Understanding and tuning sliding friction

Liefferink, R.W.

Publication date
2021

CHAPTER 1

Introduction

1.1 From sliding a bookcase over the floor to skating on ice: What controls the sliding friction?

When one tries to slide a bookcase over the floor, a force prevents it from moving. No matter what — and in which direction — it will act to hold the bookcase in place. The resistance to sliding, *the friction force*, can be overcome if one push hard enough and, obviously, it would have helped if one had emptied the bookcase first.

Although friction is a part of everyday life, the physics behind it is still not properly understood. For example, is the force required to slide a bookcase over the floor dependent on the number of legs? Intuitively we could argue that with more legs, the area within which friction is generated has been increased. This is not true, sliding a bookcase on its side, or with eight furniture legs instead of four, results in a similar friction force. While the contact area, i.e., the number of furniture legs, may not directly influence the friction, the interface does: the geometry of the surfaces and its roughness control the friction force. Sliding furniture with pointy legs over a floor with little irregularities can be very difficult and, horribly, can lead to scratches on the floor. Furthermore, the type of floor strongly influences the experienced resistance; a wooden, tile, or carpet flooring, or — why not? — an icy surface influence how hard one has to push.

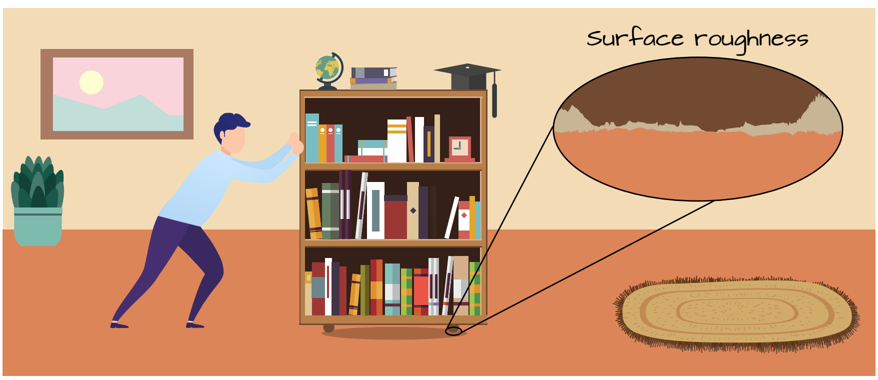

Figure 1.1: How to slide a bookcase over the floor?

In this thesis, we make a contribution to answering the seemingly simple question, 'What controls sliding friction?' We aim to bridge the gap between macroscopic observed sliding friction and the underlying microscopic behaviour at the interface between the sliding surfaces (the 'interface geometry'). We use a combination of experimental and numerical techniques and focus on the sliding friction for three very different types of surfaces, namely (wet) sand, ice, and a collection of artificial surfaces whose geometry we can precisely control. (i) We perform sliding friction experiments on partially water-saturated sand. Adding water to sand strongly influences the mechanical behaviour of this granular material; a sandcastle can be constructed only with sand to which some, but not too much, water is added to. We show that, together with the slider geometry, the water fraction determines how hard it is to slide over the sand and how deep the trace that is left after passing is. (ii) In addition, we measure the slipperiness of ice and discuss why this surface is extraordinary slippery. We 'skate' on a miniature ice skating rink and measure the sliding friction on ice as a function of temperature, contact pressure, and speed. In our experiments, we show that ice is not always slippery: The slipperiness of ice can be suppressed by increasing the contact pressure, set by the geometry of skate and its surface roughness, or lowering the temperature. (iii) In the final chapter of the thesis, we explore how one can tune the sliding friction using geometrically controlled surfaces. We demonstrated that well-designed surface roughness and control of the (mis)match the surface roughness on the sliders allows one to vary the friction force by more than an order of magnitude.

