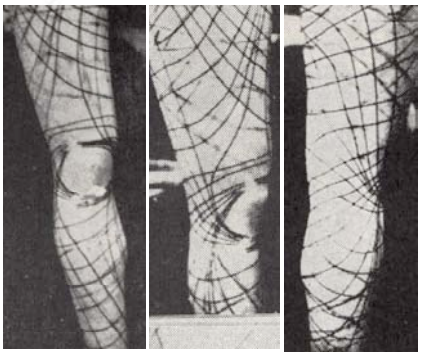

Figure 1. Iberall's depiction of the lines of nonextension, drawn on a mannequin [Iberall, 1970].

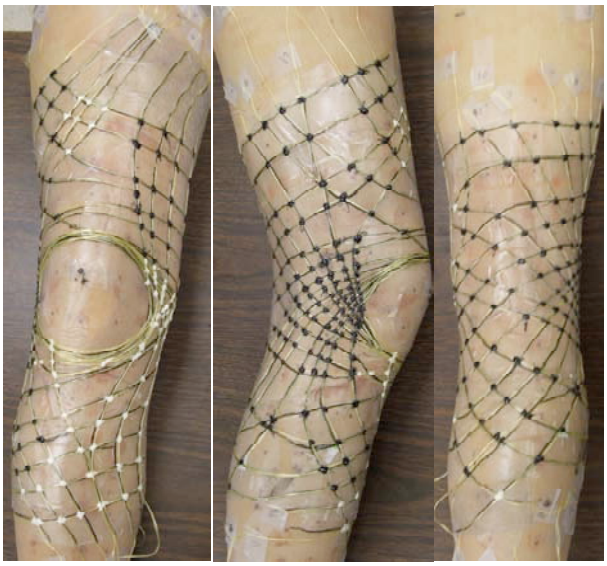

Figure 2. Recreation of Iberall's lines on a full-scale replica of a current subject, with Kevlar and epoxy garment overlaid on top. Yellow fibrous strands are Kevlar; black or white dots are epoxy sealant used to fuse the Kevlar joints.

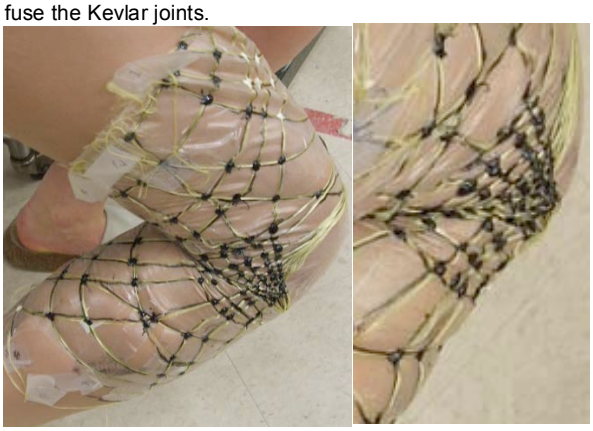

Figure 3. Lines of non-extension garment worn by the subject. Knee flexion was easily achieved, as the Kevlar mesh fibers rotated but did not stretch.

Bio-Suit Patterning: Testing the Lines of Non-Extension

Analyses of the leg skin strain during locomotion suggest the optimal directions for the fibers of a "second skin" Bio-Suit pressure garment. For maximum mobility, the tension-bearing fibers of a leg garment should lie along the directions of minimum skin stretch. Iberall referred to these directions as the "lines of non-extension" [Iberall, 1970]. One goal of the Bio-Suit research is to verify these lines through digital strain field mapping and to transfer the digital results into an optimal suit fiber pattern [NIAC Bimonthly Report, Bio-Suit Phase II, January, 2005]. At this stage of research, before the digital verification is complete, Bio-Suit researchers have conducted an empirical test of Iberall's lines of non-extension.

The goal of this effort was to determine if a leg garment patterned by Iberall's lines of non-extension would actually preserve knee flexion capability. Iberall's lines were drawn on a 3D full-scale replica of the subject's leg, using Iberall's 2D drawings (Figure 1) as a guide for the 3D recreation (Figure 2). Very high modulus Kevlar fibers (DuPont Kevlar 49 Aramid Fiber) were laid out on top of the lines, using double-sided tape to temporarily hold them onto a base of nylon stocking. To lock the fibers into place, a joint was formed at each fiber intersection by adhering the two crossing fibers together with urethane-epoxy. Kevlar fibers were chosen because they are virtually inextensible; if knee flexion demanded stretching of the fibers, the subject would not be able to provide the force required to stretch them, and it would be evident that the line was not actually non-extending.

To test the "non-extension" property of Iberall's lines, the Kevlar garment and its nylon backing were removed from the leg replica and put on the subject's leg. The subject easily achieved full knee flexion, without extra work output or discomfort. Figure 3 shows the subject's leg with the garment donned and the knee bent.

