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DOI:10.3109/13645706.2015.1012083

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MINIMALLY INVASIVE THERAPY & ALLIED TECHNOLOGIES (2015) 24(4): 204-210
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Abstract
Background: This paper investigates different types of crimped, braided sleeve used for a soft arm for robotic abdominal surgery, with the sleeve required to contain balloon expansion in the pneumatically actuating arm while it follows the required bending, elongation and diameter reduction of the arm. **Material and methods**: Three types of crimped, braided sleeves from PET (BraidPET) or nylon (BraidGreyNylon and BraidNylon, with different monofilament diameters) were fabricated and tested including geometrical and microstructural characterisation of the crimp and braid, mechanical tests and medical scratching tests for organ damage of domestic pigs. **Results**: BraidPET caused some organ damage, sliding under normal force of 2-5 N; this was attributed to the high roughness of the braid pattern, the higher friction coefficient of polyethylene terephthalate (PET) compared to nylon, and the high frequency of the crimp peaks for this sleeve. No organ damage was observed for the BraidNylon, attributed to both the lower roughness of the braid pattern and the low friction coefficient of nylon. BraidNylon also required the lowest tensile force during its elongation to similar maximum strain as that of BraidPET, translating to low power requirements. **Conclusion**: BraidNylon is recommended for the crimped sleeve of the arm designed for robotic abdominal surgery.
Keywords: Abdominal surgery, soft robots, braided sleeves, crimped sleeves, pneumatic actuatio

Introduction

Soft robotics is a new field of robotic engineering that involves modules made from "soft" materials such as elastomers (1), most often incorporating pneumatic or hydraulic-based actuation mechanisms. The aim is to achieve smooth form and fluidic-type of motion compared to the traditional, rigid, multiple-component, multi-joint robots (2). The concept is particularly attractive for medical operations (Figure 1a): This includes diagnosis and surgery, where a soft arm can co-exist and navigate in a friendly manner amongst the soft organs (3).

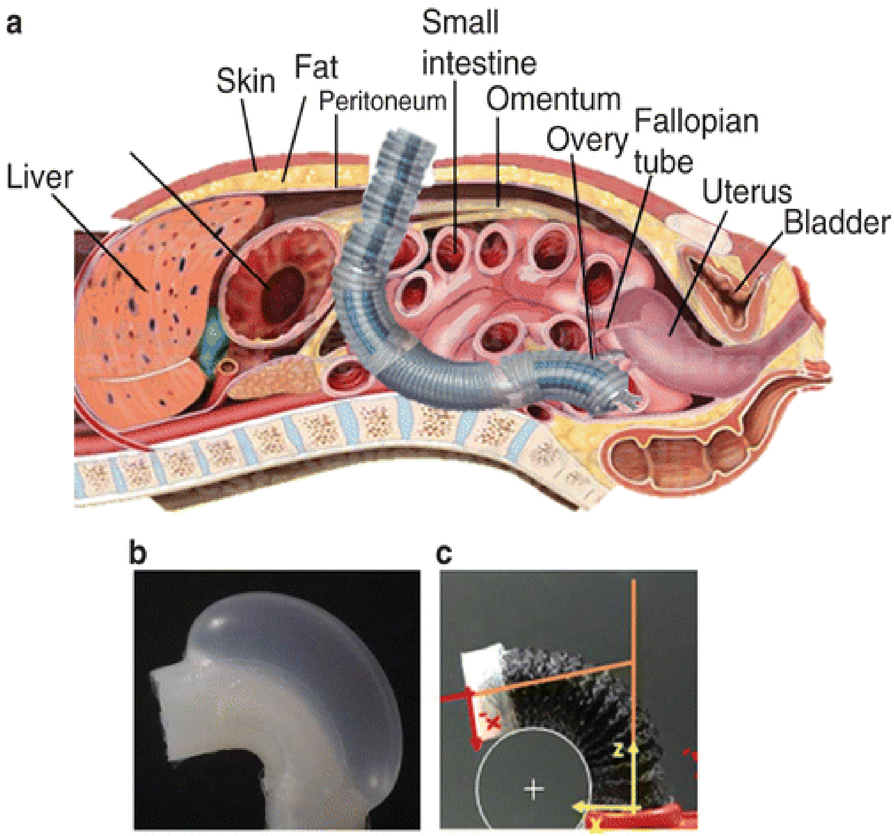


Figure 1. (a) Concept of abdominal surgery robotic arm consisting of soft actuating modules; (b) example of silicone soft module bending under pneumatic actuation; (c) system of silicone module and crimped braided sleeve bending under pneumatic actuation. In both (b) and (c) cases the bending angle is about 100^o.

