Tribology, friction and traction: understanding shoe-surface interaction

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Abstract

Friction has been studied since the early investigations of Leonardo da Vinci, Amontons, Coulomb, and Euler, and many experimental investigations have been used to measure the friction force between contact surfaces. However, in the case of non-homogenous and different surfaces commonly experienced in sports, all of the laws of friction are violated. The area of tribology provides an opportunity to describe the relationship between footwear and the surface in engineering terms and explain how traction is generated on sports surfaces. The paper firstly examines the mechanisms used to explain dry friction, and uses these to explain the complex mechanisms associated with field footwear-surface interaction.

Much has been written about the shoe-surface interaction and its role in performance and injury prevention (Nigg, *et.al*., 1986; Frederick, 1986; Nigg and Seggeser, 1988; Milburn and Barry, 1999; Gronquist, *et.al*., 2001). However, very little is understood about the mechanisms that underlie how this interaction occurs yet the theory has existed for many years. The area of tribology provides an opportunity to describe the relationship in engineering terms and explain how traction is generated on sports surfaces.

Dowson (1979) in his book on the *History of Tribology* mentioned how the notion of tribology involving "…interacting surfaces in relative motion" (page 1) was forever present in devices invented by man and had affected mankind's quality of life, by stating that

> … surface interactions dictate or control the functioning of every device developed by man to enhance the quality of life through his inventiveness and the utilisation of the resources of the physical world (, page 1).

Similarly, footwear was a device invented by man to protect the foot from injury and wear, and to enhance mobility. The same protective and mobility criteria apply in the realm of sport where the footwear impinges on the sport surface. However, sport usually involves a contest and the athlete who is able to stop, accelerate, or change direction more rapidly than their opponents because of superior traction on the surface would have an advantage over their opponents provided they are not injured while competing. Without friction it would be impossible to play football irrespective of the materials utilised for the contacting surfaces. This would apply whether the outsole surface of the shoe was leather, rubber, or polyurethane, or whether the sport surfaces were artificial or natural, solid or granular, covered in grass (turf) or bare, or soft or hard. From Newton's Laws of Motion, it is essential that athletes develop sufficient ground reaction force (GRF) while pushing on the surface to lift or lower their body, to change direction, and/or accelerate in the chosen direction, or to stop. Traction on the surface is gained because of the presence of friction between the contacting surfaces and it hopefully provides sufficient GRF for the athlete to complete the manoeuvre (McNitt, 2000; Barry, 2004; Luo and Stephanyshyn, 2011).

In a review of the quality of sports surfaces, Bell, *et al.* (1985) provided a useful definition of friction and traction.

> Friction and traction are the properties which enable the player to make movements necessary in sport without excessive slipping or falling. The term ‘friction’ applies to smoothed-soled footwear and ‘traction’ to footwear having studs, cleats or spikes to provide extra grip, although clearly there are sole types which could be considered intermediate, in which case either term would suffice. (page 34).

Frederick (1984) defined traction as “…the frictional coefficient between different shoes and surfaces.” (page 281). However, traction in this context was based on the notion of one of the contacting surfaces being freely mobile. The term 'traction' is utilised where one of the bodies has the ability to develop its own power while it attempts to gain motion by contacting the other body which is usually stationary, and perhaps flat and level. For example, the runner or sprinter on the athletic track, the tractor or bulldozer in the field, the tennis player on the tennis court, and the footballer on the playing field, all rely on friction to initiate or change motion. In each case one body is trying to move by pushing on the stationary surface. Therefore traction is considered to be the propulsive or braking force generated on the sport surface by an athlete or machine to achieve a chosen manoeuvre. Traction is always parallel to the stationary surface and is directed opposite to the motion of the moving object. This paper attempts to explain the interaction between the outsole and natural turf surfaces in engineering terms and restricts the movement to human beings wearing footwear and the surfaces associated with field sports.