References:

[1] Iberall, A.S. "The Experimental Design of a Mobile Pressure Suit." Journal of Basic Engineering. June, 1970, 251-264.

[2] Newman, D.J. "NIAC Bimonthly Report, Phase II" January 2005.

Bio-Suit Material Requirements

A Bio-Suit "second-skin" garment may consist of a fine mesh of fibers or narrow fabric tape, all oriented along the lines of non-extension. For this design to be realized, the material property requirements of the fibers or fabric, as well as their orientation, must be determined. Bio-Suit researchers have established preliminary requirements for these fibers. An ideal Bio-Suit fiber or narrow fabric has a tensile strength of greater than 60 N (13 lbf) and an elastic modulus that is initially high but that approaches zero as the strain surpasses 30% and the load reaches 30 N. The target operating range for the fiber or fabric is at tensile loads of 30 N +/- 5 N and strains of 50% +/- 20%.

The derivation of these requirements follows: The garment must provide 30 kPa of pressure on the leg surface, and the leg radius can be as large as 10 cm. Garment tension (per longitudinal width) is equal to the product of pressure and radius, so the desired operating tensile load is (30 kPa x 10 cm=3000 N/m =) 30 N per centimeter of garment. Assume that one fiber or narrow fabric strip bears the load for each longitudinal centimeter, and assume a desired factor of safety of 2. The final tensile strength requirement is (2 x 30 N =) 60 N. The zero-modulus portion of the force-displacement curve allows for the same level of tension to be maintained even when the leg shape changes slightly.

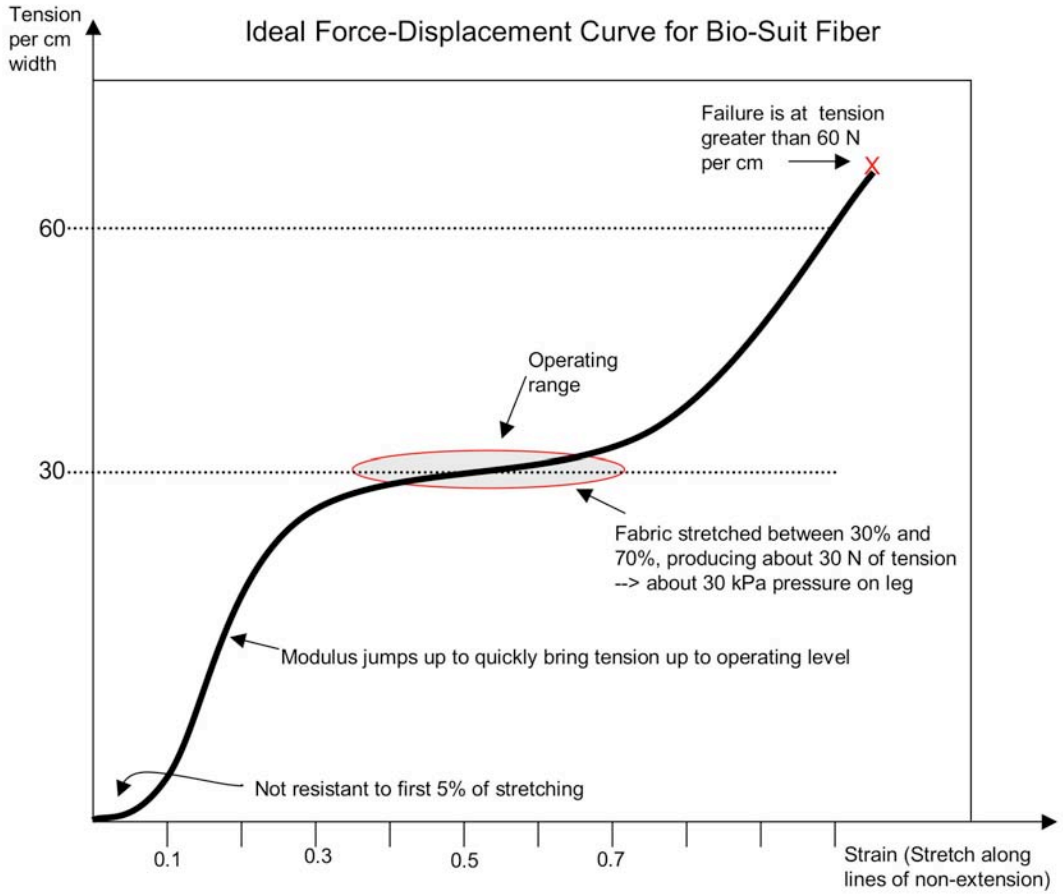

Figure 1. The ideal material properties for a fiber or narrow fabric for a Bio-Suit lines of non-extension garment. Curve indicates tension (per centimeter of longitudinal garment length) as a function of fiber or fabric stretch.