Elastomer-based robotics are new and a great promise in the field of laparoscopic surgery, as elastomers are reliable and low-cost materials, and allow for safe actuation within the surgical environment using low acting pressures. They also open the field for disposable surgical manipulators, reducing the high cost of maintenance and sterilisation of current laparoscopic tools. Past research includes designs to mimic the muscular hydrostatic systems found in nature (4,5), such as the octopus arms (6), caterpillars (7), jelly fish and asteroids (8).

The present study is part of the European funded project STIFFness controllable Flexible & Learnable Manipulators for surgical Operations (STIFF-FLOP), which involves the development of a soft, pneumatically actuating robot arm for robotic abdominal surgery. The use of soft elastomeric materials in pneumatically actuating arms (9,10) has two drawbacks:

- a sizable radial expansion of the elastomeric wall of the pneumatic channel, forming a balloon (Figure 1b) that may cause adverse sudden interference with adjacent soft organs in endoscopy and surgery;
- the risk of burst of this balloon wall under the actuation gas pressure.

One approach to limit the ballooning effect of elastomeric modules under pneumatic actuation is to combine the elastomeric actuator with a sleeve that restricts radial expansion, while maintaining the bendability of the actuating arm, in addition to providing a protective sheath to the silicone. Textiles including braided, knitted, or woven architectures have long been in use in medical applications of orthopaedic casts (11), soft tissue grafts such as vascular grafts (12), or ligament grafts (13).

However, although sleeves of Dacron® crimped, vascular grafts may restrict balloon expansion and allow bending of an elastomeric pneumatic actuator, they would not comply with an additional requirement of our current project (STIFF-FLOP), to allow for elongation and contraction of the actuating arm to be able to squeeze through narrow passages (14). Hence, a braided bellow-type of sleeve was proposed in the STIFF-FLOP project, operating as in Figure 1c.

Braided fibre structures have been used in artificial pneumatically-actuated muscles, also known as the McKibben actuator (15,16) or in a directionally biased actuator with different braiding angles on either side of the module's body (17), but these actuators do not allow for multiple degrees of freedom (DOF). Furthermore, bellow designs are commonly used in actuating robotic modules (18,19) to accommodate bending, expansion under pneumatic actuation, elongation and shortening.

The solution proposed in STIFF-FLOP is to use an accordion-shaped, braided sleeve surrounding a soft silicone module with three internal pneumatic channels, so that the sleeve will allow multi-directional actuation and bending while constraining radial balloon-type of expansion of the pneumatic channel in the silicone module. This study focuses on the development of a crimped, braided sleeve for the soft robot. Different types of braided sleeves were tried in this study, including two fibre materials: Polyethylene terephthalate (PET, also known under its commercial name Dacron® as used in vascular grafts) and nylon (commonly used in medical sutures), as well as different braid structures for which innovative crimping techniques were developed in this study. Assessment involved mechanical deformation tests to compare the behaviour of alternative sleeves to a reference sleeve, which has functioned most satisfactorily in the actuating module (Figure 1c), and also medical tests in porcine organ system to assess the suitability of the braid material and structure during endoscopy or surgery.

Material and methods

Materials and crimping procedures

The following braided flat tubular structures were used as starting materials to crimp:

- BraidPET, braid made from PET filaments of 220 µm monofilament diameter;
- BraidGreyNylon, a braid with silver-plated nylon filaments of 260 µm monofilament diameter (braid typically used for cable electromagnetic shielding);
- BraidNylon, a braid with nylon 6,6 filaments of 200 µm monofilament diameter.