Traction is developed because of the complex frictional resistance offered by the sliding surfaces and the ideas pertinent to friction mechanics are examined below. These concepts are explored firstly in relation to two solid surfaces and secondly where one surface is solid and the other granular, and concludes by examining the traction of flat and cleated plates on granular materials that exhibited inter-particle friction and adhesion.

Friction on two solid surfaces

Friction has been studied since the early investigations of Leonardo da Vinci, Amontons, Coulomb, and Euler, and experimental investigations were used to measure the friction force between contact surfaces (Dowson, 1979; Czichos, 1986). In the late 14th Century the “classical laws” of friction were first stated by Leonardo da Vinci. In 1699 Amontons ‘rediscovered’ these laws and confirmed by experiment that the friction force was independent of the area of the surfaces and was directly proportional to the normal load as shown by Equation 1.

$$F_S = \mu\ F_N \qquad (1)$$

Where F_S = the sliding traction force,

F_N = the normal force, and

μ = the apparent coefficient of friction.

Coulomb in 1785 confirmed the first two laws and added the third - that the friction force was independent of the velocity of sliding (Bowden and Leben, 1939; Brungraber, 1976; Tabor, 1981). In 1835, Morin introduced the idea that friction could be differentiated into static and dynamic friction. Static friction was considered the force necessary to begin motion rather than maintain it whereas dynamic friction was usually slightly smaller and is described as the force necessary to maintain the motion (James, 1983). However, in the case of non-homogenous and different surfaces, all of these laws were violated (Derieux, 1934).

Despite considerable experimental and analytical research, no ‘simple’ theoretical model has been developed to calculate the friction between two given surfaces (Suh and Sin, 1981; Czichos, 1986). It was stated by Bowden and Leben (1939) that there is “…no clear understanding of the mechanism of friction of sliding solids” (page 371). Our knowledge of the sliding process is considered inadequate (Rabinowicz, 1956) and friction still remains one of the most familiar and yet least understood facets of mechanics (Brungraber, 1976). A theoretical explanation of friction still does not exists and there is no simple model that allows the prediction or calculation of friction for a given pair of solid surfaces (Czichos, 1986). Heilmann and Rigney (1981), stated

> Most of us can agree on a simple definition of friction, but when we try to go much further, we find considerable disagreement about its fundamental nature. Moreover none of the analytic expressions which have been developed can be used to calculate reliable values for friction coefficients. (page 15)

The current state of our knowledge of the mechanism of friction is covered below and will be extended to cover surfaces that are not sensibly solid but are granular instead. When Coulomb established the ‘classical laws’ of friction, the physical model of the process he attributed friction to the force required to slide rigid high points (termed asperities) on one rough surface over the asperities of the other surface by a lifting action. Coulomb also recognised that adhesion played a role, but it was Desagulier in 1854 who first suggested that adhesion was an important factor in friction (Johnson, 1981). The idea of surfaces with high friction being rough and surfaces with low friction being smooth originated with Coulomb. The apparent correlation between rough and smooth surfaces, however, is now considered to be false as expressed clearly by Tabor, (1981).

> ... it is still customary to refer to frictional surfaces as rough, and frictionless surfaces as smooth - this is spite of the fact we know that this correlation is false and completely out of date. (page 170)

The Coulombic laws of dry friction relevant to an understanding of traction are:

(i) The friction force is dependent on the kinds of materials in contact and their roughness;
(ii) The static friction force developed at the point of sliding is dependent upon the normal force applied to the surfaces;
(iii) The friction force is independent of the apparent geometric area of contact; and
(iv) The friction force is inversely dependent on the velocity - decreasing as velocity increases (Jenson and Chenoweth, 1990; Nigg, 1990; Czichos, 1986).

However, if the surfaces were lubricated the corresponding laws become:

(i) The friction force is <u>independent</u> of the kinds of materials in contact and their roughness.
(ii) The static friction force developed at the point of sliding is <u>independent</u> of the normal force applied to the surfaces.
(iii) The friction force is <u>dependent</u> upon the apparent geometric area of contact.
(iv) The friction force is dependent upon the velocity - <u>increasing</u> as velocity increases (Jenson and Chenoweth, 1990).

