-to-image.

One issue we encountered was the bleaching of the natural color of the finger pad as it pressed into the stimulus with greater force, making brightness values too uniform for feature extraction. Given this situation, we used the end of a stiff-bristled paintbrush to mark the finger pad with discrete points of blue ink in order to maximize spatial resolution. The numerous ink spots on the finger pad greatly increased the feature matching efficacy for point co-location (Figure 2D).

D. Corrections to Image through Transparent Stimuli

Introducing the transparent stimuli between the stereo cameras and target objects caused those objects to be magnified slightly by about 4%, due to the refraction of light through the material. This can be seen in Figure 3, in which a grid pattern was positioned approximately 87 mm below the stereo cameras (7 mm below the stimulus). One can compare the position of the grid points with and without a stimulus in the optical path. In particular, two single-camera images of the grid pattern are shown, one “no stimulus” image without a stimulus between the camera and grid pattern and one “uncorrected” image with a stimulus in-between. Grid points were identified in both the “no stimulus” and “uncorrected” images by a grayscale threshold, and matched to the corresponding grid point in the other image by smallest Euclidean distance. As can be seen visually in Figure 3B, points near the left and center of the camera view were relatively unaffected, while points near the right edge of the camera view were more heavily distorted.

This error was greatly decreased through the introduction of experimentally-determined image corrections. In particular, first, we calculated the Euclidean distance between each pair of matched pixels from “no stimulus” to “uncorrected” images. Next, a cone was fit to these distances which located the epicenter and magnitude of the distortion. Finally, a scaling transformation based on this cone was applied to the “uncorrected” image to fix the distortion. The entire process was repeated for both left and right cameras and across all compliances to create a library of correction transformations. In experiments using transparent compliances, images were always corrected by these transformations before performing 3-D reconstruction.

It is worthwhile to note that the magnification effect changes slightly as the finger pad compresses the stimulus to some fraction of its original thickness. This is an unavoidable shortcoming of imaging through the compliant material. However, we found this change to

negligibly effect our measurements until the material was compressed by about 3 mm, as is further detailed in Experiment 1.

E. Contact Area Measurement Procedure

From the reconstructed 3-D surfaces, we created a procedure to estimate the gross contact area. This procedure first required a preparation step with just the stimulus positioned below the cameras, before introducing the finger pad. A piece of 2-D patterned paper (marked with ink points, approximately 5 per mm²) was pressed against the bottom of the stimulus and imaged using the disparity-mapping method; subsequently, a plane was fit to these points representing the initial position of the stimulus surface. In human finger pad experiments that followed involving that particular stimulus, points on the finger pad surface were flagged as “in contact” with the stimulus if they laid above that initial plane.

At this juncture, therefore, we would have identified all of the individual points that would be in contact. The next step is to estimate an exterior surface area bounded by these points. As the contact region was typically bowed into the stimulus and not flat (especially with the softer stimuli), simply taking the area from the 2-D perimeter of the points is not sufficient. In order to bound a 3-D surface to the exterior of the points, we used a Delaunay triangulation procedure. In the “flattened” plane orthogonal to the camera axis – i.e., temporarily ignoring the “Z” direction values for each point representing depth from the camera – a 2-D Delaunay triangulation was performed to create a contiguous surface. This 2-D surface was then brought back into three dimensions by reintroducing the “Z” direction values per point. Finally, an estimate of gross contact area was formed by summing the areas of each triangle, given their 3-D coordinates.

III. Experiments

Four experiments were performed in order to validate and test the stereo imaging technique. The first experiment was conducted using a rigid cylinder similar in diameter to the distal digit of the index finger. The remaining three experiments indented stimuli into a human index finger pad. Enrollees granted their consent to participate under a protocol for informed consent approved by the Institutional Review Board at the University of Virginia.

Experiment 1: Validating the 3-D surface reconstruction procedure and evaluating measurement variability.

In this experiment we sought to validate that the system could accurately and consistently reconstruct the spatial curvature of a rigid cylinder (lying flat at an angle of 0°) indented by the transparent compliances. Four tests sought to determine the curvature estimation's: 1) accuracy in extracting the actual diameter, 2) variability given repeated measurements, 3) error given stimuli of varying compliance, and 4) error given indentation depth. For these tests, a cross-section of CPVC pipe dimensionally similar to a human index finger was employed (15.9 mm (5/8 inch) outer diameter, 55 mm long), and stimuli were moved into the pipe at 5 mm/s.