Although moulds were used to crimp knitted vascular grafts (20–22), the crimping process applied in this project is based on the buckling of tubular sleeves, sliding over an internal cylindrical mandrel under axial compression. An inert mandrel with a diameter 2-5 mm smaller than the nominal braid diameter was inserted inside the braided tubular structure. The ends of the sleeve were tied using cotton rope and then pushed towards each other causing the formation of accordion-shaped bellows. All sleeves were subjected to the same mechanical crimping procedure but the shape stabilisation procedure differed depending on the fibre material.

The PET braids were subjected to heat treatment at 130^{o}C for 45 min, to soften the PET while the bellow shape was mechanically maintained by a constant force for the PET crimped braid to relax and retain that shape after cooling. The nylon braid was subjected first to chemical treatment involving its immersion in a formic acid solution of concentration varied from a low 71 wt% to a high 76 wt%, for 15 s, causing the nylon to partially dissolve and set the links of the bellow. Formic acid is commonly used in the processing of collagen and other polymers in tissue engineering (23). Finally the braid was washed under running water to remove the formic acid, before undergoing the same heat treatment as the PET braid.

Characterisation of crimped braided sleeves and medical tests

Microstructural braid characterisation was conducted using optical microscopy and image analysis. Uniaxial tensile testing of the crimped braids was conducted in an Instron machine at 500 mm/min crosshead speed, where the crimped braid was clamped using pneumatic force grips.

With regard to medical tests, it is considered that the manipulator is specified to safely interact with the surgical environment, while it is able to navigate in the body cavities during a surgical task and move around organs and through narrow passages. The testing of the crimped braided sleeves for organ damage in scratching tests is considered an important criterion for sleeve selection and it was thought that it needs to be performed in *in vivo* environment rather than any artificial environment of synthetic materials. In order to assess safety of the sudden stiffening during the actuation of the robot arm, maybe even in a blind area, the *in vivo* interaction between the crimped braided sleeves of the robot arm and the abdominal organs was tested. An electronic load cell was used with a standard pin at the tip which we glued to a semi-spherical surface in order to mimic the round shape of the tip of the arm. The entire distal part and plastic cover were surrounded with the tested crimped braided tubular sleeve. The aim of the test was to detect micro and macro modifications of the surface of abdominal organs after perpendicular scratching on stiff surfaces covered by the different samples of tested sleeves. Tests were conducted on 50 kg domestic pigs. The animals did not receive specific preparation for the tests. The test protocol was approved by the Local Ethical Committee and the tests were performed at the AIMS Academy in Milan, Italy. The following potential organs were considered: stomach, liver, spleen and bowel. Hence, the test involved scratching the crimped braided sleeve over the surface of each of the previously listed organs by pressing the load cell and gliding the sleeve over the organ perpendicularly at different pressures, i.e. 2N, 3N and 5N, representing typical force levels experienced during surgical navigation and manipulation. Pressure was kept in the range of +/-0.5N of the target by constant visualisation of the display of the load cell while sliding the sleeve over the organ surface. The sleeves were moved under pressure on the tissue in both axial sleeve direction (crimps perpendicular to the direction of arm movement) and transverse direction (crimps parallel to the direction of arm movement) with the aim of simulating any possible realistic interaction between the robot arm and the vital organs. We also considered the feedback of four members of the surgical team, personally observing and recording the macroscopic and microscopic results as no clear objective evaluation could be conducted by microscopic histology examination.

Gravity force *in vivo* tests on the same organs (stomach, liver, spleen and bowel) were conducted to detect micro and macro modifications of the surface of abdominal organs after scratching (sliding over tissue at gravity pressure) of a standard gastroscope covered by the different samples of sleeves. The standard gastroscope (Karl Storz, Tuttlingen, Germany) was chosen as most resembling the final STIFF-FLOP module in dimensions. No consideration about its flexibility/stiffness was paid in this study. The crimped braided sleeve was placed around the tip of the scope, some 3 cm from the distal end. The sleeve was maintained in tubular shape and anchored with tissue tape.

