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Skin tribology phenomena associated with reading braille print: The influence of cell patterns and skin behavior on coefficient of friction

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ABSTRACT

Efficient transmission of tactile information is vital for individuals who rely on their sense of touch to interact with and navigate their surroundings, including visually impaired persons. Somatosensory phenomena have been investigated with respect to surface topologies and neuron sensitivities in the skin, but there is little knowledge of the specific skin tribology when reading tactual-coded information such as braille. Braille is a tactual code that employs raised dome-shaped dots in six-position cells (2 columns by 3 rows per cell), with various dot patterns representing individual text characters, punctuation or mathematical operators. Due to the hypothesized significance of friction on tactile sensitivity, the authors investigated the effect of basic braille dot configurations on friction coefficient in fingertip sliding. Initial studies investigated the effect of multiple dot-row configurations and media type on friction coefficient, but the tribological effect of individual features and associated skin interactions was ill-defined. Subsequently, the frictional effect of an individual dot of varying radius was investigated and modeled against a multi-term frictional model implementing Hertzian contact, the Greenwood–Tabor hysteresis component of a spherical indenter against a soft surface, as well as Wolfram's traditional adhesion model. The results of the study show that macro-scale deformation of the fingerpad during fingertip-on-dot sliding is the primary friction mechanism and suggest that the contribution due to a macroscopic feature is largely independent of sample medium. Based on this understanding, the effect of braille dot spacing on a dot's friction contribution was investigated. The results from the spacing study indicate that the fingerpad's interaction with dot pairs is highly influenced by dot feature spacing. Further work is necessary to identify the fundamental sliding mechanics at the finger-dot interface, but the ability to identify the frictional mechanisms as well as the sliding interactions will provide a means to understand how much of a role friction plays in braille character recognition, as well as suggest potential friction-based methods to enhance the information density of braille codes.

1. Introduction

The sense of touch is one of the most fundamental ways by which an individual can interact with the surrounding environment. Touch and perception play a key role in handling and manipulating objects, evaluating products, or even obtaining tactual information. When it comes to investigating tactility, researchers have had great difficulty in understanding and modeling the extreme complexity of the somatosensory system. Whereas most individuals rely on multiple senses in order to obtain information and navigate surroundings, instances exist where individuals rely almost entirely on their sense of touch to decode their environment; such as the case for blind or visually impaired persons (BVI). Where sighted individuals receive written language through visual text, BVI individuals read through their means of touch, via the tactile language, braille. It is understood that BVI persons use their hands and fingers to perceive and decode braille, but there have been and continue to be research studies that investigate what exactly is occurring in the somatosensory system of individuals with BVI.

Phillips et al. first discovered that certain afferent neurons located throughout the hand (SA1 mechanoreceptors and Merkel-cell end organs) are the main contributors in one's ability to distinguish spatial form, and they investigated the use of braille cells to prove this. These receptors permit the fingertips to perceive the number and orientation of the dots involved, and the brain can then discriminate between individual braille patterns and interpret

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them into the intended meaning [1]. As previously mentioned, individuals who experience early onset blindness have been shown to adapt and eventually exhibit greater tactile acuity in these receptors [2]. Conversely, individuals who experience late onset blindness do not have such acuity and are at a disadvantage due to their lower tactile resolution. Tactile confusion plagues braille readers with decreased tactile acuity, but the specific source of this confusion is unknown. Other tactile studies have investigated perceptive thresholds and tactile resolutions through texture, feature, or grating densities [2–8], but they fail to ultimately define what lies at the heart of tactility. At its core, tactility is driven by skin tribology, the fundamental interaction of skin and a countersurface under contact and sliding.

Friction is believed to be a significant player during braille reading, as the soft fingertip slides over and interacts with complex arrangements of braille dots, but little to no research has been performed to characterize the tribological interactions of skin on braille dots. More specifically, the frictional mechanisms that govern these interactions have not been studied extensively. To understand frictional behavior during braille reading, it is essential to first understand its fundamental mechanisms.

As one surface passes over another surface asperities interact with one another and produce resistive forces that are manifested as a bulk coefficient of friction. Given an applied normal load, these resistive forces will vary depending on the two surfaces in contact. The area of contact governs the adhesion between two surfaces, where secondary bonding and Van der Waals forces are generated at each contact and repeatedly form and break under sliding. Originally, Greenwood and Williamson implemented Hertzian contact theory towards investigating the sliding of two nominally flat, rigid surfaces [9], but Wolfram and Adams further developed the model to apply to the coefficient of friction between a rigid body against a soft, viscoelastic material [10,11]. This latter model has wide applicability to any viscoelastic material and smooth surface and can be used in the investigation of friction of human skin sliding against a rigid substrate. Given such, numerous studies have examined different regions of skin (fingerpad, palmar hand and forearm) sliding against smooth surfaces such as paper, glass or plastics in both dry and lubricated settings [12–14].