1.2 Sliding friction in the past

Overcoming the resistance to sliding when moving objects relative to each other, was — and still is — a costly problem; it has been estimated that a third of the world energy consumption is spent on friction and wear [1]. The study of sliding friction, wear, and lubrication is called tribology, this term was coined in the 20th century [2]. The prefix *tribo-* is Greek for rubbing; the field was initially defined as "the science and technology of interacting surfaces in relative motion and of related subjects and practices." Although this definition came much later, the applications or problems of tribology are ancient. A famous example comes from ancient Egypt. Various tomb drawings demonstrate how the ancient Egyptians transported large stones and even complete statues on sledges pulled by many men [3–5]. Intriguingly, in one of these drawings, one person pours water onto the sandy surface in front of the sledge (see Fig. 4.1 in Chapter 4 for one of these tomb drawings). Water may influence the friction between a sledge and the sand. This is like walking on the beach: slightly wet sand makes the walk easier than dry sand. The addition of some — but not too much — water to sand can therefore make the transportation of statues over sand easier [6]. The tomb drawings suggest, although still widely debated [5,7–9], that the Egyptians already made use of this knowledge and can be considered as some of the earliest tribologists.

The moving of large stones and colossal cultural statues has been reported frequently [10]. Many (tribological) solutions have been developed and applied, ranging from simple manpower and a sledge to the use of log rollers, horsepower, and spiked-wheeled cars. Another creative solution was developed in the 15th century: Chinese builders transported a massive stone over a distance of 70 km using an artificial ice road to build the famous Forbidden City [11]. This imperial palace complex in Beijing was constructed between 1406 and 1420 and was in use by many emperors up to 1912. A quarried stone with a weight of 300 tons was heaved to the Forbidden City using rolling logs in summer. In winter, workers poured water

Figure 1.2: *'The Large Stone Carving'* (left) is placed as a ramp flanked by stairs towards the Hall of Preserving Harmony, *Baohe dian* (right top). The heaviest stone of the Forbidden City is 16 m by 3 m by 1.7 m with a weight of 200 tons [10]. It originally weighted roughly 300 tons; when it was re-hewn in 1761, its weight was reduced to about 200 tons. The chiselled ornamentations on the stone include the dragon (right bottom), the symbol of celestial power. The pictures are from www.dpm.org.cn.

along the transportation road to create a slippery ice track and slide the huge block along the ice. Once the rock was in place, it formed a ramp flanked by stairs towards the Hall of Preserving Harmony (*Baohe dian*) as can be seen in Figure 1.2. In Ming dynasty times, the emperor was brought from his residence, the Palace of Heavenly Purity in the inner court, to this hall in the outer court before attending a grand ritual or ceremony to change into ceremonial robes. It has been argued that the Chinese builders preferred wooden logs and slippery ice as the load was too heavy for wheeled carriages [11].

1.3 The laws of friction, a macroscopic approach

Leonardo da Vinci (1452–1519) can be seen as the father of modern tribology. In his notebooks an incredible amount of tribological studies are discussed: He reported studies in friction, wear, and bearings which include a full circular ball bearing design [12, 13]. In his sliding experiments, a block is horizontally pulled over a substrate with the use of weights, a connecting string, and a pulley (see Fig. 1.3). The observations of da Vinci, however, remained unpublished in his notebooks and were only re-discovered in the 1960s [14]. Independently, 200 years later Guillaume Amontons arrived at similar conclusions for the sliding friction of dry solids [15]. After the contribution of Charles-Augustin de Coulomb in 1785, their findings can be summarised in three laws:

- The friction force is directly proportional to the normal force
- Friction is independent of the apparent area of contact between the two surfaces
- Dynamic friction is independent of the sliding speed

The laws of friction were the result of simple sliding experiments with wooden blocks: The friction doubles if two identical blocks are stacked, the friction is independent of the face of the block on which it is sliding, and friction is not affected by the sliding speed. These empirical laws are obeyed in most dry sliding systems and, due to the proportionality of the friction force F to the normal force N, allows the definition of the *friction coefficient*:

$$\mu := \frac{F}{N} \,, \tag{1.1}$$

The friction coefficient is often quantified for surfaces sliding over each other and enables prediction of the friction force. When the coefficient of friction is known, the friction force can be calculated if the normal force is measured.