Tests 1) and 2) were done without a stimulus in place, and used metrics of percent error and standard deviation, respectively. In particular, the first test compared the percent error

between the measured diameter and the known diameter of the CPVC pipe. We took measurements of the pipe cross-section positioned 70 mm below the camera with three separate sets of images. A circle was fit to the mean of these measurements and its diameter compared to the known diameter. In the second test, we estimated the variability across repeated measurements, by taking the standard deviation over three measurements at each point in the cross section. After confirming accurate measurement, the “no stimulus” case was considered to be “ground truth,” to which further measurements were compared.

Tests 3) and 4) were done with a stimulus in place, and estimated error introduced by stimulus compression, using a metric of mean absolute error from “no stimulus” measurements. In particular, for the third test we examined the error introduced by stimuli of varying compliance. The pipe cross-section was measured when pressed 2 mm deep into each of the three stimuli, and at the same position but with no stimulus in place. At each point in the cross section, absolute errors were calculated between each stimulus and the “no stimulus” case. For the fourth test, we examined the error introduced by varying the compression depth into the pipe. Absolute errors were compared between soft stimulus and “no stimulus” cases at depths of 0, 1, 2, and 3 mm.

Experiment 2: Validating the contact area measurement procedure.

In this experiment, we sought to validate the measurement of the gross contact area, at the peak indentation magnitude, comparing the 3-D reconstruction method to the prior “ground truth” ink-based method [8]. Hard and soft stimuli were indented into the finger pad (inclined at an angle of 30°) at 5 mm/s to depths of 0–5 mm in independent trials. Before each trial, the stimulus surface was wiped with a cloth to remove any ink or dust and the finger pad was marked with ink using a paintbrush. Within each trial, the stimulus was pressed continuously into the finger pad up to the terminal depth, at which force was recorded and a stereo image was taken of the finger pad. Immediately afterward, the stimulus was withdrawn and an ink print was taken from the stimulus to be measured via custom software [8]. Each trial was repeated three times.

Experiment 3: Measuring spatial detail of the finger pad surface to evaluate differences across compliance.

We measured the surface of a real finger pad to compare geometric shape and maximum penetration depth across compliant stimuli. We indented the hard and soft stimuli into the finger pad (inclined at an angle of 30°) at a rate of 1 mm/s to a displacement of 4 mm, taking measurements from stereo images at depths of 0, 2, and 4 mm. Both the indentation velocity and depths were chosen from within the range of prior psychophysical experiments [7, 9]. A displacement-controlled paradigm was selected due to prior work which identified this manner of stimulus to be more perceptually efficient than a force-controlled paradigm [7]. 3-D reconstructions resulting from these images were compared across stimulus compliance.

Experiment 4: Measuring temporal detail of the finger pad contact area.

We measured relationships between force, displacement, and contact area at the finger pad (using the method outlined in Section II.E.) over the course of an indentation. For the hard and soft stimuli, each stimulus was indented into the finger pad (inclined at an angle of 30°)

to a depth of 3 mm at either 1 mm/s or 15 mm/s, with three replications per each velocity. During each indentation, force was sampled from the load cell at approximately 50 Hz, and stereo images of the finger pad were taken at 30 frames per second.

IV. Results

Experiment 1: Validating the 3-D surface reconstruction procedure and evaluating measurement variability.

We found that the stereo imaging technique was able to measure the diameter of the pipe section accurately, with low variability between measurements. This finding held across repeated measurements, across multiple stimuli of varying compliance, and across multiple indentation depths (Figure 4). In particular, in Test 1) without a stimulus in place, the measured cross-section of the pipe was found within 0.5% (Figure 4B) with a measured radius of 7.90 mm as compared to the true radius of 7.94 mm. In Test 2), across three repeated measurements, there was an average standard deviation per measurement point of 0.05 mm (Figure 4B). In Test 3), measurements exhibited only a small amount of error over the full range of compliances, after image correction. With the pipe pressed 2 mm deep into each stimulus, the mean absolute error from the “no stimulus” case ranged from 0.09 to 0.10 mm (Figure 4C). In Test 4), measurements were not greatly affected by how deep the pipe was indented into the stimulus, with a mean absolute error between the soft stimulus and no stimulus ranging from 0.10 to 0.15 mm (mean = 0.12 mm) (Figure 4D). The greatest distortion appeared at the terminal depth of 3 mm, which was most likely due to slight changes in magnification caused by compressing the stimulus to some fraction of its original thickness.