Clearly, the laws for lubricated surfaces are different to those for dry friction, because of the effect of the film of lubricant between the surfaces. In the case of footwear traction, the types of contact surfaces are many and varied and may be dry, dusty, fibrous, granular, organic and wet, moist or 'lubricated'. For example, from the experiments conducted by Valiant (1994) and Van Gheluwe, *et al.* (1983) the friction force for footwear with rubber or polymer outsoles moving over artificial turf surfaces increased with increase in contact area in violation of the ‘classical’ laws of friction. Bonstingl, *et al.* (1975) also reported this finding. However, for dry friction the friction force was independent of the area of contact (Jenson and Chenoweth, 1990) contrary to the above findings.

An excellent statement that summarises the current thinking on the nature of friction was given by Heilmann and Rigney (1981).

> Two major approaches have dominated attempts to understand the origin of sliding friction. One of these has emphasized the role of surface roughness and the interlocking of surface asperities of various geometries. The other has focussed on the role of adhesion and direct inter-atomic forces. …
>
> The most widely accepted model for friction, that of Bowden and Tabor, incorporates both of these approaches, since it involves adhesion of surface asperities to form junctions and subsequent shear of junction materials. In this model one assumes homogeneous and isotropic materials which are in contact only at surface asperities. These asperities deform elastically or plastically until the contact area, A, supports the normal load, L. (page 15)

Therefore, analytical investigations of friction currently attribute friction to a complex molecular-mechanical interaction that occurs between the contacting surfaces. This complex interaction was thought to be due to the combined effects of asperity deformation, ploughing by hard surface asperities and wear particles, and adhesion between flat surfaces (Suh and Sin, 1981; Czichos, 1986). Three basic notions are used in an attempt to explain the sliding process and how friction develops between unlubricated sliding solids (Tabor, 1981; Czichos, 1986). To understand the sliding process and how friction is developed requires an understanding of:

(i) the area of real or true contact between the sliding surfaces;

(ii) the type of strength of bond (adhesion) that is formed at the interface where contact occurs; and

(iii) the way in which the material in and around the contacting region is sheared and ruptured during sliding (by ploughing or deforming).

Firstly, the real area of contact is the sum of each individual contact at the asperities. This depends on the topography of each surface (shape, number, height, and distribution of the asperities) and their material deformation properties (whether they are elastic, plastic, viscoelastic, viscoplastic, brittle, or combinations of these; and the value of the following variables: Young's modulus, yield pressure, plastic index, and hysteresis loss leading to a time dependence). As sliding of the surfaces occur, the real area of contact varies in value and at present, it is impossible to experimentally measure. It can only be deduced before and after the surface contact (Tabor, 1981; Czichos, 1986; Lambe and Whitman, 1979; Chang, *et al.*, 2001). At the molecular level, smooth solid surfaces in fact are not perfectly smooth - they have valleys and ridges or asperities, and at a given instant, some of these asperities will be touching, as shown in Figure 1. The sum of the area of these contacts is the real area of contact and is usually smaller than the apparent geometric area of contact. The topography of the surface (roughness) is dependent on the distribution of asperities and the deviation of their heights and their slopes. (Czichos, 1986).

Figure 1 about here

Secondly, the adhesion component of friction or the strength bond arises from the adhesion of the molecules in the surfaces in contact with each other. This adhesion may be so strong that at some contacts, tiny fragments are torn off and stick to the other (Rabinowicz, 1956). The larger, short-range forces, where the surfaces are in more intimate contact, include metallic, covalent, and ionic forces, and the smaller longer-range forces are van der Waals bonds (Czichos, 1986; Chang, *et al.*, 2001). Of significance to understanding shoe-surface interaction is the point made by Tabor (1981) that the bond could develop in a region of failure distant from the stronger surface interface.

> It [the bond] may depend to some extent on the mutual orientation of the two surfaces but broadly speaking the bond will be as strong as the metal itself. In fact, because of the plastic yielding and work hardening the interface may be stronger than the undeformed material in the hinterland. This means in sliding, separation will not occur in the interface itself but at some distance away (Tabor, 1981, page 173).

