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Variable Stiffness Structure for Limb Attachment

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Abstract—**In robotic rehabilitation, the way of attaching the robotic device to the users' limb constitutes a crucial element of product quality, particularly for assuring good fitting, comfort, accuracy, usability, and safety. In this article, we present a new technological concept – 'Variable Stiffness Structure' – allowing for an improvement of these aspects in the 'robotic device to limb'- connection by offering a compound of materials that are together able to switch from a flexible textile-like state to a more rigid state by applying negative pressure. The paper describes the concept and the basic behaviour of the material, based on experiments.**

Keywords – limb connection; robotic rehabilitation; body fitting element

I. INTRODUCTION

Physical therapy has the aim to treat disorders of the musculoskeletal or neuromuscular system in order to restore maximal functional independence of individual patients. In the last decades, a number of robotic devices have been introduced to facilitate such therapy and release the therapist from part of his tasks being time- and resource consuming and/or needing a large physical effort in manual therapy. A specific and essential component of robotic devices for physical therapy is the connective part that attaches/fixes the robot's end effectors, its exoskeleton parts, or the device in general to the human limb(s). Two examples are given in figure 1, one is device for arm training, the ArmAssist [1] in development at Tecnalia, and the other the Lokomat, the well-known gait rehabilitation system from Hocoma [2]. In these examples the connective parts, that are the subject of this paper, are encircled.

Although the aspect of limb attachment and fixation in rehabilitation robotics design does not often receive major attention in research, neither in the design process nor in the publications in the field, it is a crucial component that determines the eventual properties of the robot towards the user, i.e. the patient that is training. Proper design of this part becomes indispensable as soon as reaching towards the commercialization of a device. Comfort, safety, accuracy, and speed of the don/doff procedure are crucial factors defining the product quality, and all of them are partially determined and/or affected by the design of the connective parts.

Particularly in stroke rehabilitation, which is characterized by intensive repetitive training, there is increased need for optimization of these elements as the involved robotics may have to be used for long durations of training, with a relative high level of (assistive) force interaction. In general, the design of the connective parts is most critical when the transmitted forces are highest. This is typically the case in gait and balance rehabilitation, where the full body weight comes into play [3,4]. Nevertheless, its importance is also not to be neglected in upper extremity devices.

Today, the most common approach to solution for device attachment are constructions of stiff and flexible parts, similar like orthoses, using, e.g., fiber reinforced polypropylene, carbon fiber reinforced thermoplastic composite material, Velcro straps, textile belts, and similar. In many cases, to be applicable to full range of patient measures, different elements have to be replaced and attached to the device.

From the functional viewpoint, an ideal solution would provide a (1) comfortable connection that (2) is sufficiently rigidly connected to assure safety and precise control of the robot and the human in the rehabilitation exercises, (3) is easy and fast to attach and detach to/from the limb, (4) needs only one component to automatically fit to any patient, and (5) is easy to clean.

Figure 1. ArmAssist [1] (left) and the Lokomat [2] (right). The limb attachment or connective parts that are encircled in these pictures are the topic of this paper.

II. PROPOSED SOLUTION AND ITS IMPLEMENTATION

In order to approach the abovementioned ideal characteristics of the connective part of a robotic device, we propose a new technological concept: 'Variable Stiffness Structure'. This technology recently patented by Tecnalia provides a 'material' that is able to switch from a flexible textile-like state to a more rigid state (similar stiffness as

HDPE) by applying negative pressure (vacuum). This 'material', referred to as 'Variable Stiffness Unit' (VSU), consists of a **laminate of several flexible textile layers** being integrated into a **hermetic flexible envelope suitable for pressure regulation**. When applying a vacuum, the layers are compressed, which decreases their mutual distance and increases the friction between them. This in turn increases the stiffness of the VSU 'material'. By a proper selection of materials, it has become possible to achieve sufficient stiffness at acceptable thickness to apply this technology for limb fitting, for example in rehabilitation robotics. The characteristics of the identified solution are described in the following. A related technology can be found in [5] where a similar solution was applied for wearable haptic displays.

We believe the proposed solution offers benefits over the common solutions of using strapped bands that are closed with velcro, or inflatable cushions, as those solutions necessarily bring about a pretension and therefore already exert force on the skin already without any interaction force with the robot, which decreases comfort [4]; furthermore these connections lack rigidity. Whether the proposed solution really offers a better interface will have to be evaluated in user tests.