Experiment 2: Validating the contact area measurement procedure.

Figure 5A shows the contact area estimated from a 3-D reconstruction of the finger pad and Figure 5B depicts the identified region as it would appear from the left camera alone. Figures 5C and 5D compare the peak gross contact area measurements, at the peak indentation magnitude, for the 3-D reconstruction method and repeated again with the previously reported ink-based method [8]. Error between the reconstruction procedure and ink-based procedure was an average of 3.2% with a maximum error of 12% (excluding initial contact). Some amount of this error is unavoidable due to our triangulation procedure, which only approximates the curved contact region. We therefore see a good alignment with the direct measurements made with the ink-based method.

Experiment 3: Measuring the spatial detail of the finger pad surface to evaluate differences across compliance.

Examining a cross section of the 3-D surface (Figure 6A), we found that, at the same indentation depth, the finger pad penetrated more deeply into the soft stimulus as compared to the hard stimulus (Figure 6C). The finger pad also better retained its original geometric shape when pressed into the soft stimulus, compared to flattening against the hard stimulus (Figure 6D).

Experiment 4: Measuring temporal detail of the finger pad contact area.

Displacement-contact area relationships remained highly consistent even with large changes in indentation velocity (Figure 7A). Since force is rate-dependent upon indentation velocity for elastic objects, the force-contact area relationships for each stimulus shifted noticeably with indentation velocity, with up to a 93% increase in force (Figure 7B, C). When indented at the same velocity, force-contact area relationships were well-separated between hard and soft; however, when the hard stimulus was indented more slowly than the soft stimulus, the relationships overlapped (Figure 7C).

V. Discussion

This work developed a stereo imaging technique to measure the surface deformation of the finger pad as it interacts with objects of varying compliance. To our knowledge, this is the first work to directly measure unique patterns of three-dimensional skin deformation, over an indentation time course, for highly deformable stimuli (61 to 266 kPa). As part of this effort, we compared two methods of 3-D reconstruction, one with low spatial resolution (~1 mm) but the ability to track specific points on the finger pad surface, and one with much higher spatial resolution (60–120 microns), both at 30 frames per second. With this spatial and temporal resolution, we begin to observe new 3-D cues that might underlie our ability to discriminate compliances, including the retention of the finger pad surface's geometric shape and the penetration depth of the finger pad's surface into the compliant surface. Preliminarily, for example, we could observe that the finger pad skin penetrates more deeply into softer materials (approximately 0.8 mm for soft compared to hard) and better retains its original geometric shape. From a temporal perspective, we could observe that indenting into a stimulus more quickly makes one compliance look like another in terms of their force per contact area relationships at the finger pad surface.

3-D spatial cues:

With a spatial resolution of 60–120 microns, we can capture the 3-D curvature of the finger pad, and its incremental deformation over the time course of the indentation. Therefore, given a displacement, one can use metrics tied to surface geometric shape and penetration depth to differentiate compliances, in contrast to metrics such as gross contact area. In particular, compare the distinct cross-sections of the 3-D surface of the skin in Figure 6B to the very similar plots of contact area per displacement from Figures 5C and 7A. While a broader cohort of subjects will be required to confirm this trend, this technique's ability to directly image spatial details at this resolution may help us unlock cues critical to rendering naturalistic perception.

While the technique's current spatial resolution is 60–120 microns, further increases to its resolution to reach 10–30 microns are feasible and could afford spatial examination at the level of finger pad ridges and/or lines (approximately 50–60 microns tall [21]). Such improvements are achievable using higher resolution cameras and point co-location methods with sub-pixel accuracy. That said, reaching resolutions of 20 nm as observed in the single-camera imaging of rigid interactions may prove logistically difficult due to constraints on point co-location that underlie 3-D reconstruction [22].

Temporal cues.