This phenomenon of the transference of the failure surface to another slip plane in the weaker surface is used in soil mechanics and is based on the plastic equilibrium theory applied to semi-infinite soil masses. For example, this theory is used to estimate bearing capacities of foundations, or solve what is more relevant to this research, the Grouser-plate problem (Wu, 1970) and is described later.

Thirdly, the material behavioural components of friction involve two mechanisms: the ploughing component and the deformation component. In contacts where one surface is harder than the other, its asperities and wear particles penetrate into the softer surface and plough through it. The deformation component depends on the surface material load deformation properties and slip-line theory. That is, the materials' Young's modulii (E), hardness (H), and shear strengths, and the use of rigid perfectly plastic behaviour. How the asperities in contact respond to each other also depends on their material deformation properties, that is, their Young's modulii, and hardness, along with the yield pressure (p_y) . For inelastic materials like polymers, viscoelastic, viscoplastic, and relaxation effects lead to a time-dependence of the contact area and hysteresis losses associated with the loading-unloading cycles. However, the ploughing and deformation components separately overlap and interact in a complex way in reality (Czichos, 1986).

While there is no accepted theory of friction, the complex molecular-mechanical interaction models mentioned above have been used to explain how the friction force is developed. Clearly, the types of materials in contact and their geometry have an important influence on the friction force. In the case of field footwear, the materials in contact would be outsoles made from polymers, plastics or rubber with various patterns or cleat configurations, interacting with either natural or artificial turf. However, the mechanisms used to explain dry friction can provide the basis to explain the mechanisms associated with field footwear-surface interaction.

Traction in and on soil or granular surfaces

The 'classical laws' are based on experimental studies and apply to dry, smooth and rough solid homogeneous surfaces in contact. It has, however, been acknowledged that the laws for dry friction do not fully explain the reason traction is developed between footwear and defined surfaces. It is already well known that the laws that explain dry friction change when the contacting surfaces are lubricated (Jenson and Chenoweth, 1990; Meriam and Kraige, 1992). Therefore, the mechanism that explains traction would be different to the mechanism explaining dry friction when one of the contacting surfaces is not smooth or solid but is granular and/or is wet, or when the footwear has cleats or studs. . Natural field surfaces are usually turf made from selected soils sown with various grass species, therefore the material properties used in the study of soil mechanics and terramechanics would be relevant.

Soils differ from solids in that they consist of discrete particles that are not strongly bonded together and are relatively free to move with respect to each other (Lambe and Whitman, 1979). The surface soils on playing fields are also subject to weather so the spaces between the particles are usually partly filled with water and what space remains would be filled with air. Therefore, the soil matrix consists of two spaces but has three phases: a mineral skeleton of solid rigid particles in contact with each other at their asperities, a pore space filled with different percentages of air; and water depending upon the degree of saturation of the pore space.

When a load is applied to the soil's surface through the outsole, and through cleats after they penetration the soils surface, the soil resists the applied loads by developing contact forces wherever they touch at their asperities. There are a large number of contacts within a soil mass, for example, about five million contacts within one cubic centimetre of fine sand (Lambe and Whitman, 1979). These contact forces can be resolved into normal (N) components and tangential (T) components (Figure 2). At each contact, the particles respond by deforming in three ways: the particles can compress; they can bend; and they can slide as shown in Figure 2. Deformation due to sliding is usually the most significant, and is non-linear and irreversible, therefore, the load-deformation behaviour of soil is usually non-linear and irreversible (Lambe and Whitman, 1979).

Figure 2 about here

Because sliding between particles predominates, some of the mechanisms used to explain dry friction have been applied to soils. The external forces that cause sliding within soils are resisted by friction and bonding forces between the particles. If the applied forces become large enough, failure of the soil mass may occur. Failure occurs when the contact resistance (friction and bonding) reaches its limit and the soil mass as whole slides. The plane connecting all the particles where failure has occurred is known as the failure or slip plane, and the limiting contact resistance has reached the shear strength (τ) of the soil. Unlike solid surfaces and dry friction, where the failure plane generally corresponds to the plane between the two surfaces, the failure plane in soils is not predefined. Somewhere in the soil mass the stress levels may exceed failure values and all these localities connected form the slip plane over which sliding occurs.

