Study of the temporal characteristics of friction and contact behavior encountered during braille reading

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Study of the temporal characteristics of friction and contact behavior encountered during braille reading

Abstract
Beyond the sense of sight, the sense of touch is one of the primary ways that individuals experience their surrounding environment. Fundamentally understanding the relationship of skin-surface tribology and its elicited tactile attributes could provide a breakthrough in improving the ability to efficiently transmit tactile information to those who rely on the sense of touch to interact with their surroundings, such as the blind and visually impaired (BVI) community. The tactile language of braille has been adopted by the BVI community, employing configurations of raised dome-shape dots to convey what is ordinarily presented in text and image form. The coefficient of friction caused by skin sliding across these dot features is hypothesized to affect the reader’s tactile sensitivity, and skin-on-braille coefficient of friction has been investigated in previous work, where macro-scale deformation of the human fingerpad sliding over the dot contour was identified as the dominant friction mechanisms. This investigation succeeds that study by examining a simplified large-scale, two-dimensional representation of skin-on-braille sliding to characterize the underlying contact mechanisms in the loading behaviors that dictate the resulting coefficient of friction. This was accomplished by using a multi-axis tribometer to sliding a 25.4 mm radius cylindrical polyurethane (representing a human fingerpad) rod over a lubricated 3.17 mm aluminum half rod (representing a braille dot) under displacement-displacement-controlled conditions. The results from the tribometer study indicate that the presence of the dot feature drastically affects the vertical and lateral loading behavior by vertically displacing the body’s elastic bulk, generating rubber-like Poisson effect contributions. Most importantly, the Poisson effect rapidly increases the lateral load when the body contacts the dot’s leading edge, and rapidly decreases when the body rests largely in contact with the dot’s trailing edge. This rapid decrease is caused by a “propulsion” effect, where vertical compression expands the material laterally, and when situated on the trailing edge of the dot, propels it into the direction of sliding, virtually negating adhesive surface friction. Computational modeling of this system discovered that while normal contact pressures dominated the fluctuations seen in the vertical loading, effects due to both normal contact pressures and frictional shears nearly equally drove the lateral loading behavior.

Keywords
Skin tribology, Braille, Tactile, Friction

Disciplines
Cognition and Perception | Mechanical Engineering | Other Communication | Tribology

Comments

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Investigation of the tribology and contact behavior encountered in braille print by use of physical and computational models

M.A. Darden and C.J. Schwartz

Abstract

Beyond the sense of sight, the sense of touch is one of the primary ways that individuals experience their surrounding environment. Fundamentally understanding the relationship of skin-surface tribology and its elicited tactile attributes could provide a breakthrough in improving the ability to efficiently transmit tactile information to those who rely on the sense of touch to interact with their surroundings, such as the blind and visually impaired (BVI) community. The tactile language of braille has been adopted by the BVI community, employing configurations of raised dome-shape dots to convey information. The coefficient of friction caused by skin sliding across these dot features is hypothesized to affect the reader’s tactile sensitivity, and skin-on-braille coefficient of friction has been investigated in previous work, where macro-scale deformation of the human fingerpad sliding over the dot contour was identified as the dominant friction mechanism. This study was focused on confirming the deformation hypothesis through visualization of the sliding behavior, both empirically and computationally. Initially, a large-scale, two-dimensional representation of skin-on-braille sliding was used. This was accomplished by sliding a 25.4 mm-radius cylindrical polyurethane rod over a lubricated 3.2 mm aluminum half rod (representing a braille dot) under displacement-controlled conditions. The results from the tribometer study validated previous results and indicated the importance of Poisson effects during feature traversal. During one phase of sliding, the friction coefficient is substantially lower than that of sliding on a flat surface because of a propulsive effect generated by the elastomer-dot interaction on the trailing side of the feature. Computational modeling validated these findings and also indicated that while normal contact pressures dominated the fluctuations seen in the vertical loading, effects due to both normal contact pressures and frictional shears nearly equally drove the lateral loading behavior.
1. Introduction

Touch is one of the fundamental sensory mechanisms that allow individuals to physically interact with and learn about their surrounding environment. Tactile exploration is generally not the primary method that individuals use to acquire information, for this designation would be given to the sense of sight. Unfortunately, not all individuals possess the ability to employ vision as their principle means of learning; and as a result, the blind and visually impaired (BVI) community relies on touch and tactile perception. Varying types of tactile language were developed in order to provide non-sighted with the tools to learn with and function in the same way that sighted individuals can, and the braille writing system was adopted as the standardized tactile language for the BVI community.