The Wolfram and Adams model provides an estimate of the surface adhesion contribution during skin sliding. On the other hand, it does not directly address sliding against macroscopic features, such as braille dots, where it may be hypothesized that deformation has a strong impact on overall friction. Greenwood et al. investigated this very issue by developing a macro-friction model to describe the hysteresis, or deformation component of friction caused by hard, spherical sliders against a bulk elastomeric surface [15]. Studies have been performed by investigating skin on macro-textured surfaces such as ridge and groove patterns [13,16], but these geometries are somewhat too complex to be directly addressed using existing hysteresis models such as Tabor's. A fundamental understanding of skin sliding against a simple geometry, such as a braille dot, must first be established in order to explain the frictional behavior in more complex situations such as full braille text.

The purpose of this investigation was to determine the underlying friction mechanisms that occur during braille reading. The first aspect of this study was to observe the frictional behavior of skin sliding across a single dot feature in order to determine the relative magnitudes of the adhesion and deformation components of the frictional contribution solely due to a dot feature inclusion. The second aspect of this study entailed extending this mechanistic understanding to more complex braille configurations, studying the effect of directional dot spacing on the coefficient of friction of a fingertip sliding across multiple dot features.

2. Materials and methods

2.1. Fundamental friction mechanisms involving individual dots

The emphasis of the initial phase of the investigation was to determine fundamental tribological mechanisms involved in fingertip sliding against braille-dot feature types. The focus was on determining the relative impacts of both adhesion and deformation on friction during braille reading. This was accomplished by investigating the effect of dot size and normal load on the coefficient of friction as the human fingertip slides across said feature. In order to apply Tabor's model of a bulk soft material passing over a rigid sphere, it was necessary to ensure that the fingerpad completely surrounded a single feature during sliding. While Tabor's model assumes a spherical cross-section, standard braille dots have ellipsoidal cross-sections. As defined by the Braille Authority of North America, a standard dot has a height of 0.48 mm and base diameter of 1.44 mm (projected circle with radius of 0.72 mm). With this in mind, three dot radii (dot heights) were selected: 0.48 mm (standard braille dot), 0.75 mm, and 1.0 mm.

Each sample consisted of a single row of four dots, spaced sufficiently far apart so that only a single feature would be encountered at any instance during sliding. For the sample media, 100 lb cardstock printing paper was selected due to its likeness to that of braille textbooks and reading material for the blind and visually impaired. The standard-sized braille dots were embossed using an American Printing House braille slate and stylus. The larger dots were created using an acrylic stencil and the embossing stylus. As the media lay across circular holes in the stencil, features were embossed using the braille stylus as the paper deformed under light pressure. Like that of the standard-sized braille dot, the features had ellipsoidal cross-sections. These topographies were consistent for all three sizes, where the ratio of each ellipsoid's cross-sectional height and width was maintained. These dimensions were verified through the use of a Dino-Lite digital microscope and calipers. To ensure the structural integrity of the larger features, a hardening agent was used to reinforce the underside of each dot. Once all samples were constructed, they were affixed to a rigid substrate to be mounted for friction testing as shown in Fig. 1.

The coefficient of friction of a fingertip sliding against a sample was determined by recording the normal and shear forces produced during a fingertip swipe. These forces were measured with a piezoelectric three-force dynamometer and amplifier (Kistler 9254), and the data was exported to a data acquisition system. Data were taken at a sampling rate of 1000 Hz and written to files for subsequent processing and analysis. To maintain that all finger swipes were performed consistently, the testing facility was maintained at 23 °C and 50% humidity. The tester's left index finger was also cleaned with hand soap and water and thoroughly

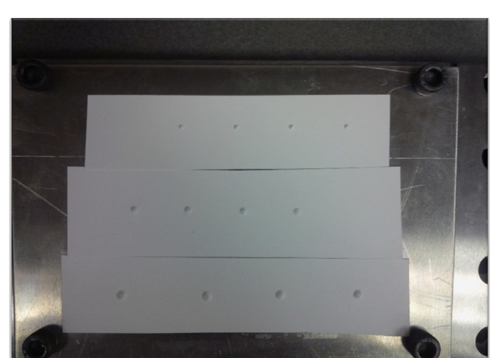

Fig. 1. Embossed paper samples showing dot features of varying heights: 0.48 mm, 0.75 mm, and 1.0 mm, respectively.