The presence of water in the pore space has a significant influence on the shear strength of the soil. Water influences the shear strength in three ways: it can introduce chemical elements to the contact surfaces and may separate the particles, when flowing it can alter the magnitude of the contact forces between particles, and it can immediately share a suddenly applied load by developing a pore pressure. The pore pressure can subsequently dissipate if free to do so, and therefore soil can also exhibit a time dependency (Lambe and Whitman, 1979).

The size and shape of the soil particles and their bonding called cohesion also influence the shear strength developed. Coarse grain soils such as sands and gravels develop shear strength mainly from inter-particle friction. The very fine grain plate-like soils such as clays develop shear strength mainly from inter-particle bonding or cohesion. The combined influence of friction and cohesion on the shear strength of soils was incorporated in the law governing the shear failure of soils proposed by Coulomb in 1773. Shear strength was frictional in nature and was assumed to be proportional to the normal force pushing the particles together and added cohesive effects. It is known as the Mohr-Coulomb (1882) failure because the state of stress from a number of peak points of the stress-strain curves are constructed as Mohr (1882) circles that are enclosed by a straight line as shown in Figure 3. The line is known as the Mohr failure envelope. Stress conditions above the line cannot exist - those below can - and those on the failure line are at a state of imminent failure. The shear strength is obtained from the Mohr-Coulomb law expressed as

$$\tau = c + \sigma_N \tan \varphi \qquad (1)$$

where τ = shear strength of the soil at failure,
c = cohesion of the soil,
σ_N = normal stress on the soil, and
φ = the angle of friction of the soil.

Figure 3 about here

The Mohr-Coulomb law is generally accepted as providing a physical description of the mechanism of shear failure of soil-on-soil surfaces. It implies that when the shear strength of the soil is exceeded, the shear force has overcome the cohesion and the friction forces that exist between the soil particles, and the two soil surfaces then slide relative to each other along their common failure surface (Koolen and Kuipers, 1983).

Static and dynamic (kinetic) friction

Generally the traction force for a plate sliding on sand reaches a peak at a small slide distance and then drops to a residual value as the sliding distance increases as shown in Figure 4 for a steel plate under increasing vertical loads while sliding over air-dry sand. Static friction is associated with the peak value before gross sliding has occurred and kinetic or dynamic friction is based on the residual values immediately after sliding has occurred. That is, the static friction is found from the force needed to initiate sliding of the surfaces and the kinetic friction is the forced needed to sustain the sliding (Pooley, 1978; Bell, *et al.*, 1985). Furthermore, the roughness (Spoor, 1969), and hardness of the plate surface (Nichols, 1931), along with the moisture content (Koolen and Kuipers, 1983), density and porosity (Butterfield and Andrawes, 1972), and particle size of the sand (Nichols, 1931) also affect the friction coefficients.

Figure 4 about here

Soil penetrating elements (Grouser plate)

Attaching soil penetrating elements such as vertical grousers, stops, studs, cleats, or blades to the underside of a sliding plate or the sole of a football boot changes the shape of the boundary between the contacting surfaces. The slide surface is no longer flat and the penetrating elements recruit deeper layers of soil beyond the immediate surface structures (for example, grass). Each penetrating element would be surrounded by soil that could now develop a resistance to sliding. To produce optimum traction the soil pressure (passive) needs to be fully developed over the front surface of all the elements. The optimum traction would depend upon the arrangement of the penetrating elements such as their number, spacing, size and shape, and the cohesive and frictional properties of the soil. The failure surface would then change its position, and where the failure plane developed would depend on the arrangement of these penetrating elements. Therefore, basic research from terramechanics into the design of vehicle tracks, in particular the traction of a single track element or grouser plate when travelling over different surfaces, provides useful information to help understand the traction of football boots on sports fields (Barry and Milburn, 1999).