Perceiving and decoding the braille language requires an individual to tactually scan the text or images with the fingerpad, and this form of tactile perception is governed by the tribological skin-surface sliding interaction experienced during the exploration of the dot configurations. It is believed that during this sliding interaction, the resulting changes in coefficient of friction (COF) aid the reader in translating the code, in the same way that coefficient of friction has been believed to influence perceived tactile attributes in other surfaces such as paper media [1, 2], or textile fabrics [3-8], or ridged textured metals and polymers [9, 10]. In the case of skin sliding over featureless paper media, Skedung et al. found that coefficient of friction was positively correlated to both perceived coarseness as well as the media’s surface roughness. Conversely, friction correlations to tactile perception have not been as prominent for skin interactions with textiles or ridged surfaces. Highly specific attributes such as abrasiveness or softness were not found to be related to skin friction [6], but perceived comfort and friction have been positively correlated for both wearable textiles as well as rigid textures, primarily influenced by the degree of moisture at the skin-surface interface [3, 4, 7]. Complementary to this finding, variations in surface topographies with macroscopic features have been found to produce skin deformations and surface vibrations that in turn affect friction and perception [8, 9]. While not explicitly dictating tactile perception, skin friction and its interaction with topographical surfaces still affect the tactile experience to some degree, and understanding these sliding interactions would prove valuable for a multitude of applications.

Understanding the fundamental friction and contact mechanics of the skin on braille dot tribology would allow for a deeper understanding in friction’s impact on the quality of learning and perception for the BVI community. The tribological interaction of a human fingerpad sliding over a braille dot is analogous to Wolfram and Adams’ model of a small rigid sphere being dragged across an elastic half-plane [11, 12] (based on Greenwood and Tabor’s [13, 14]), and this model was key in discovering the major impact that the friction mechanism of deformation has on coefficient of friction behavior during skin-dot sliding [15]. During this investigation, the trends exhibited in the coefficient of friction behavior were investigated, but the specific contact mechanisms driving the loading behavior, which in turn dictated the COF, were not analyzed.

The purpose of this investigation was to determine the underlying contact mechanisms and loading behavior during braille reading, and this was executed in two phases. The first aspect of
the study was to observe the vertical and lateral loading behavior of a large-scale, two-dimensional representation of a simulated braille reading. The second aspect of the study entailed validating the data and claims drawn from the initial phase by performing computational modeling and decomposing the loading components and coefficient of friction behavior.

2. Materials and Methods

Previous work has determined that the friction mechanism of deformation plays a major role of sliding interactions during braille reading, where a soft fingertip slides against a rigid braille dot feature. The motivation for this study was to gain a better understanding of the exact contact mechanics that occur during this tribological interaction. This paper investigates the force interactions and presents two phases that were performed concurrently in order to complement and validate the other’s data and analyses.

2.1 Empirical study

The first phase of this investigation explored the contact mechanics of braille reading by simulating the tribology of braille reading with a large-scale physical model. While braille reading involves three-dimensional forces and deformations, this study simplified the problem by reducing the finger’s and dot’s spherical geometries to a two-dimensional projection by the use of long cylindrical entities. Here, sufficiently long cylinders exhibit plane strain conditions, where strains and forces were restricted to primarily planar behavior in order to be comparable to plane strain computational models used in related work. The testing during this phase employed a multi-axis tribometer (Rtec Instruments) for all sliding interactions and force measurements.