Results

Figure 2 presents microstructural images of the three braids used in this study, the measured average filament diameter and the measured average R_z roughness (peak to valley distance). Each tow of BraidPET consists of three filaments, has a medium-size filament but the greatest roughness due to the excessive bowing of the PET filaments at the cross-overs. Each tow of BraidGreyNylon consists of four filaments, has the largest size filament and great roughness due mainly to the large filament size and some extra bowing at the cross-overs. Each tow of BraidNylon consists of three filaments, has the smallest filament size and, hence, the smallest roughness. With regards to the fibre material, nylon has the lowest friction coefficient (0.25-0.28) of most polymers, certainly much lower than PET (0.4-0.5), and the pure nylon in BraidNylon has a lower friction coefficient (due to smoother surface) than the silver-coated nylon in BraidGrayNylon.

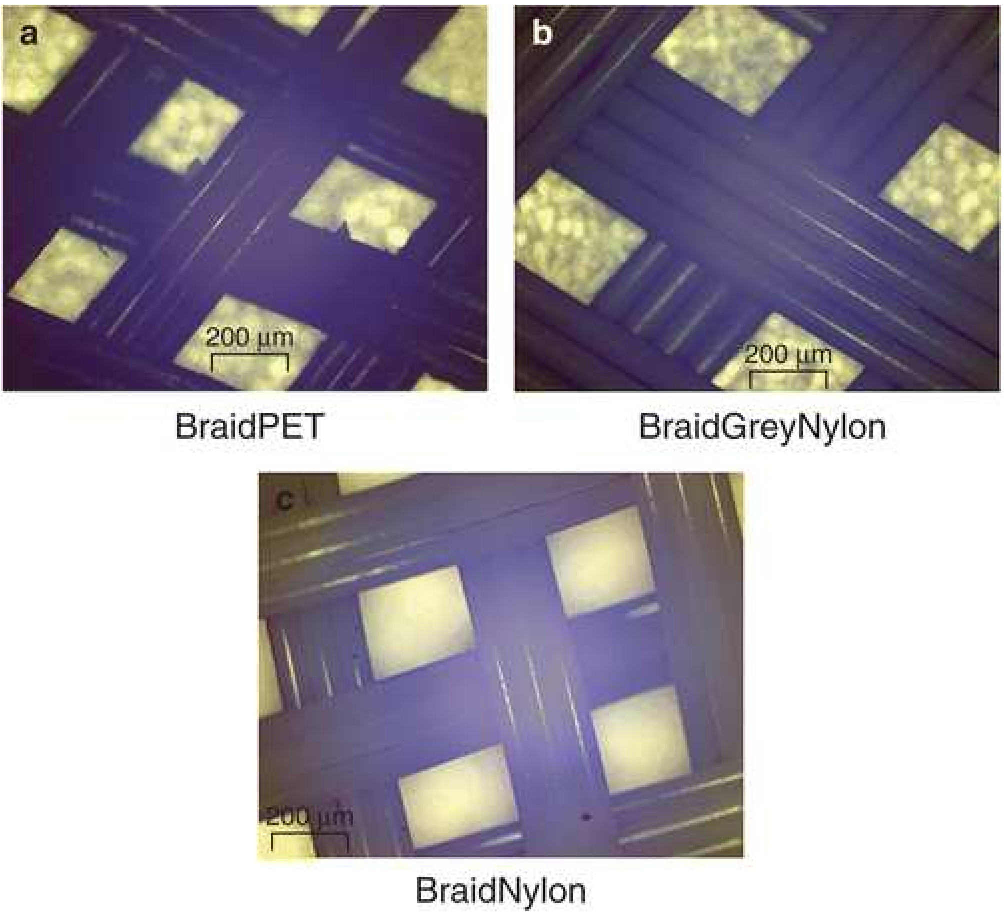
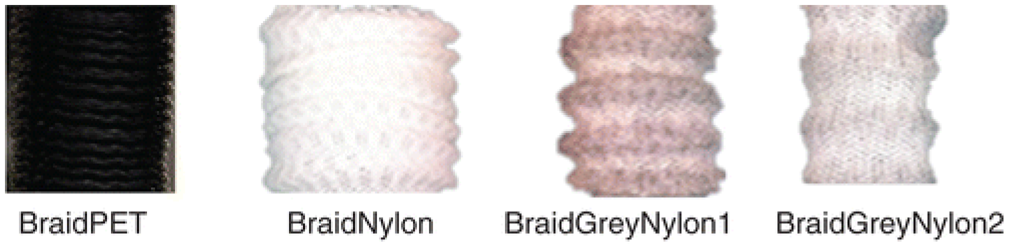


