Journal of Biomechanics 38 (2005) 2390–2396

JOURNAL
OF
BIOMECHANICS

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Lubrication regimes in mesothelial sliding

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Accepted 11 October 2004

Abstract

To function normally, the lungs, heart, and other organs must undergo changes in shape and size, sliding against surrounding body walls. It is not known whether the delicate mesothelial surfaces covering these organs and body wall are in contact during sliding, or if hydrodynamic pressure in the lubricating liquid increases separation between their surfaces. To address this question, we measured the coefficient of friction (μ) of the mesothelial surface of nine rat-abdominal walls sliding in saline on a smooth glass surface. Sliding at physiological velocities of 0.0123–6.14 cm/s with normal stresses of 50–200 Pa, μ varied with velocity ($P < 0.001$). On average, μ was relatively high at low speeds (0.078 at 0.041 cm/s), decreased to a minimum at intermediate speeds (0.034 at 1.23 cm/s), and increased slightly again at higher speeds (0.045 at 6.14 cm/s), consistent with a mixed lubrication regime in which there is at least partial hydrodynamic separation of surfaces. We conclude that mesothelial surfaces, sliding under physiological conditions, are protected from excessive shear by hydrodynamic pressures that increase separation of surfaces.

Keywords: Pleural; Tribology; Stribeck curve; Peritoneum; Elastohydrodynamic lubrication

1. Introduction

If they are to function normally, many of the body's organs, e.g., lungs, intestines, heart, must be able to change shape and size, and move relative to the enclosing body walls and other adjacent structures. For example, parts of the lung slide against the chest wall at velocities up to 20 cm/s during vigorous respiration, whereas intestines slide against each other and the abdominal wall at much lower rates, characteristically less than 1 cm/s. The surface of such organs and the surrounding body cavity are covered with a single layer of thin mesothelial cells overlying supporting connective tissues (Wang, 1975). The tissues are lubricated by a layer of fluid, typically 20 μm thick in the pleural space (Agostoni, 1986; Lai-Fook, 2004). The mesothelium can be easily damaged by gentle handling (Zocchi, 2002), yet these mesothelial surfaces are able to slide continuously on one another without damage, thereby preventing pathological adhesion between moving organs and surrounding structures. A central question concerning pleural sliding mechanics has been whether the surfaces of the lung and chest wall come into contact as they slide against each other (Agostoni and D'Angelo, 1991; Lai-Fook and Rodarte, 1991). Despite decades of experimentation, this question remains controversial, and the mechanisms involved in the tribological (frictional) behavior of sliding mesothelial surfaces have not been established.

The tribological behavior of engineering materials sliding in the presence of lubricating liquids is often described with a Stribeck curve (see, e.g., Adamson, 1982) in which the coefficient of friction (μ) varies characteristically with velocity (Fig. 1). Different regions

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doi:10.1016/j.jbiomech.2004.10.012

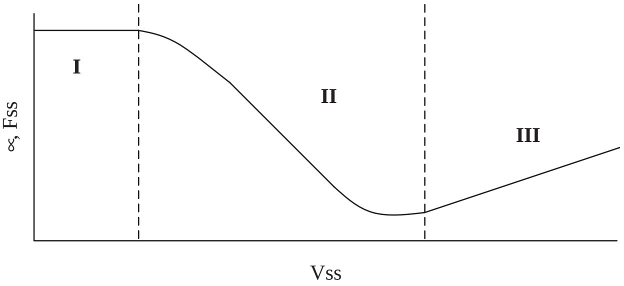

Fig. 1. Schematic Stribeck curve of material sliding in the presence of lubricant, showing variations in coefficient of kinetic friction (μ) and steady state frictional force (F_{ss}) as a function of steady state sliding velocity (V_{ss}). Numbered regions are associated with boundary lubrication (I), mixed lubrication (II), and fully developed hydrodynamic lubrication (III). See text.