The projected contact area of the human fingerpad is ellipsoidal in shape, but as observed in previous work [15], it can be reasonably analyzed as a homogeneous, elastic spherical (for this sake of this study, cylindrical) body. A representative diametral dimension for the fingerpad curvature is approximately 20 mm (10 mm radius), and the standard hemispherical braille dot is 0.48 mm high. This comparison yields roughly a 20:1 scale between fingerpad and dot feature radii. Due to the availability of commercial materials, the scale of the finger-to-dot ratio in this study was reduced to 8:1. A 50.8 mm (2 in.) diameter polyurethane rod was selected as the soft body in the tribological couple, and served to reasonably emulate the elasticity of the finger. In order to simplify the model to maximum extent possible, in order to observe first-order behavior, viscoelastic effects were minimized by the use of slow sliding velocities. The polyurethane rod had a durometer hardness rating of 40A, which can be estimated to have an equivalent modulus of elasticity of 1.35 MPa. The rod was cut to 30 mm in length so that the loads produced from the required displacements would not exceed the limitations of the tribometer’s load cell.

The rod’s circular cross-section was squared on three of the four sides so that it could be mounted into a stainless steel U-channel. This was performed in order to ensure that both the vertical and lateral displacements were uniformly applied, as well as to eliminate cylinder rotation during sliding. This mounting treated the rod as a half cylinder where applied displacements and boundary conditions could be maintained at the vertical center of the cylinder. A stainless steel shaft was welded to the top surface of the channel to mount to the tribometer’s load cell.
The simulated two-dimensional braille-dot geometry counterface consisted of a 6.35 mm diameter half cylinder affixed to a 152.4 mm square aluminum plate of 6.35 mm thickness. The top surface of the counterface was manually polished with P2500 grit abrasive paper and subsequently cleaned. This counterface was then mounted to the tribometer’s dual-axis stage, as shown in Figure 1.

![Figure 1. The polyurethane rod brought into contact with the counterface surface prior to a tribological test.](image)

A 6-axis, 500 N limit load cell was used to record both the vertical and lateral forces at a sampling rate of 1 kHz during all sliding tests. Additionally, the tribological tests were performed under displacement-controlled conditions in an environment with temperature and humidity measured at 23.8°C and 50% humidity, respectively. Vertical displacements were controlled by a Z-axis motor and load cell suspension, and lateral displacements were controlled by a dual-axis stage (X-axis only). Additionally, a high definition video camera (GoPro HD) was mounted to the stage to record video of the rod sliding across the surface. This footage was then synchronized with the force data to visualize the sliding interaction with respect to the loading behavior.

To minimize the potential for cylinder rolling, and to focus primarily on the deformation components of the sliding friction, the surfaces of both the polyurethane rod and counterface were coated with a thin film of food-grade mineral oil lubricant. Each run was displacement-controlled,
where the rod was brought into contact with the flat portion of the counterface on one side of the dot feature and then vertically displaced by 10 mm. This displacement was chosen during preliminary testing in order to guarantee that the soft material would fully surround the dot feature during sliding to simulate a fingertip during braille reading.

Once vertically displaced, the counterface stage was laterally translated for 60 mm at a velocity of 1 mm/s. This low sliding speed was used in order to reduce dynamic sliding effects and promote a quasi-static force analysis, complementary to the investigation’s computational modeling phase. The vertical and lateral forces were recorded at all times during sliding, and ten independent trials were performed under identical conditions.

### 2.2 Computational simulation

The second phase of this investigation employed computational modeling techniques to validate the loading behaviors observed in the large-scale tribometer study and aid in identifying the fundamental contact mechanics in the sliding interaction. Finite element analyses (FEA) was performed using a commercially available FEA software suite (Abaqus). The simulation’s components and parameters were set up to mirror those of the empirical methods described previously, with some simplifications for computational tractability. The model was created in 2-D planar space, where the solution followed plane strain conditions. It consisted of two independent parts: one representing the soft cylindrical body, and the other representing the dot-feature counterface. The soft body was simplified as a semicircle with a radius of 25.4 mm, and its material properties were defined as a homogeneous elastic body with a modulus of elasticity of 1.35 MPa and a Poisson’s ratio of 0.48 (similar to that of the polyurethane used in the experiments). The counterface was modeled as an analytical rigid surface that consisted of two smooth 50 mm segments separated by a 3.17 mm semicircle representing the dot feature. The corners created by the dot’s semicircle were smoothed with 1 mm fillets to avoid computational discontinuities. The modeled assembly is shown in Figure 2.