Da Vinci did derive Amontons' laws based on his experiments performed two centuries before Amontons work. However, he had a different third law of friction; he stated that the resistance to sliding has a constant value of $\mu = 0.25$. This finding is quite striking as some materials are certainly more slippery than others: Steel on ice has a friction coefficient near zero, whereas a rubber shoe on the pavement has good grip due to a high friction coefficient. The fascinating inconsistency between da Vinci's results and modern tribology has been resolved by Dowson et al. [16]. They re-performed da Vinci's experiments roughly 500 years later, including an attempt of recreating the sliding setup. For various objects they quantified the material-dependent friction coefficient μ. Only when they performed their experiments with dry wood that were handled and sullied by hand, the performed measurements indeed correspond to a friction coefficient of roughly 0.25. Dowson et al. wrote: [the

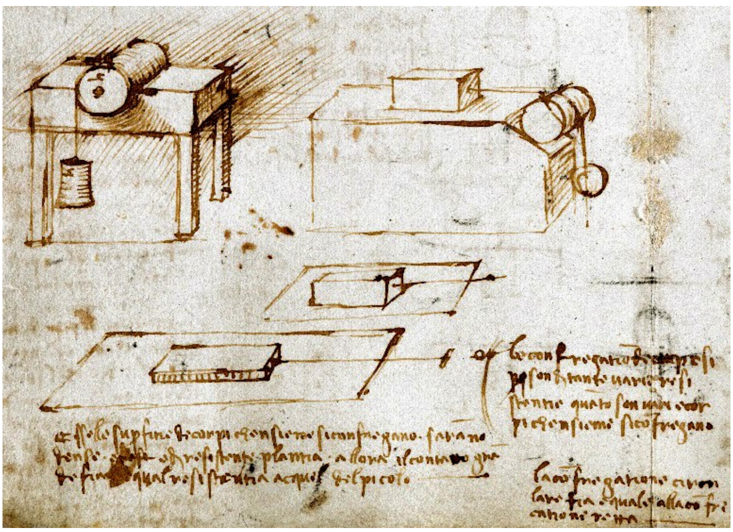

Figure 1.3: Original sketches from Leonardo da Vinci for his experiments on friction that were reported in his notebooks *Codex Atlanticus* and *Codex Arundel* [12, 13, 17]. In the right top, he measured sliding friction between a block and a flat surface with the use of weights and a pulley system where he calibrated how much weight is necessary to maintain the block sliding at a constant speed. On the bottom, the sliding of wooden blocks with various widths and lengths is illustrated. Da Vinci also reported on (lubricated) rolling friction: In the left top, a cylinder is illustrated that is placed in a shaped cavity and is rotated with weights.

sliding surfaces] “were intentionally exposed to fingerprint oils and airborne dust, resulting in a ‘sullied’ environment.” A small layer of oil (i.e., finger fat) and dust lubricates the wood-on-wood sliding experiments. “Such a procedure of sample preparation is entirely reasonable for the time period and suggests an active, dusty, and dynamic laboratory environment.” [16]. Friction, therefore, often depends on the experimental conditions. It also teaches us that modern lab experiments, experiments performed in a clean and well-controlled environment, cannot always be directly converted to real-life situations.

1.4 Towards a microscopic picture of friction

1.4.1 The real contact area

In order to understand sliding friction in more detail, there is a need to bridge the gap between the macroscopic and the microscopic scales. One of the intriguing questions, raised after performing sliding experiments on the macroscale, is why the sliding friction is independent of the contact area? Intuitively, one could argue that when the contact area increases, the friction should increase proportionally. The key ingredient here is surface roughness. Although the friction force is independent of the apparent contact area, i.e., the area that appears to be in contact when surface roughness is not considered, it is in fact proportional to the so-called Real Contact Area (RCA). The irregularities of the surfaces touch and push on each other and the formed real contact area is directly proportional to both the normal and the friction force. The friction, therefore, is the result of shearing the microscopic contact points over each other; see Figure 1.1 for an illustration of the formed contact between a furniture leg and the floor.