of the Stribeck curve are associated with different lubrication regimes, as follows. At low speeds, μ is relatively invariant with speed. This is the region of *boundary lubrication* (region I in Fig. 1), in which solid-to-solid contact is the predominant mode of friction. At intermediate speeds, μ decreases with increasing speed to a minimum value and then begins to increase. This region of the Stribeck curve is the region of *mixed lubrication* (II in Fig. 1), in which the decrease in μ with speed is attributed to the increasing effect of hydrodynamic pressure within the shearing lubricant, which acts to separate the surfaces, thereby limiting contact between asperities. At higher speeds, in the region of fully developed *hydrodynamic lubrication* (III in Fig. 1), hydrodynamic pressure is sufficient to completely separate the sliding surfaces. In this regime, the increase in μ with increasing speed is due to increasing viscous shear stress in the lubricant. When the sliding surfaces are deformed or smoothed by hydrodynamic forces in mixed lubrication, such behavior is termed *elastohydrodynamic lubrication*.

To what extent normal mesothelial sliding velocities generate sufficient hydrodynamic pressure to smooth and separate asperities of soft mesothelial surfaces is not established. The earliest investigations of mesothelial friction examined static friction between pleural surfaces (Brandi, 1970; D'Angelo, 1975), and only recently have investigators published dynamic tribological experiments to explore these issues. D'Angelo et al. (2004) measured the coefficient of friction of mesothelial tissues sliding sinusoidally at peak velocities of 0.88–3.02 cm/s, and they found no dependence of μ on velocity. Here we examine the tribological behavior of mesothelial surfaces sliding at similar physiological velocities in steady state. We found that sliding mesothelial surfaces usually exhibit a strong dependence of μ on speed, and, unlike D'Angelo et al., we conclude that hydrodynamic pressure is often sufficient to at least partially separate sliding mesothelial surfaces.

2. Methods

These experiments were reviewed by the Standing Committee on Animal Use at Beth Israel Deaconess Medical Center. We studied the mesothelial (peritoneal) surface of the ventral belly wall of nine Sprague–Dawley rats of a range of ages, sizes and sexes. To minimize fibrin formation on the peritoneal surface or within the fluid, heparin (5000 units i.p.) was administered ~5 min before an animal was killed (sodium pentobarbital, >200 mg/kg). Immediately following cessation of heartbeat, the skin and subcutaneous tissues covering the abdomen were reflected. The intact abdominal wall (mesothelium plus overlying muscular layers, total thickness of 2–4 mm) was excised en bloc and kept moist with normal saline, taking care not to damage the mesothelial surface.

With its mesothelial surface facing outward, the abdominal wall was mounted over the opening of a shallow metal cup, 3.7 cm diameter, and secured with an encircling ligature making an airtight 'drumhead' (Fig. 2). Care was taken not to stretch the abdominal tissue while mounting it, so that the attached tissue drumhead visibly sagged under its own weight. Pilot studies suggested that the mechanical behavior of these tissue specimens does not significantly change during the first two hours postmortem; experiments included in this study were completed in less than 1.5 h.

The metal cup with its attached tissue drumhead was mounted on a rotational tribometer with the center of the tissue drumhead at the axis of rotation of a rotating glass plate (Fig. 2). The non-rotating mesothelial surface, submerged in physiologic saline solution, was pressed against the rotating glass plate by air pressure within the chamber formed by the metal cup. Rotation of the glass plate was driven by a computer-controlled stepper motor (SloSyn, Werner Electric, Minneapolis, MN) via a toothed belt. Frictional force on the tissue drumhead during rotation of the glass plate was measured as torque with a device based on a commercial

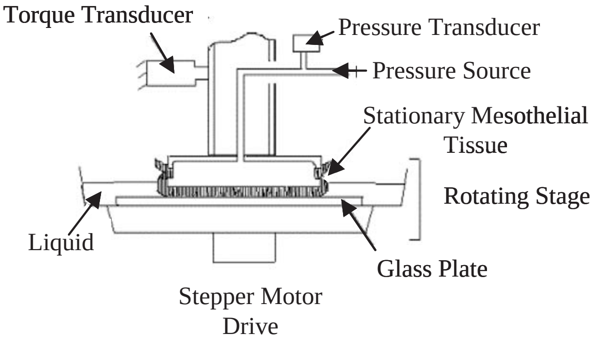

Fig. 2. Rotational tribometer used for the experiments. See text.