![Figure 2. The soft semicircular body rests in contact with the rigid counterface prior to any applied displacements.](image-url)
The frictional interaction (smooth surface-to-surface coefficient of friction) between the two surfaces (soft body and rigid counterface) was pre-defined as 0.25, similar to that of the lubricated rubber sliding on aluminum or a finger sliding on paper media as measured in previous work [15]. For the model’s applied displacements, the rigid dot counterface was fixed in all directions of motion and rotation, and all displacements were applied to the soft body’s top surface.

The simulation consisted of displacing the soft body’s top surface downward by 10 mm then laterally for 60 mm. The force balance calculations were performed under quasi-static analysis, thus minimizing any inertial effects due to sliding speed. During displacement, the relative positions of the nodes across the top surface were held constant with each other. This constraint kept the top surface horizontal and prevented it from expanding under vertical displacement, similar to that of the tribometer’s mounting device (described above). Throughout sliding, the total interaction forces in both the lateral (1) and vertical (2) directions were recorded, and each was decomposed into contact mechanisms: a) due to contact pressure (CP) normal to the contoured surface, and b) due to frictional stresses (FS) tangent to the contoured surface. Forces were also recorded for each surface node on the body that came into contact with the counterface, and during post processing analysis, global nodal positions were attributed to the nodal loads to classify loads as being produced either due to contact with the counterface’s flat, background region (Base) or raised dot region (Dot). Figure 3 indicates the both the Base and Dot regions as well as the initially deformed soft body.

![Figure 3](image)

Figure 3. The soft body is displaced vertically by 10 mm, and stick-slip (red and blue, respectively) contact points are indicated at the interface. Additionally, Base and Dot contact regions are identified for determining loading sources.

3. Results and Discussion

3.1 Empirical results

Figure 4 illustrates the time histories of both the vertical and lateral loads during sliding, as well as the repeatability of the empirical results. In the figure, negative vertical values indicate a compressive load, and positive lateral values indicate a net force oriented in a direction to opposed sliding. Over ten replications of each loading condition, the sliding behavior for both
loading directions, as well as in the coefficient of friction, was consistent for all behaviors and extremely repeatable among trials. The pre-loading interaction is analogous to a simple Hertzian cylinder-on-cylinder contact in order to estimate contact pressures at the interface. In this scenario, the rigid, flat counterface can be represented by a cylinder with an infinitely long radius with an infinitely high modulus of elasticity (relative to the polyurethane). Under these assumptions, the composite radius and effective modulus of elasticity were directly proportional to that of the polyurethane cylinder. The applied displacement produced a vertical force of approximately 400 N, and under this load and the experiment’s design parameters, the maximum contact pressure on the baseline surface was calculated to be 913 kPa. Throughout sliding, the calculated Hertzian contact pressure reached as high as 1.0 MPa at the largest achievable vertical load of nearly 500 N.

Figure 4. Vertical load (top left), lateral load (top right), and coefficient of friction (bottom) for three of the ten trials are presented to demonstrate the repeatability of the test and consistency of the sliding behavior.

Upon initial observation of the data, two interesting trends were apparent: a unique, two-peak behavior in the vertical loading component; and a rapid decrease of lateral load (and COF) well below the baseline values at a particular point during sliding. For all data sets, it was hypothesized that the each would begin to increase once the soft body came into contact with the dot, stabilize as it passed over the dot, and subsequently decrease as the trailing edge lost contact with the leading baseline surface. Instead, after the predicted initial increase, the vertical load unexpectedly decreased rather suddenly, only to stabilize temporarily before rising to and falling
from peak smaller than the first. This resulted in two independent peaks separated by a brief stabilization. The lateral load and COF did not behave as originally hypothesized either, and while consistent with each other, their trends differed from that of the vertical load. After reaching a brief maximum, the lateral load and COF suddenly drop to values nearly 75% below their baseline values and 90% from their maximum values.