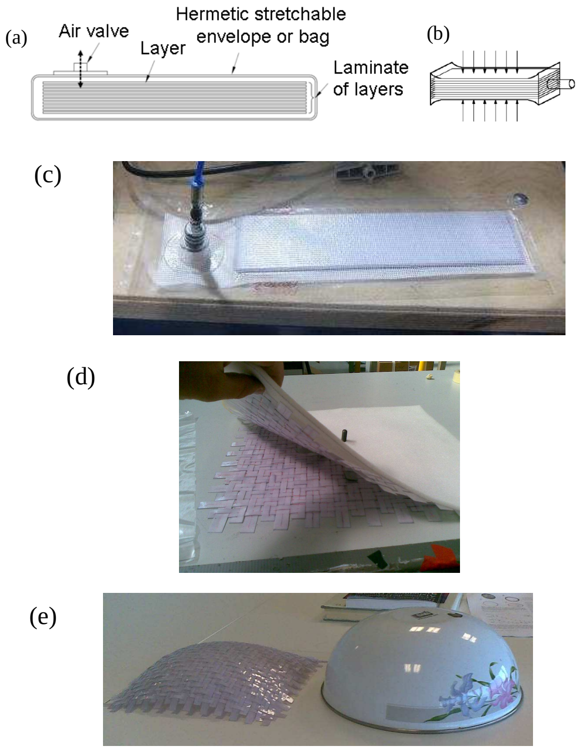

Figure 2. Several visualizations and pictures of the VSU 'material'. (a) core elements of the Variable Stiffness Structure material, (b) 3D impression of the VS Unit [5] (c) rectangular sample of VSU, a beam as used in the three point bending tests, (d) VSU layers implemented as textile, suitable for fitting to shapes with 2D curvature, (e) VSU material of textile/woven type, fitted onto a 2D – curved shape.

A. *Variable Stiffness Unit*

The figure 2a and 2b show the basic elements of the VSU. In order to make the concept work properly, it is important that the layers have good flexibility in bending but at the same time a high tensile stiffness. These properties are typical in textiles made of (synthetic) fibers. Furthermore, the friction between the layers should show a high (static) coefficient of friction and without electrostatic adhesion or similar effects that would cause friction between the layers when no external pressure is applied. These characteristics can be achieved by coating a PET fiber textile with a specific high friction PVC film. The bag, or envelope, needs to be sealable, flexible, and free of leakage. In the particular implementation described here, it was made of PVC.

The simplest version of a VSU consists of a number of layers with a specific shape (such as the rectangular shape in the sample shown in figures 2c), that can be bent in the flexible state in one main direction at a time. To make a fitting of 3D shapes, which requires simultaneous bending in two directions of the surface, use is made of a textile-like weave of ribbons of the same materials (figure 2d and 2e).

B. *Automatic Fitting*

Basing on the VSU units just described, the following method is applied to allow for automatic fitting of the material onto objects of arbitrary shape: Three compartments – two VSU compartments and a pressure compartment in between – are used on top of each other. By pressurizing and depressurizing the compartments in the right order, the resulting laminate material can be fitted flexibly. Automatic fitting is important to mention here as it is relevant to various applications and poses additional requirements to the pneumatic system as three air compartments have to be pressure-controlled independently.

C. *Pneumatic System*

To implement the changing of state of the VSU from flexible to stiff, pneumatic components are necessary to regulate the pressure. When targeting longer term use, it may become necessary to actively keep the pressure below a specific threshold value. As the system works with vacuum and with thin, surface-like compartments, the volume of air to be transported stays relatively low. This allows for the use of micro-pneumatic components. Figure 3 shows a unit that contains all components (valves, pump, battery, and controller electronics) to operate the automatic fitting procedure, which requires a controlled sequence of de- and inflating of the three specific compartments. The unit in the current prototype state is of the size of a mobile phone allowing therefore also for wearable solutions. Although in typical rehabilitation robotics applications the size and weight of this unit may not be critical, there may well be exceptions. So far performed tests showed the pneumatic unit to function properly on a functional level. In further development, focus will be put on a reduction of its level of noise production.

