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Research Paper

A study of friction mechanisms between a surrogate skin (Lorica soft) and nonwoven fabrics☆

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ABSTRACT

Hygiene products such as incontinence pads bring nonwoven fabrics into contact with users' skin, which can cause damage in various ways, including the nonwoven abrading the skin by friction. The aim of the work described here was to develop and use methods for understanding the origin of friction between nonwoven fabrics and skin by relating measured normal and friction forces to the nature and area of the contact (fibre footprint) between them. The method development work reported here used a skin surrogate (Lorica Soft) in place of skin for reproducibility. The work was primarily experimental in nature, and involved two separate approaches. In the first, a microscope with a shallow depth of field was used to determine the length of nonwoven fibre in contact with a facing surface as a function of pressure, from which the contact area could be inferred; and, in the second, friction between chosen nonwoven fabrics and Lorica Soft was measured at a variety of anatomically relevant pressures (0.25–32.1 kPa) and speeds (0.05–5 mm s^{-1}). Both techniques were extensively validated, and showed reproducibility of about 5% in length and force, respectively. Straightforward inspection of the data for Lorica Soft against the nonwovens showed that Amontons' law (with respect to load) was obeyed to high precision ($R^2 > 0.999$ in all cases), though there was the suggestion of sub-linearity at low loads. More detailed consideration of the friction traces suggested that two different friction mechanisms are important, and comparison with the contact data suggests tentatively that they may correspond to adhesion between two different populations of contacts, one "rough" and one "smooth". This additional insight is a good illustration of how these techniques may prove valuable in studying other, similar interfaces. In particular, they could be used to investigate interfaces between nonwovens and skin, which was the primary motivation for developing them.

1. Introduction

Most human skin spends much of its time in contact with fabrics, and mechanical interaction between the two is central to clothing comfort. There are also some contexts in which the health of skin is critically dependent on its interaction with fabrics, such as the facing materials of absorbent pads worn by incontinent people, or (bed)clothes between the body and load-

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bearing surfaces of those susceptible to pressure sores. Yet the nature of friction between fabrics and skin is poorly understood, with the most fundamental experimental results still disputed; for example, there is no firm consensus as to the applicability of Amontons' law, or of the variation of friction with sliding speed, which must—in large measure—be attributed to a lack of robust, validated experimental methods. Furthermore, coefficients of friction are phenomenological. There is no widely recognised simple relationship between obvious surface properties and coefficients of friction for interfaces between either fabric (Ajayi, 1992; Hosseini Ravandi et al., 1994; Jeddi et al., 2003; Ramkumar and Roedel, 2003; Wang et al., 2006) or skin (El-Shimi, 1977; Nakajima and Narasaka, 1993; Bobjer and et al., 1993; Hendriks and Franklin, 2010) and other surfaces, despite the exertion of considerable experimental effort. The lack of a theory relating friction to material and surface properties denies guidance to the attempt to engineer materials with specified frictional properties.

If Amontons' law is to be rejected or placed on a firmer footing, much more must be understood about the mechanisms of friction in this instance: not only are the friction mechanisms far from clear, but the very nature of the interface is unknown. Accordingly, the work described in this paper set out to develop and validate two methods; the first, to measure the fibre footprint of nonwoven fabrics on surfaces; and the second to measure the friction forces between a surrogate skin and a selection of nonwoven materials of the kind commonly used in the body-facing coverstocks of incontinence pads accurately. Data generated using these two methods were then used to investigate the associated friction mechanisms.

2. Literature review

2.1. Methods for measuring friction between (surrogate) skin and fabrics

Methods reported in the literature for measuring friction between (surrogate) skin and fabrics can be divided into two main types: (1) rotational methods in which a circular pad or annulus faced with one material is pressed against the other material and rotated about its axis (Zhang and Mak, 1999); and (2) linear pull methods in which one material is simply translated across the other under load (Cottenden et al., 2008; Gerhardt et al., 2008, 2009; Derler et al., 2007; Gwosdow et al., 1986; Kenins, 1994; Hong et al., 2005; Comaish and Bottoms, 1971). Linear pull methods can be further divided into straight pull methods in which the translation is in a straight line across a flat surface (Cottenden et al., 2008; Gerhardt et al., 2008, 2009; Derler et al., 2007; Hong et al., 2005; Comaish and Bottoms, 1971) and curved pull methods in which a strip of one material is draped under load over a curved surface faced with the other material and is dragged along a curved path corresponding to a geodesic of the curved surface (Cottenden et al., 2008; Gwosdow et al., 1986; Kenins, 1994).

Each of these methods has its advantages and disadvantages. Rotational methods have the advantage that at least one commercial probe has been produced, lowering the barrier to beginning measurements. Such devices can also be self-contained and thus quite simple to use. However, they have several intrinsic limitations. The most fundamental is that since not all regions of the contact are experiencing equivalent conditions (sliding velocity is obviously proportional to radial distance) any reading must be an average, which cannot be interpreted without assuming some known variation of friction with velocity. These probes are thus by their nature not suited to fundamental measurements of how friction changes with velocity. Furthermore, strain fields and buckling patterns are often set up on compliant substrates, making the results hard to interpret with certainty.

Straight pull linear methods are the most direct of the three types of method, simply applying a load to an interface, putting it into sliding motion, and measuring the force required to initiate or maintain it. This has the advantage that the nominal condition of each part of the interface is the same, making the results easier to interpret. Due to the rectilinear pull the issues with buckling are generally less since the surface can move *en bloc* to accommodate, though for some interfaces problems still occur. The two main disadvantages of this type of method are that there is no known neat commercial implementation – thus requiring the equipment to be built in-house – and, more seriously, that it is difficult to provide a pulling force without either imparting a moment (due to the non-colinear pulling force and friction) or making the method very reliant upon perfect alignment of parts and non-robust against deformation.

Both rotational and straight pull linear methods suffer from difficulties with the shape of the probe on which the moving sheet material is mounted. It is well-known (though not universally appreciated) that a flat punch impressed into a compliant surface does not give rise to a uniform pressure distribution below it; rather, there are sharp peaks in pressure at the periphery (Johnson, 1985a). Though for interfaces that obey Amontons' law, departures from uniformity of pressure are clearly unimportant this is not so for more general interfaces. Further, frictional forces at an interface themselves distort the normal force distribution (Johnson, 1985b), quite apart from any incidental moments introduced by the equipment. These effects appear never to have been assessed or corrected for in friction measurements.

The curved pull linear method is the most indirect of the three methods, relying as it does upon the curvature of the surface to turn a tensile stress in the draped sheet into a normal stress which gives rise to friction. It is also an "integrated" method; that is, the measured force is the sum of a continuum of different contributions since the tension (and thus normal loading) change around the contact region. It is therefore necessary to use an established model to extract any desired interface parameters, and this will generally require some parameters of the curved surface to be known. In view of these points this type of method is not suitable for making fundamental friction measurements, though it is very suitable for certain routine measurements where a friction model has been established and one material is not usually flat, for example *in vivo* skin.

The novel method described and validated here aimed to overcome the majority of the problems exhibited by existing methods.

2.2. Skin surrogates

Any material co-opted as a surrogate skin must be equivalent to skin in the capacity in which it is being used. The overwhelming