To better understand the specific contact and sliding mechanisms that produced these changes in behavior during the empirical investigation, the times at which the events took place were noted and used to construct a storyboard for visual analysis. Figures 5 and 6 identify seven points in time at which highly identifiable transitions take place for the loading components and COF data. These points were compared to the captured video to determine the physical behaviors occurring at each.

Figure 5. The times at which noteworthy behaviors occur have been noted for the vertical and lateral loading trends: A) steady state sliding, B) onset contact with the surface feature (“dot”), C) maximum lateral load and COF achieved, D) beginning of vertical load stability, E) end of vertical load stability, F) minimum lateral load and COF achieved, G) stabilization of normal and lateral loads. Negative vertical values indicate a net compressive force.
Based upon examination of the video footage, the following seven events were identified and analyzed: A) steady state sliding, B) onset contact with the dot, C) maximum lateral load and COF achieved, D) beginning of vertical load stability, E) end of vertical load stability, F) minimum lateral load and COF achieved, G) stabilization of loads and friction coefficient. These events are shown in Figure 7.

During the first 10 seconds, the polyurethane was vertically displaced, and once this pre-load was applied, sliding began. For the vertical loading, it can be seen that there is a minor decrease in load once sliding commences. As the rod was lowered onto the surface, it deformed symmetrically about the central point of contact. Once sliding began, stick-slip had to be overcome.
before the body could reach steady state sliding. As stick-slip was overcome, the bulk material shifted, and the rod’s surface in contact with the counterface was dragged, creating an asymmetry in the polyurethane’s cross-section. This asymmetry loading situation led to the slight reduction in vertical force at the onset of sliding.

Instance A indicates the point in time at which the vertical and lateral forces reached equilibrium. Instance B indicates the moment in time at which the soft body initiated contact with the dot feature. When the body came into contact with the dot feature, the contour resisted the motion of the body in the lateral direction and vertically compressed the bulk material. As the body continued to slide forward, it deformed over the contour of the dot, and both the lateral and vertical forces began to increase. This resistance yielded a cumulative effect: 1) the lateral force increased due to sliding resistance, and 2) the vertical force increased as lateral compression caused the bulk to expand vertically via the Poisson effect as well as due to vertical compressive displacement (Figure 8).

Instance C represents the time at which the lateral force and COF achieved a maximum value. As seen in Figure 7, the leading edge of the soft body reached the top of the dot feature (referred to as the 12 o’clock position). In addition to the dot feature resisting bulk sliding through the Poisson effect, frictional forces around the contour of the dot resisted the body’s sliding tangent to the dot’s face. As the soft body climbed over the dot contour, tangential forces resisted the clockwise sliding motion of the surface. The lateral force, and in turn the COF, reached a maximum as the body climbed to the 12 o’clock position on the dot because the entirety of the material in contact with dot surface rested on the left, or leading, side of the dot. It is believed that once the material surpassed the 12 o’clock position on the dot, the Poisson effect began to have an adverse effect on the total lateral load and COF. Figure 8 (part 3) illustrates this as the material on the right side of the dot expanded laterally (similar to Figure 8 part 1), but in this case, the lateral Poisson expansion of the soft material dot effectively propelled it in the direction of sliding. This contribution rapidly decreased the lateral friction force (e.g. the resistive sliding force was decreased) until instance F, where the lateral force and COF reached a minimum. At this point, the
soft body reached the 12 o’clock position, except the entirety of the material rested in contact with
the trailing side of the dot. It was here where the Poisson effect was at a maximum in terms of
propelling the bulk forward, promoting sliding. The contributing effect was so great that the lateral
load and COF decreased to 75% less than that of baseline sliding, rendering adhesive frictional
behavior as negligible in comparison to the deformation effects. This finding was extremely
noteworthy, in that it demonstrates the significance of the friction mechanism of deformation and
the impact macroscopic-scale geometries can have on frictional forces and sliding behavior.

