MEASUREMENTS OF THE FRICTIONAL PROPERTIES OF THE GASTROINTESTINAL TRACT

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SUMMARY
Locomotion inside the human body is an intriguing challenge for Biomedical Engineering and it is becoming more and more addressed by researchers and medical doctors studying novel monitoring and diagnostic microdevices for the gastrointestinal tract (GT). To design an effective locomotion mechanism for the GI tract, a deep understanding of the environment in which the microdevices have to navigate is mandatory. In particular, it is necessary to measure the biotribological properties of the surfaces in order to evaluate the entity of frictional forces exploitable to perform locomotion without damaging the tissue. In addition, the tribological mechanism, which is responsible for frictional forces, has to be understood since few researches have been carried out thus far on this topic. In this paper, the authors describe the experimental apparatus they have used to perform frictional measurements on pig colon, the most relevant results regarding the value of the friction coefficient and a simple model to justify the results obtained.

Keywords: Biotribology, friction, gastrointestinal tract, endoscopy.

1 INTRODUCTION

One of the main efforts of modern medicine is focused on the research of diagnostic and therapeutic techniques that conjugate effectiveness and reduction of the discomfort for the patient [1]. The ability of the surgeon to operate in the human body with minimally invasive techniques strongly depends on the available technical means. The next and rapidly approaching frontier of minimally invasive surgery is the introduction of miniaturized devices and microtools which will allow the surgeon to operate in the human body [2] entering from the natural orifices, e.g. using wireless autonomous swallowable robotic devices. The new micro instruments will be fully biocompatible and safe. At the same time, they will provide the surgeon with good locomotion control, i.e. exact positioning in the desired place and controlled displacements toward the areas of interest with a desired velocity. The gastrointestinal tract (GT) is noteworthy because it is commonly afflicted by a large number of severe pathologies [3]. Though the GT can be easily reached from the mouth or anus, it shows relevant difficulties for the locomotion of an autonomous microdevice which has to propel itself in normally collapsed and bent tubular organs. In order to counterbalance the locomotion resistance, the microdevice has to apply traction forces on the internal walls of the GT organs which, for physiological reasons, are slippery and extremely compliant. In order to devise a viable solution for the locomotion problem the experimental investigation of the tribological properties of the GT is mandatory.

It is a known fact that different organs in the GT show different biotribological properties. From a practical point of view, it is precautionary to investigate the locomotion in the worst possible situation (i.e. most lubricated). For this reason, the colon has been used to study the problem of friction since it is known to be the most lubricated part of the GT.

2 THE EXPERIMENTAL APPARATUS

The biotribological properties of the colon depend on the microstructure of its surface, depicted in fig. 1, and on the biological fluid which is used as a lubricant. To take into account the surface features and to neglect other factors (spatial dislocation and dimensions), in-vitro measurements on freshly explanted samples of tissue have been performed. The measurement of friction on biological surfaces requires attention in the in-vitro replication of physiological conditions. Biotribological studies have been conducted on articular cartilage surfaces [4], on flexor tendon [5] and in brain [6], but the physiological conditions in the GT cannot be compared to any of the previous organs. Consequently, a dedicated measurement set-up must be purposely designed.

The aim of the experimental measurements is the determination of the frictional force that is exerted by a surface loaded with a constant normal force as it slides with constant velocity on a colon tissue sample. Measurements have been conducted by varying both sliding velocity and normal load. The measurements have been performed with two different friction
surfaces to evaluate which effect the contact area and the profile of the sliding surface can have. The scheme of the set-up is depicted in fig. 2. The sample tissue is extracted from a pig’s colon, which has physiological properties similar to those of the human colon. The samples are roughly rectangular in shape with typical dimensions of 300 x 45 x 2 mm$^3$. Two aluminium parallel bars, screwed to a support, act as mechanical clamps to constrain the tissue. The support consists in a 15 mm thick aluminium plate. A test aluminium surface, with known mass, is loaded with calibrated weights. The surface is pulled by means of a flexible wire which winds round a pulley. The pulley is in turn connected to a DC servomotor (Portescap SA, model 17N-R16) that rotates with constant angular velocity despite of a varying torque. The motor is connected to a rigid frame by a load cell (Sensotec Inc., model 11) which measures the traction force $T$. To avoid the drying of the tissue and to preserve its integrity, the sample is continuously moistened with physiological solution at 37°C. The temperature of the support plate is also kept at the same temperature with the aid of six electric heaters (embedded in the plate) and a thermocouple (Stanford Research Systems, Inc., model SR630). Moreover, the high thermal capacity of the thick plate ensures that its temperature does not fluctuate too rapidly. In fig. 3 the set-up is shown during a typical test.

Figure 2: Experimental set-up

Figure 3: The set-up during a measurement

3  FRICITION TESTS RESULTS

The same set of measurements has been repeated using two types of aluminium friction surfaces (fig. 4). The first type, A, is smooth, while the second type, B, is grooved. For each surface a set of 18 measurements has been repeated for every possible combination of normal force and traction velocity reported in table 1. For each of the two sets of measurements a different sample of tissue (again explanted from adjacent regions) has been used, in order to avoid the abrasion of the surface.