Figure 2. Optical micrographs of the different types of braids used in this study. Measured average filament diameter from 100 measurements for each type of braid: $d_{braidPET}$ = 220 ± 20 µm; $d_{braidGreyNylon}$ = 260 ± 30 µm; $d_{braidNylon}$ = 200 ± 20 µm. R_z roughness: $R_{z,braidPET}$ = 620 ± 30 µm; $R_{z,braidGreyNylon}$ = 610 ± 20 µm; $R_{z,braidNylon}$ = 500 ± 10 µm.

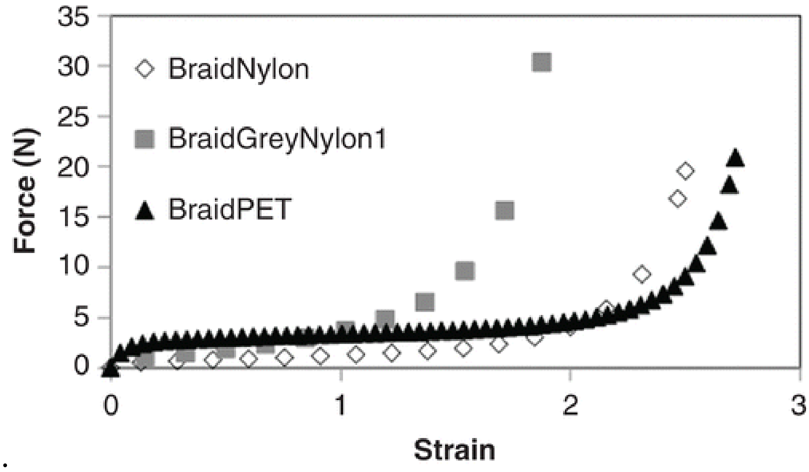
Figure 3 displays the types of fabricated and tested crimped braided sleeves and the values of their crimp parameters. The difference between the two BraidGreyNylon sleeves is due to the strength of treatment of the nylon braid in formic acid: Low acid concentration or short residence time in the acid bath leads to less crimping, i.e. longer crimp wavelength, as in BraidGreyNylon2.



Type of sleeve	Valley diameter (mm)	Peak diameter (mm)	Wavelength (mm)
BraidPET (black)	20 ± 2	25 ± 3	2 ± 0.2
BraidGreyNylon1	21 ± 2	23 ± 2	6 ± 0.4
BraidGreyNylon2	19 ± 2	21 ± 2	9 ± 0.4
BraidNylon	25 ± 3	29 ± 3	4 ± 0.4

Figure 3. The four types of fabricated and tested crimped, braided, tubular sleeves, and the values of their crimp parameters. The values are averages derived from the measurements of all these parameters in 20 specimens of 7 cm length each for each type of sleeve.

Figure 4 presents the results of mechanical testing of the different types of crimped braided sleeves in tensile mode in the axial direction of the tubular sleeve. In this direction, the fibre tows are initially at $\pm 45^{o}$, hence, the braid is in fact sheared in the fibre tow directions with the tows rotating during the test. The force-strain curves presented in Figure 4 start with a very low modulus, related to the shear modulus of the braid, and end up with shear stiffening due to the locking angle of the braid, as is expected in the shear deformation of bidirectional fibre textiles (24). The crimped sleeve from BraidPET functions most satisfactorily with the pneumatically actuating silicone module developed in the STIFF-FLOP project. The crimped sleeve made from BraidNylon has similar mechanical behaviour as the BraidPET sleeve, in fact with lower initial modulus but similar strain at stiffening, at about 250% strain, corresponding to similar shear locking angle due to the similar size of tows for the two braids. However, the BraidGreyNylon sleeves reach shear locking angle at a lower strain, about 150%, which can be explained by the wider tows of four filaments.



filaments.