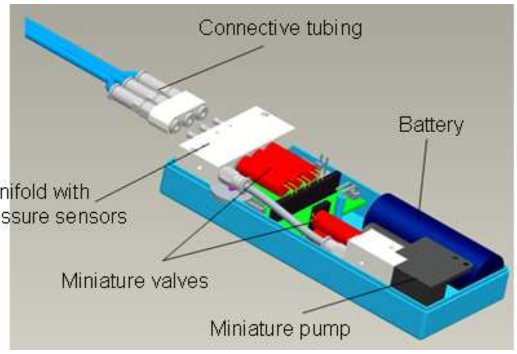

Figure 3. The micro-pneumatic Automatic Fitting Controller unit, including all elements for pressure control in three separate compartments. This unit has the size of a regular mobile telephone.

D. Material Behavior

The variable stiffness unit is a technology, but can be considered and described as a material. Stress–Strain curves and strength are important aspects of describing a material and are relevant to describe the behavior of the VSU. As the material resembles a laminate, also theoretical approaches from laminate theory may be applicable to predict the behavior of the VSU as material in the elastic range, which will however not be treated here due to limitations of space.

Instead, we will mainly focus on three-point-bending experiments, carried out on samples as shown in figure 2c. Important parameters that determine the bending behavior of the VSU are used materials and production methods, number of layers and pressure. The latter two will be evaluated here for the given materials.

The measurement procedure is as follows. First the stress-strain curve is determined, through a three-point bending test, giving results as shown in figure 4. Where these curves steeply drop, the material undergoes a plastic deformation, which is a failure mode, connected to the bending strength of the material. From the linear part of the curve the bending modulus was determined (the range from 0.2 until 0.4 % strain was chosen to be able to include all pressures). From this a pressure-bending modulus curve can be determined (one line in figure 5). This procedure then has been repeated for several samples with 6, 8 and 10 layers laminates, respectively, resulting in figure 5. Finally from these moduli, the resulting bending stiffness of the sample is calculated, which also depends on the shape and thickness of the beam, according to the formula E·I, resulting in figure 6.

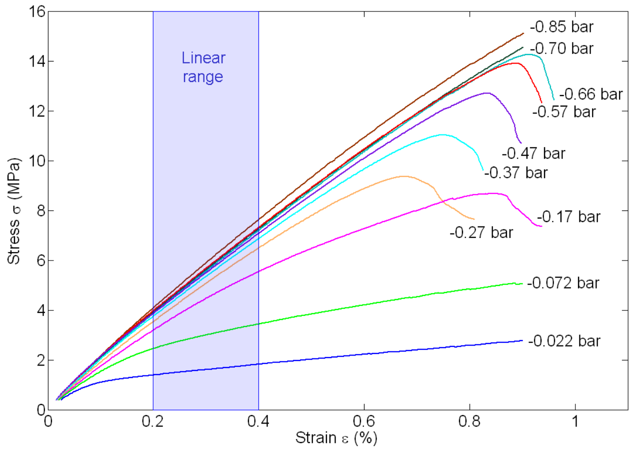

Figure 4. Stress-strain curve for an eight-layer sample for different pressures. The supposedly linear part, between 0.2% and 0.4% strain to determine the bending modulus is indicated with a grey area.

From this final figure we can conclude in the first place that the stiffness reaches a platform already at a negative pressure of about 0.3 – 0.4 bar, and only slightly increases with increasing vacuum. Still the pressure also has an effect on the failure mode of plastic deformation, which can be read from the sharp drops of the lines as shown in figure 4. A second conclusion is that even if the bending modulus decreases with an increasing number of layers, the resulting bending stiffness of the beam increases, obviously because of the effect of increase of thickness. When the plateau reached in figure 5 for a specific number of layers is considered as 'the' bending modulus at this number of layers, the dependency between bending modulus and number of layers appears to be linear (figure 7), at least for the range described here. A third conclusion is that the behavior is reproducible for different samples (figure 5 and 6). Finally it should be noted that after a certain point (stress, strain) the elastic behavior is surpassed and the material undergoes a irreversible plastic deformation, eventually resulting in a kind of breaking (the bending, and the sharp drops of the lines in figure 4 respectively). It should be noted that this is not a true failure mode and the VSU can be recovered by repeated re- and de-pressurizing.