<table>
<thead>
<tr>
<th>Traction velocity (mm/sec)</th>
<th>5, 11, 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load (N)</td>
<td>0.41, 0.66, 0.90, 1.39, 1.88, 2.37</td>
</tr>
</tbody>
</table>

Table 1: Velocities and loads used in the measurements

In the case of surface A the friction coefficient was estimated to be in the order of $10^{-3}$ and it could not be determined exactly because the value of the traction force $T$ was very close to the lowest sensitivity limit for the set-up which is determined by the minimum value of force which can be measured by the load cell ($9.8 \times 10^{-3}$ N) and by the presence of undesired friction forces in the mechanical transmission. Fig. 5 shows the experimental results for the surface B. The experimental data have been interpolated with a linear function of the form:

$$T = \mu L \quad (1)$$

where $L$ is the normal load and $\mu$ the friction coefficient. Table 2 reports the values of $\mu$ obtained for surface B at each velocity. The friction coefficient is only slightly affected by the traction velocity; consequently, we can use a mean value of $\mu$, neglecting the dependence from the velocity. We finally have:

$$\mu = 0.49 \quad \text{(surface B)}$$

The in-vitro results may differ from reality since the lubrication properties of the mucus which covers the colon walls are different from those of the physiological solution used to moisten the explanted samples. Anyway, the low friction coefficient for the smooth surface (0.001 ca.) is of the same order of magnitude of that of the articular joint lubricated with synovial fluid (0.003) [4] and this seems to indicate that the use of physiological solution instead of the natural mucus may have not a noteworthy influence. This consideration could be explained assuming that residual mucus
remains trapped in the ansae of the mucosa after the gentle cleaning of the surface.

Figure 5: Experimental data for the grooved surface

<table>
<thead>
<tr>
<th>Velocity (mm/sec)</th>
<th>µ</th>
<th>Variance (σ²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.47</td>
<td>0.990</td>
</tr>
<tr>
<td>11</td>
<td>0.53</td>
<td>0.989</td>
</tr>
<tr>
<td>14</td>
<td>0.47</td>
<td>0.979</td>
</tr>
</tbody>
</table>

Table 2: values of the friction coefficient for the grooved surface

4 DISCUSSION

The low value of µ for smooth surfaces indicates that any attempt to achieve locomotion exploiting the tangential force resulting from a normal pressure is likely to fail, because the slippery surfaces would require pressure values higher than the safety limit beyond which ischemia occurs [7]. On the other hand, surface B shows a two order of magnitude higher friction coefficient, indicating that grooved surfaces can dramatically increase the feasibility of a self-propelling micro device for the GT able to overcome the drag force of peristalsis. Since the change of the profile of the sliding surface has remarkably changed the value of the friction coefficient, it is of practical interest to understand the tribological mechanism responsible for this behavior in order to design safe and effective locomotion systems.

4.1 Lubrication mechanism

It is experimental evidence that dry GT tissues show a remarkable friction over many types of material, probably because micro-adhesion phenomena occur. On the contrary, lightly moistened samples show very low friction coefficients over smooth surfaces. In addition, the lubricant efficiency of the moistening liquid does not change with the velocity of the load, thus excluding the possibility that hydrodynamic lubrication occurs. Taking into account the microstructure of the GT walls depicted in fig. 1, a possible lubrication mechanism can be identified. In fig. 6 a schematic section of the GT tissue is shown. The volume between adjacent colon villi is supposed to be filled by physiological fluid (mucus). When a tangential stress is applied to the tissue, the deformation of the villi forces the fluid to squeeze out from the interstices thus producing a lubricating film in a sponge-like mechanism. As soon as the stress is removed, the fluid refills again the interstices. In this way, very small amount of fluid is sufficient to guarantee effective lubrication and protection of the fragile mucosa.

Figure 6: The lubricant fluid in the interstices (up) is squeezed out by the bending of the villi when a tangential stress is applied (down).

4.2 Friction due to hysteresis

Soft biological materials, as skin and vessels wall, show viscoelastic behavior [8] and dissipate a considerable amount of energy in hysteresis when subjected to load-unload cycles. The GT samples used in the measurements are extremely compliant and loads less than 0.5 N are sufficient to produce visibly large deformations. Consequently, loss of mechanical energy for hysteresis may be the main cause of friction.

If v represents the traction velocity of the friction surface, l and w respectively its length and width, E the energy loss per volume unit due to hysteresis and b the thickness of the sample, the balance between the dissipated energy and the work done by the friction force is:

\[
E w b v \, dt = T v \, dt \quad (2)
\]

or:

\[
T = E b w \quad (3)
\]

The value of E does not depend on the traction velocity [8] but only on the maximum value of the stress σ reached during the loading phase. By assuming a linear dependence of E from the stress we obtain:

\[
E = k \frac{L}{w l} \quad (4)
\]

From Eqs. (1), (3) and (4) we finally obtain:

\[
\mu = k \frac{b}{l} \quad (5)
\]

Eq. (5) justifies the experimental independence of µ from the velocity and describes how friction depends on the shape of the sliding surface.
The grooved surface (B) may be seen as a sequence of \( n \) (\( n = 8 \)) smooth surfaces each of which has a length \( l' = 2 \) mm. Eq. (5) can be modified to apply to surface B:

\[
\mu' = n \frac{k \beta}{l'}
\]  
(6)

Eq. (6) predicts the coefficient of friction of surface B is \( n l/l' = 220 \) times higher than that of the surface A. This theoretical result shows a very good correlation with the experimental data, because it predicts a friction coefficient for the smooth surface of \( 2 \times 10^{-3} \).

5 CONCLUSIONS

In the paper an experimental set-up to measure the coefficient of friction on GT samples has been described. The measurements have been performed on pig colon samples kept at a constant temperature of 37°C and moistened using physiological solution. The measurements have been repeated using two different shaped aluminium surfaces, one of which is smooth while the other is grooved. The smooth surface shows a very low friction coefficient even with little moistening. A possible lubrication mechanism has been described. The coefficient of friction has been evaluated in terms of energy dissipation in hysteresis cycles. With this assumption, it is possible to explain why the coefficient of friction is not dependent on velocity. In the future, further investigations will be performed to experimentally determine the viscoelastic behaviour of GT tissues, thus improving the accuracy of the friction model.

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7 REFERENCES