Figure 4. Force as a function of strain in tensile tests in the axial direction of crimped, braided tubular sleeves. The tests were repeated with three different specimens for each type of sleeve, yielding a ±5% variation for each curve in the force axis.

Scratching medical tests were performed for each crimped braided sleeve covering the tip of the load cell sliding over the surface of the stomach, liver, spleen and bowel at different pressures: 2 N, 3 N and 5N and the observations of four members of the surgical team were recorded in Table I. Figure 5 illustrates different effects: Spot bleeding of liver surface (Figure 5a), spot bleeding and diffuse bleeding on the spleen surface (Figure 5b), superficial tears and diffuse erythema on the stomach surface (Figure 5c). Table I demonstrates that the crimped BraidNylon sleeve does not cause any visible damage when sliding under a force of 2-5 N over any of the examined organs. In contrast, the BraidPET sleeve causes erythema scratching the stomach and the bowel and superficial tears when sliding under 5 N over these organs, bleeding when sliding under 3 N or more over the spleen, and spot bleeding when sliding under 5 N over the liver. This can be explained by the greater roughness value of BraidPET compared to the low roughness value of BraidNylon, as well as the low friction coefficient of the nylon material. The crimped BraidGreyNylon sleeves cause erythema to the surface of bowel and stomach sliding under a force of 3 N or greater while the crimped BraidGreyNylon1 (of higher crimp frequency than BraidGreyNylon2) also causes spot bleeding to the spleen. The same tests were repeated with the sleeve sliding over an organ under gravity only, without any other external force. All four members of the surgical team could not detect any particular effect on the organ surface.

Table I. Results and conclusions from the observation records of the surgical team during the scratching tests.

Force applied	**BraidPET**	**BraidNylon**	**BraidGreyNylon1**	**BraidGreyNylon2**
Liver				
2N	No visible damage	No visible damage	No visible damage	No visible damage
3N	No visible damage	No visible damage	No visible damage	No visible damage
5N	No visible damage	No visible damage	No visible damage	No visible damage
Spleen				
2N	No visible damage	No visible damage	No visible damage	No visible damage
3N	Spot bleeding	No visible damage	Spot bleeding	No visible damage
5N	Diffuse bleeding	No visible damage	Spot bleeding	No visible damage
Stomach				
2N	Erythema	No visible damage	No visible damage	No visible damage
3N	More erythema	No visible damage	No visible damage	Erythema
5N	Superficial tears	No visible damage	Erythema	Erythema
Bowel				
2N	Erythema	No visible damage	No visible damage	No visible damage
3N	More erythema	No visible damage	Erythema	Erythema
5N	Superficial tears	No visible damage	Erythema	Erythema

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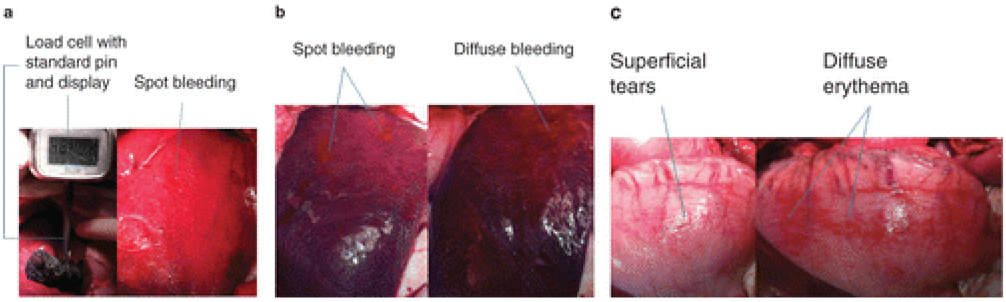

Figure 5. (a) Load cell pressed with 2N on the surface of the liver (left); spot bleeding on the liver surface (right). (b) Spot bleeding on the spleen surface (left); diffuse bleeding on the spleen surface (right). (c) Superficial tears on the stomach surface (left); diffuse erythema on the stomach surface (right).