The real contact area was quantified by Bowden and Tabor in the early twentieth century [18, 19]. They performed loading experiments and measured the electrical conductivity at the metal-metal interface. They observed that just a fraction of the apparent contact actually touches. Bowden described this in a BBC radio program (1950): “... putting two solids together is rather like turning Switzerland upside down and standing it on Austria – their area of intimate contact will be small.” [20]. The performed tests also demonstrated that the real contact area, the ‘mountains’ of the surfaces in contact, at the metal-metal interface was proportional to the load pressing the two surfaces together. As the real contact area is proportional to the load (RCA $\propto N$) and the friction force needed to shear the microscopic contact points is also proportional to the real contact area ($F \propto$ RCA), they immediately arrived at Amontons' laws: The friction force increases linearly with the normal force and is independent of the contact area ($F \propto N$).

1.4.2 Contact mechanics

The growth of the real contact area with the normal force does depend largely on the surface materials and their roughness. The study of contact mechanics focuses on the deformation of solids when they are loaded. The metal-on-metal loading experiment from Bowden and Tabor emphasised the influence of plasticity. The rough surfaces are brought into contact and, consequently, first the highest 'mountains' will touch and experience a large contact pressure. When this contact pressure exceeds the yield stress of the material, the highest 'mountains', called asperities, will irreversibly deform. The asperities in contact will flatten out, and more contact spots between the asperities of the surfaces will form. The increased real contact area lowers the contact pressure until the yield stress is not exceeded anymore and the surfaces are in mechanical equilibrium. The experimental results led Bowden and Tabor to conclude that, for a rough-on-rough contact, the pressure is constant at the yield stress and, consequently, the real contact area increases proportionally with the normal force [19].

The Bowden-Tabor theory was, however, conflicting with elastic Hertz theory which describes that for a sphere touching a flat surface the real contact area grows sublinearly with the loading force and, therefore, is inconsistent with Amontons' laws. Hertz developed a theory in 1882 that describes the contact formation between smooth and non-adhering elastic surfaces [21, 22]. He proposed that surfaces reversibly deform as a rubber ball pressed onto a table: The curved elastic surface is flattened out and, after unloading, relaxes back to its initial form. Many theories are introduced to avoid some of the assumptions inherent to Hertz theory, which include surface roughness, adhesion, and plasticity. Greenwood and Williamson did, for example, apply Hertz theory on the asperity-scale [23]. They approximated a rough surface as a distribution of spherical asperities that all individually deform based on Hertz theory. They found that under these assumptions, the real contact area is proportional to the applied load [22]. However, it is widely accepted — including by Greenwood himself [24] — that modelling the real contact area with the macroscopic (non-adhesive) Hertzian theory on the asperity-level is limited. The surface height variations on the nanoscale, the asperities on the asperities [25], and the influence of plasticity limit the application and highlight the influence of the broad domain of length scales of the surface roughness. The real contact area must be determined for surface height variations in the range from the atomic level up to the macroscopic size of the slider geometry [26].

Many authors have contributed to the field of contact mechanics in an attempt to include all realistic effects: elasticity, plasticity, and adhesion [27–32]. Recently, the pioneering work of Persson (2002) provided an alternative model that considers the fractal nature of surfaces — the asperities on the asperities — and also predicts a linear dependence between the real contact area and the normal force [33]. Furthermore, experimental techniques, such as (frustrated) total internal reflection microscopy [34, 35] and fluorescence microscopy [36, 37] allow surpassing the existing limitations and enable quantifying the real contact area which, normally, is difficult to measure as it is buried between the two loaded surfaces. We can attempt to summarise saying that elastic, elastoplastic or plastic behaviour in the micro-contacts can largely depend on the normal force while at the macroscopic level the approximation of a linear increase of the contact area with normal force is regularly observed for many surfaces of practical interest.