In the case of significant events for the vertical loading behavior, Instances D and E appear
to be notable and represent the start and endpoints that the vertical load appeared to stabilize after
its initial climb and descent. Unlike the maximum lateral force, the maximum vertical force did
not occur simultaneously with that of the coefficient of friction, and instead it reached a maximum
shortly afterward. Even though the vertical maximum was not in phase, the COF behavior
indicated that vertical loading is not the driving frictional component, but instead was driven by
the lateral force. Interestingly, the video data showed that the vertical load stagnation first occurred
when the leading edge of the soft body came into contact with the trailing baseline surface. The
stagnation continued as the bulk material transitioned its surface contact from the leading baseline
surface to the trailing baseline surface, and once contact was lost with the leading side, the second,
although smaller vertical loading peak began. This second peak occurred due to the Poisson effect on
the trailing side of the dot, in the same manner as on the leading side. Additional vertical expansion
resulted from the dot pushing the bulk forward, thereby increasing the vertical load compared to
its stagnant, transitional contact behavior.

Instance G was consistent for both loading cases as well as the COF behavior. Here, the
soft body lost contact with the trailing side of the dot feature, and equilibrium baseline sliding
resumed. The lateral force and COF were nearly identical to the original steady-state values, but
the vertical load decreased from its initial pre-load. The vertical load did not equate with respect
to its initial pre-sliding state because the bulk was still in a laterally deformed state due to the
frictional adhesion to the counterface.

3.2 Computational modelling results

The second phase of the investigation employed finite element analysis to computationally
validate and confirm the hypothesized mechanisms observed and reported during the empirical
testing phase. Because of the geometry and material properties used in the FEA approach versus
the empirical study, the magnitudes of the simulation can be compared to that of the empirical
study by multiplying the computational loads by a factor of 30 (the polyurethane rod was 30 mm
long, and the FEA model assumed a unit depth in plane strain). For the sake of computational time
required to complete the analysis, a sliding speed of 5 mm/s was used, as opposed to 1 mm/s as
seen with the tribometer, but due to the fact that the simulation was performed using quasi-static
analyses that disregarded all dynamic effects, sliding speed and inertial behavior did not influence
the data. Additionally, modifying the modulus of elasticity only affected the scale of the loading
magnitudes and not the loading behavior, as Hooke’s Law would suggest. In the illustration below, all data sets begin at 2.0 s, when the onset of steady state sliding occurred in the FEA models.

The FEA model proved to be a reasonable facsimile of the empirical behavior when comparing the loading and COF trends to that of the tribometer testing data. Figure 9 displays representative modeling results, and employs the same event markers as described above, but at somewhat different times due to the scale differences between empirical and computational model. The exception is Instance C, where maximum vertical load was encountered in the tribometer testing. The peak is apparent in the FEA results, but not nearly as pronounced as before and so it is not indicated in the figure.

![Computational Force and COF Behavior](image)

Figure 9. Aside from the magnitude of the maximum vertical load (Instance C from before), the modeled loading (top) and COF (bottom) predictions for Instances A-G were quite agreeable with the empirical tribometer data.

The major difference between the general behavior of both results is that the maximum vertical load (Instance C in the empirical results) was much less pronounced in the FEA data. Here, as opposed to a sharp climb followed by rapid decline, the lateral load stabilized until the trailing edge of the soft body released contact from the leading baseline surface. It was hypothesized that the sharp decline was possibly due to dynamic effects on the empirical model. Future computational work may be performed to model the loading behavior with dynamic effects. It is essential to note that the dot’s negative effects on lateral load and frictional were evident in the predicted model as well, validating the previous claim that the dot feature promoted sliding and
decreased the total lateral loads and COF. Plots of the FEA results at the various time markers are shown in Figure 10.

Figure 10. The storyboard from the predictive computational model is nearly identical to that of the empirical study, barring Instance C due to the dynamic effects that were not taken into consideration in the simulation.