Discussion

This investigation is part of the collaborative effort between the engineering and materials teams of the University of Surrey and Scuola Superiore Sant' Anna and the surgical team of Università degli Studi di Torino to develop a soft actuating arm for robotic abdominal surgery: A set of multidisciplinary tests covering material, engineering and medical aspects have been introduced in all stages of the design and development of the soft actuating arm to select the most appropriate materials and arm design for the specific application. The focus in this study is on the crimped braided sleeve of the pneumatically actuating tube, which provides the bellow component of the deforming arm. Current commercial endoscopes (25) incorporate a bellow component in the form of concentric tubular segments of two different diameters for adjacent segments, so the larger segment has the ability to slide over the smaller adjacent segment, with the full segment assembly acting as a bellow with the ability to bend. This is the first time that a crimped braided sleeve has been proposed for a bending surgical robot arm, although crimped, knitted PET (Dacron®) fibre sleeves (impregnated with gelatine) have been used as vascular grafts. Such knitted grafts can bend as per the requirements of the actuating arm in the STIFF-FLOP project but cannot shrink in diameter to the project requirements. Only a crimped, braided tubular fibre structure would comply with all the requirements of bending, elongation and arm diameter reduction when the soft robotic arm needs to navigate through a small opening or a narrow path during abdominal surgery. Hence, commercially available braids were crimped and investigated for their potential to be used as sleeves for the pneumatically actuating, soft arm in this study.

All types of crimped, braided sleeves of this study contained the balloon effect of the pneumatically actuating soft arm when used as sleeves (Figure 1). Mechanical test data in Figure 4 show that BraidPET and BraidNylon reach higher elongation (also translated to higher robotic arm bending angles above 180^o) than BraidGreyNylon1, due to the latter braid reaching shear locking earlier because of its wider tows than the former two braids. Additionally, BraidNylon requires the lowest force for deformation (up to 150% strain), much lower than the force required for the deformation of BraidPET, due to the low friction coefficient between the nylon fibres at the cross-over points of the braid: This translates into reduced power requirement for the actuation of the soft robotic arm with the crimped BraidNylon sleeve.

In terms of the induced crimp pattern of braids following the fabrication procedures described previously, it seems that the braid buckling process produces a pattern of braid folds depending on the processed material, as is demonstrated by the different values of the crimp parameters of the different types of braids (or their treatment) in Figure 3, even if the mandrel diameter, braid diameter and mechanical procedure were kept the same.

Medical tests showed that the crimped BraidNylon sleeve does not cause any visible damage when sliding under a force of 2-5 N over any of the examined organs, namely liver, spleen, stomach and bowel (Table I) and, hence, at this stage the sleeve can be recommended for the design of the soft actuating arm for robotic abdominal surgery. In contrast, the BraidPET sleeve caused problems for all organs, these problems being initiated when sliding under different levels of force over each organ (Table I). Hence, it is recommended to exclude this BraidPET sleeve from further development studies of the soft actuating robotic arm, with the reported medical problems attributed to a combination of a higher roughness of the used PET braid, the higher friction coefficient of PET compared to nylon, and the short crimp wavelength of this crimped braid (2 mm from Figure 3) translating to a high frequency of crimp peaks scratching the organ surface when sliding over it. Both BraidGreyNylon1 and 2 sleeves also caused some problems in the medical tests as reported in Table I, although not so many as the BraidPET sleeve despite the different crimp parameters between BraidGreyNylon1 and 2, with BraidGreyNylon2 being fabricated with longer crimp wavelength, 9 mm, against 6 mm for the former: This means that the roughness of the braid pattern and the material friction coefficient are critical factors in determining the degree of scratching and its effects when a crimped braided sleeve slides over an organ surface.

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