Grouser plates have been used to model off-road vehicle track tread elements and agricultural implements (Bekker, 1960; Wong, 1989; Wu, 1970; Yong, *et al.,* 1984; Koolen and Kuipers, 1983). The grouser plate is formed from two plates joined to form a right angle. The vertical plate (grouser) penetrates into the soil and is rigidly attached to a horizontal plate resting on top of the soil (Figure 5).

Figure 5 about here

By increasing the inclined load applied to the grouser plate while it is held at a constant angle (α) it reaches the limit load whereupon the soil erupts along and up from the failure surface. Haythornthwaite (1961) first solved this problem and found lower and upper bound values for the inclined load based on the assumption that soil behaved as a rigid-plastic material. That is, the soil behaves as a rigid mass up to the point of failure, thereafter it yields along the failure surface without any increase in load. Yong and Sylvestre-Williams (1969), Yong, *et al.,* (1984) and Harrison (1973a, 1973b) found the limit load for a grouser plate on sand and demonstrated good agreement between the theoretical and experimentally measured results.

The effect of the spacing and shape of multiple grouser plates have been studied by Bekker (1960), Ikeda and Persson (1968), Cho, *et al.* (1969), and Yong, *et al.* (1984). Bekker (1960) adapted Terzaghi’s method used to find the bearing capacity of a continuous footing to find the minimum spacing between grouser plates so that each grouser fully developed it traction capacity. Ikeda and Persson (1968) tested seven differently shaped grousers on soft soil singly and in pairs at various spacing. Using the same number of grousers, Cho, *et al.* (1969) measured the effect of lengthening and widening the array of grousers on the traction force. Yong, *et al.,* (1984) varied the spacing between grousers and measured the traction force to find the optimum spacing for three different grouser shapes. Barry (2004) found that the location and length of two side by side grouser plates (called keys in this work) influenced the traction developed while sliding on and through air-dry sand. Keys placed near the middle third of the fine-ground steel plate measuring 100mm wide by 190mm long, that is, between

75 to 135 mm from the front edge (40% to 70% of the plates length) tended to produce larger traction forces than keys in all other positions. Generally the longer keys developed a greater traction force than the shorter keys and no keys. (Figure 6).

Figure 6 about here

Therefore, it would be anticipated that the size, shape, number and spacing of penetrating elements, such as conical stops or rectangular blades should theoretically affect the magnitude of the traction force developed by football boots holding different configurations of these penetrating elements. Furthermore, the way the loaded Grouser plate interacts with sand through its horizontal 'sole' bearing plate, and through its vertical penetrating plate, that eventually causes the surface to erupt at the maximum traction, may be used to help explain how football boots interact with sports surfaces. Finally, these ideas can be extended to study the traction of football boots on natural turf surfaces that have the soil particles reinforced by the fibrous roots of grass in their root-zone.

Conclusion

This paper has attempted to bring to the reader's attention the complex mechanism used by engineers to describe how traction is developed as two irregular surfaces slide over each other. It is hoped this will help explain how the shoe and surface interacts to provide traction in sporting footwear with stops that penetrate into the turf and granular surfaces. For example, it can explain why the middle third positioned grousers, stops or cleats develop greater traction than the others due to the confining pressure of the shoe's footprint on the surface impeding the surface material from erupting more readily from under the shoe. However, it also cautions there are no theoretical relationships at present that allow traction to be estimated from a knowledge of the properties of the shoe, the surface and sub-surface that are interacting as they bear load and slide over each other. Devices such as those at RMIT University (Barry and Milburn, 1999), the NIKE Sports Research Laboratory (NIKE Inc.,1990) and more recently as presented by Wannop et al (2009) have been developed to measure and analyse the variation in traction as the shoe slides on the turf surface to provide some understanding of the behaviour and design of sports turf footwear and can provide some insight into the theory behind sporting footwear design.

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