Further loading analysis was performed to better understand how the counterface’s two contact regions (baseline or dot region, Figure 3), explicitly affected loading behavior. Total loading due to each contact region was calculated by tracking the specific contact load at each surface node with respect to its vertical position, and nodes in contact with the surface at a vertical position greater than the baseline were defined as loading due to the dot region. Performing this analysis successfully explained the two-peak effect seen in the vertical loading behavior. As seen in Figure 11, classifying the loading contributions as either baseline or dot contact regions shows that the two peaks are produced as a cumulative effect of the loading from both regions. As originally hypothesized, the inclusion of the dot feature produced an increase in loading, but that hypothesis did not consider that loading due to the baseline surface would vary over time. As the soft body passed over the dot, the baseline forces decreased due to decreasing contact with the baseline region, and were at a minimum when the body was centered over the dot (when dot region forces are at a maximum).
Loading contributions were then further classified by specific loading mechanism: due to contact pressure normal to the surface (CP), or due to frictional stresses tangent to the surface (FS). To clarify, the surface normal and tangential directions become different than the global vertical and lateral directions over the surface of the dot feature. Figure 12 plots the lateral forces with respect to zone of origin. As expected, contact pressure was the primary mechanism driving the vertical loading. As the soft body traversed the dot region, the surface elements were vertically displaced, producing a contributory vertical elastic load. It can also be seen that vertical loading over the baseline zone was positively affected when the body first contacted the dot. As the bulk was laterally deformed starting at Instance B, the Poisson effect caused the material to expand vertically, briefly increasing the vertical load. An unexpected finding also came from this analysis. While minimal, frictional stresses around the contour of the dot both contributed to, as well as
reduced the total vertical loading, depending on the position of the soft body. Prior to Instance E, the soft body resided mainly on the leading edge of the dot contour, flowing in the clockwise direction. This clockwise motion on the leading edge of the dot produced frictional shear with an upward force component, resisting the downward loading due to contact pressure. Once the body lost contact with the leading baseline surface, the frictional shear component from dot contact produced a minor downward force component and promoted the clockwise sliding.

The primary contributors to lateral force behavior differed from those of the vertical force. Here, both loading mechanisms, contact pressure and frictional stresses due to the dot, influenced the loading behavior much more equally. As the soft body traversed the dot, forces due to contact pressure in the dot region were so great that they equaled the pre-defined frictional shear of the baseline and essentially doubled the total lateral force. This drastic increase resembled the trend seen in the tribometer testing, where the lateral force increased because the dot resisted bulk motion, resulting in resistive horizontal force components over the dot contour. The observation of propulsive lateral forces – those that were oriented in the direction of sliding – from the tribometer testing was also validated based on the mechanism decomposition. The simulation clearly depicted that once the soft body lost contact with the leading baseline surface at Instance E and rapidly climbed the leading edge of the dot, the vertical compressive forces on the trailing side of the counterface caused the bulk to expand laterally, pushing the bulk into the direction of sliding. As a result, this Poisson effect generated negative lateral loads due to contact pressure.
Figure 12. Lateral loading contributions classified according to counterface region (top), and further defined by specific loading mechanism (bottom).

4. Conclusions
The fundamental friction and contact mechanisms involved in a large scale simulation of braille-relevant interactions were investigated in both an empirical testing as well as a computational model. Based on the observed results, the following conclusions were drawn:

- As the soft-bodied cylinder slides over the dot contour under controlled vertical displacement, the elastic surface in contact with the raised dot region significantly impacts the load behavior in both the vertical and lateral directions due to bulk material deformation.
- The vertical compressive forces are cumulatively driven by compression against the flat surface, the body’s elastic deformation over the raised dot region, as well as from vertical
expansion due to the Poisson effect from lateral displacement, where the elastic surface’s vertical and lateral displacements are the primary loading mechanism.

- Due to the macroscopic geometry of the dot surface, frictional shearing effects in the vertical direction create both tensile and compressive loads on the leading and trailing sides of the dot, respectively.
- Contact pressure and macro-scale deformation contact is equally significant to lateral loading in comparison to frictional shear effects.
- Lateral loading due to contact pressure depends on the finger’s location with respect to the dot, where sliding is resisted on the leading half and aided on the trailing half.
5. References