The stereo imaging technique can measure the skin's deformation continuously at 30 frames per second over the course of an indentation. In contrast, our group's previously published method could only measure a single contact area at the peak of the indentation [8]. With the capability for continuous measurement, we found that indenting into a stimulus more quickly increases the relationship of force per gross contact area (Figure 7C). Whether this impacts our perception and ability to differentiate these compliances remains an open question. However, along those lines, in prior work, we found that force-rate cues are perceptible and more efficient than displacement-rate (velocity) cues [7]. Indeed, the capability for continuous measurement opens the door for further exploration of the utility of force-rate cues in perceptual discrimination.

Implications for haptic displays.

Many bare finger haptic displays are currently built to control contact area spread rate, in which a particular compliance is defined by a force-area relationship [1, 2, 6, 23]. In the future, it might be that greater perceptual acuity could be afforded by haptic displays that evolve their 3-D shape over time. In particular, these devices might need to precisely alter the geometric shape of the finger pad skin in the contact region, or use the current position of the skin's 3-D surface to render cues in a time-dependent manner. However, for now, the precise definition of how to move the skin's surface in three-dimensional space, over time, remains a question to be addressed.

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Fig 1. Apparatus setup.

The finger pad lies below the 3-D printed fixture, visible through the transparent stimulus. Two cameras are positioned above and manually focused to visualize the finger pad surface through the stimulus. This unit is mounted to a cantilever that is moved vertically into the finger pad via the indenter. An attached load cell passively measures uniaxial vertical force. The finger is inclined at an angle of 30° from the table.

Fig 2. Overview of two different point co-location methods.

Checkerboard method showing: **A)** left camera image of checkboard ink pattern, **B)** checkerboard squares identified from left camera to collocate common points, and **C)** reconstructed 3-D surface interpolated from co-located points. *Disparity-mapping method* showing: **D)** left camera image with diffuse ink points, **E)** disparity (in pixels) between left and right cameras as identified by the algorithm, and **F)** reconstructed 3-D surface from co-located points of higher spatial resolution.

Fig 3. Corrections to image through transparent stimuli.

Panel **A**) compares images of a grid pattern taken with and without a transparent stimulus between, while panel **B**) demonstrates the distortion in grid point location caused by the transparent stimulus (red versus black) and the grid point locations after image correction (blue). Images shown are from the left camera, but the process was repeated for the right camera as well.

Fig 4. Validating the 3-D surface reconstruction procedure and evaluating measurement variability.

Panel A) shows the cross-sectional geometry of the pipe, B) demonstrates three repeated measurements of the pipe's cross-section with no stimulus between, C) demonstrates measurements of the pipe's cross-section with each of the compliant stimuli between the cameras and pipe compared to no stimulus between, indented to a depth of 2 mm into the cylinder, and D) compares measurements taken at indentations of 0-3 mm into the soft stimulus, and with no stimulus between.

Fig 5. Validating the contact area measurement procedure against the prior ink-based method. **Panel A)** demonstrates how contact area is estimated from the 3-D surface measurement of the finger pad and the plane fit to the surface of the stimulus. **B)** Demonstrates visibly the contact area measured in A) as projected onto the image from the left camera. **C)** Compares contact area versus displacement relationships measured with the new procedure versus. the prior ink-based procedure, for hard and soft stimuli. **D)** Shows the contact area versus force relationship. Error bars denote standard deviation.

Fig 6. Measuring the surface geometry of the finger pad as it contacts and deforms hard and soft compliant stimuli.

Panel **A**) denotes a cross-section to be detailed in panel **B**) as obtained from the entire 3-D surface reconstruction for the case of the soft stimulus pressed into the finger pad to an indent of 2 mm, while panel **B**) shows such cross-sections for both hard and soft stimuli pressed 0, 2, and 4 mm into the stimuli. **C**) Shows the maximum penetration depth of the finger pad into either of the hard and soft stimuli. **D**) Shows the change in geometric shape, measured as mean change in surface height from the original finger pad shape. Notably, the finger pad penetrates more deeply into the soft stimulus compared to the hard stimulus. In addition, it better retains its original geometric shape.

Fig 7. Measuring biomechanical cues at the finger pad surface during stimulus motion.

Panel **A**) shows no difference in the displacement versus contact area relationship for hard and soft stimuli at 1 mm/s (dotted line) and 15 mm/s (solid line), whereas panel **B**) shows the force per displacement to increase with indentation velocity. Panel **C**) depicts the force versus contact area relationship for both stimuli and both indentation velocities, showing that the soft stimulus may overlap the hard stimulus when it is indented more quickly. Error bars denote standard deviation.