1.4.3 Shearing the surfaces

The contact mechanics, the deformation of solids in contact, teaches us that the real contact area at the sliding interface strongly depends on the surface topography [38]. The friction force therefore results from the resistance to slide these loaded asperities over each other. The development of the atomic force microscope made it possible to study sliding friction at the atomic scale; one surface is pushed with a cantilever on another surface where the deflection of the cantilever, which acts as a spring, can be converted to the exerted contact forces [39]. These sliding experiments serve as a model experiment for single asperity contact where the measured friction force as a function of the sliding distance displays the atomic-scale periodicity [40]. Various studies emphasise the influence of energy dissipation, phonon-phonon interaction, thermal vibrations and, in particular, adhesive interactions on the sliding friction [40–42]. The adhesive interactions between loaded asperities results in ‘glueing’ them together, e.g., by the van der Waals forces [33]. Adhesion can increase the sliding friction significantly; a smooth elastic rubber can reach a friction coefficient of around 2 [43]. In contrast, a lack of adhesive friction can result in extremely low friction. This so-called structural lubricity can be achieved for periodic surfaces where, based on their commensurability at the nanoscale, the real contact area and the resulting number of adhesive bonds is low [44]. The adhesive friction force is therefore dependent on the interface geometry.

In addition to adhesive friction, the resistance to sliding can also be the result of plastic deformation. The shear stress on rough surfaces can result in plastic flow; the yield stress of the softest material is exceeded and will irreversibly flow. This plastic deformation can occur on the atomic-level — wearing off atom by atom — or in larger chunks resulting in the formation of debris particles [45–49]. The latter can result in abrasive wear: scratching the floor when sliding a bookcase over it, or the gradual reduction of the tread on a tire in contact with the road. Plastic deformation is not limited to asperity interactions, it can also occur on the scale of the slider geometry. A rigid slider can, when loaded on a softer surface, indents the surface and plough through it laterally. Bowden, Moore, and Tabor performed sliding experiments with metals and wrote: "It is suggested that in general the frictional force between clean metal surfaces is made up of two parts. The first is the force required to shear the metallic junctions formed between the surfaces; the second is the ploughing force required to displace the softer metal from the path of the harder." [45]. Plastic deformation of the surfaces does therefore occur on various length scales. The surface topography, together with loading force and the hardness of the materials, controls the wear track and, subsequently, the ploughing force.

1.5 Understanding friction from the microscopic to the macroscopic scale

The macroscopic approach, first described by Leonardo da Vinci, has shown us that the sliding friction between two surfaces increases proportionally to the normal force and is independent of the apparent area of contact. The friction coefficient can be defined as the ratio of the friction force and normal force. A microscopic approach teaches us that the microscopic surface topography, the irregularities of the surfaces, determine where the surfaces make contact when loaded and where the consequent sliding friction occurs. The macroscopic measured friction therefore results from shearing the microscopic contact points between the surfaces over each other.

In this thesis, we aim to bridge the gap between the macroscopically observed sliding friction and the underlying microscopic behaviour. We measured the sliding friction at the macroscopic scale and combine mechanical tests, surface topography quantification, and contact mechanics calculations, to connect our large-scale observations to the underlying microscale mechanisms. We focus on the influence of interface topography, the geometry of the surfaces and their surface roughness, for three very different types of surfaces.

(i) We discuss the sliding friction on partially water-saturated granular materials, specifically sand. Sand is a loose material that consists of a mixture of grains with sizes that can vary from a micrometre up to a few millimetres. Adding a small quantity of water to sand strongly influences the mechanical behaviour. The formation of capillary bridges between the grains results in a capillary pressure causing an attractive force between the grains: a cohesive network of grains that are connected with liquid bridges is formed [50]. However, adding too much water to sand results in coalescence of the capillary bridges and thereby decreases the strong binding between the grains. The influence of pouring water onto sand — from a dry pile of sand up to a muddy surface — has been observed for the stiffness of the mixture [6,51]. The elastic shear modulus varies nonmonotonically with the addition of water and has an optimum when some, but not too much, water is added. Here, we question the role of the slider geometry dragged over wet sand, to aim for a deeper understanding of the sliding friction.