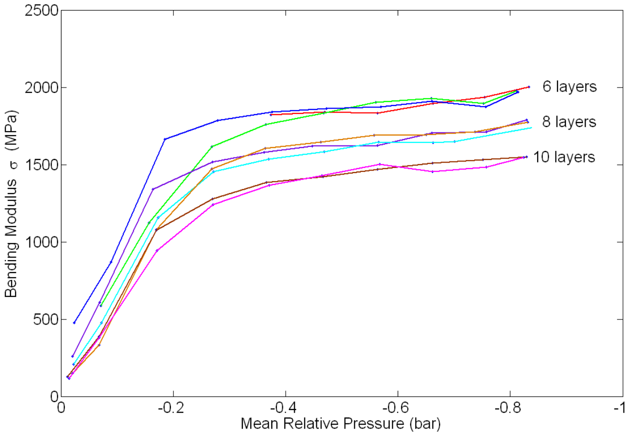

Figure 5. Pressure-bending moduli curves, for different samples and different number of layers. The bending modulus for one specific pressure is calculated from the slope of the corresponding curve in the grey area in figure 4 – this kind of curves where produced for different numbers of layers and different samples per number of layers, resulting in the 3+3+2 curves shown in this graph.

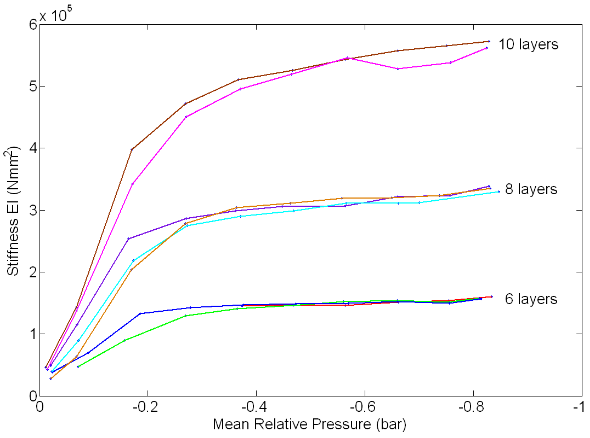

Figure 6. Bending stiffness of the different samples, with different number of layers at different pressures, based on the bending modulus from figure 5 and the corresponding sample property E·I, resulting in: $E_{measured} \cdot 1/12 \cdot h^3$.

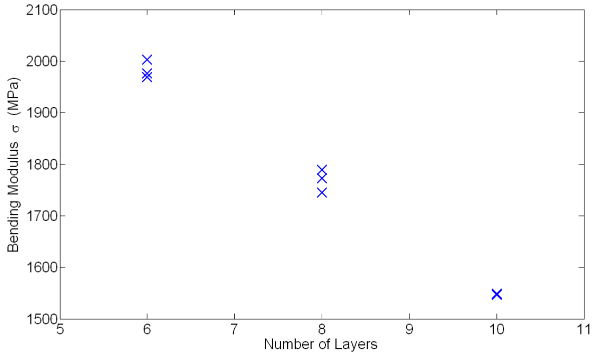

Figure 7. Platform values of the bending moduli from figure 5. The 'platform' values are taken as representative – values at -0.8 bar are taken. For this range and few values the relation between number of layers and bending modulus appears to be close to linear

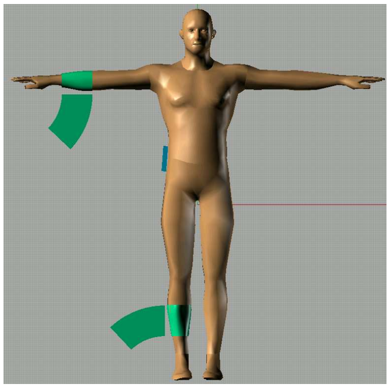

Figure 8: Example of simple shapes for body-fitting elements (picture made with MakeHuman).

III. CONCLUSION

The Variable Stiffness Technology allows designing a 'material' that can switch between a rigid state and a flexible state by controlling pressure, in a range of stiffness that makes the material very attractive to apply for connecting to human limbs, for example in rehabilitation robotics. This material has the promise to provide a solution that is (1) comfortable (2) sufficiently rigidly connected to assure safety and precise control of exercises, (3) easy and fast to attach and detach to/from the limb, (4) needs only one component to automatically fit to any patient, and (5) easy to clean.

Next steps in the project will involve producing prototypes for specific limb connections, for starting with simple shapes, as shown in figure 8, testing solutions to attach the material to other construction parts and optimizing the pneumatic system. A parallel effort will focus on describing the behavior of the VSU 'material' based on laminate theory.

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