(ii) We discuss the sliding friction on ice that, as any ice skater has observed, is a surface that is extraordinary slippery. The question *why* ice is so slippery has been debated for more than 150 years. Furthermore, ice friction is generated by an interface that includes many discrete contact points, due to the surface irregularities on the ice and slider. Understanding how this extended interface impacts the slipperiness of ice remains difficult to address because the interface is buried between two bulk materials. With the use of sliding experiments and contact mechanics calculations, we aim for a deeper understanding on how the surface irregularities of the surfaces shear over each other.

(iii) We explore how we can tune the sliding friction with geometrically controlled surfaces. Even in everyday scenarios, one can observe that two smooth surfaces slide more easily over each other than two rough ones. However, at the microscopic scale the opposite can be observed: periodic roughness can decrease the sliding friction drastically [44]. The commensurability of periodic nanoscale surfaces can result in a low amount of adhesive interaction and, therefore, direct variation of the commensurability enables the sliding friction to be controlled [52,53]. Here, we question the influence of macroscopic periodic roughness and their commensurability on the sliding friction.

1.6 Scope of this thesis

In this thesis, we discuss the macroscopic observed sliding friction and the underlying microscopic behaviour. First, in **Chapter 2**, we discuss the experimental and numerical techniques that are used in the main research chapters (Chapters 3 to 6). We discuss the two tribometers used to perform sliding tests, as well as the quantification of penetration hardness, the characterisation of surface topography, and the numerical techniques used to calculate the contact mechanics.

In **Chapter 3** we discuss the ploughing through dry and wet sand. We perform experiments where we drag a hemisphere over wetted sand and measure the friction as a function of the water volume fraction. The slider sinks into the water-sand mixture and, consequently, ploughs through the sand which leaves a deep trace after its passage. The measured friction is greatly impacted by both the water fraction in sand and the chosen geometry: The water fraction controls the hardness of the water-sand mixture and the geometry of the slider, together with its load, controls the contact pressure imposed on the wet sand. We observe that both the trace left in the sand after sliding the hemisphere and the hardness of the water-sand mixture vary significantly with the water volume fraction. Adding a small amount of water results in an optimum in the hardness and a resulting minimum in the sliding friction. We present a ploughing model for the sphere-on-flat geometry that captures the observed ploughing friction through wet sand.

In **Chapter 4** we continue the discussion of partially water-saturated sand and relate it to the performed transportation of statues by the ancient Egyptians. A Tomb drawing suggests that water is poured in front of the sledge which is pulled with the use of manpower. Indeed, adding a bit of water decreases the sliding friction as we observe — in agreement with earlier studies — for sliding a 'statue' over wet sand in miniature. However, pouring more water to sand results in a muddy surface that increases the sliding friction again. We discuss the influence of the mechanical behaviour of (wet) sand on sliding a sledge over sand and show that ploughing greatly impacts the sliding friction. Pouring a limited amount of water to sand can reduce the ploughing, thereby decreasing the pulling force required to slide a sledge on sand.

In **Chapter 5** we discuss the slipperiness of ice. Ice friction is critical to winter sports, glacier movement, and transportation risks. We combine sliding experiments, a 'skate' sliding on a miniature ice skating rink, with contact mechanics calculations and hardness tests to study this system. We discover that ice friction is low because of the diffusive motion of surface ice molecules, combined with the exceptional hardness of ice close to its melting point. It is not always easy to skate on ice, the slipperiness of ice can be suppressed by a high contact pressure or a low temperature.

In **Chapter 6** we explore how one can tune friction with the use of geometrically patterned surfaces. Sliding friction is often specific to the material and surface properties and can be hard to predict. Depending on the application, either high friction for grip, or low friction for easy sliding can be desired. We fabricate sliders with artificial macroscopic surface patterns and explore how the surface roughness controls the sliding friction. We show that direct variation of the designed surface roughness allows the friction force to be varied by more than an order of magnitude. In addition, with the use of Kirigami metamaterial surfaces the friction can be tuned externally by a direct variation of its surface roughness.