Figure 1: **Nonlinear durometer:** Left: Durometer schematics. Middle, right: We used our nonlinear durometer to measure the relationship between skin normal displacement and force, for the soft palm tissue. It can be seen that the relationship is very nonlinear. We also plot the confidence intervals, determined based on the precision of equipment used for this experiment.

Nonlinear durometer: A device to measure linear and nonlinear stiffnesses of elastic objects

Jernej Barbič, Associate Professor, Viterbi School of Engineering, University of Southern California

We describe a new type of an instrument, called "nonlinear durometer". This instrument can measure the force-displacement relationship of an elastic object such as human tissue, or soft elastic man-made objects. The instrument can simultaneously measure both the contact forces and displacements.

The first approach that comes to mind is to subject elastic objects to a small number of known external forces, such as pulling on them with force-metering equipment (Figure 2) or suspending weights from them, measure displacements, and then optimize the material. Pulling is not suitable for the human body and many man-made objects, which have no hooks or attachment points. Instead, we design a procedure to non-invasively push into the object, and measure the force and displacements. This technique relates to the centuries-old practice in medicine (*palpation*), whereby doctors diagnose diseases by detecting hardened tissue by pushing into the patient with their hands. In engineering practice, the instrument to measure hardness of a material is called a *durometer* (Figure 1, left). It is commonly used for soft objects such as rubber or soft plastic. Existing durometers, however, simplify the material relationship between indentation and force to be linear, and only report a single (standardized) value, such as Shore A Hardness. In human tissue and many man-made materials, the relationship between the force on the probe and the normal

Figure 2: **Precision Force Meter.**

indentation is nonlinear. We propose to design a durometer suitable for measuring a nonlinear relationship between the skin normal force and skin normal indentation due to contact. We demonstrate the nonlinear durometer using our preliminary experiment (Figure 1) on the soft tissue on the human palm, using a force meter (0-20N range). While the force meter is pressed in a normal direction against the skin, the probe moves relative to the housing, causing the internal spring to compress. We can observe two separate 1D motions (see Figure 1, left): the motion of the force meter itself (that is, its housing), and the motion of the force meter probe. Denote their respective positions away from some fixed reference by h and p. The 1D relationship between the relative motion of the probe $p - h$ and the spring force f is typically linear (Hook's law), and always at least monotonic, and can in any case be easily experimentally

tabulated, $f = F(p - h)$, simply by pressing the force meter against a hard surface such as a table. In our preliminary result (Figure 1), we measured the force f, and positions h using a millimeter paper, by pressing the meter into the skin with increasing force. We recorded several sample pairs (f_i, h_i), from which we then calculated $p_i = h_i + F^{-1}(f_i)$. Let p_0 be the sample where the probe just enters contact $(f_0 = 0)$. The skin indentation at sample i is then $p_i - p_0$. The pairs $(f_i, p_i - p_0)$ tabulate our desired nonlinear relationship between normal skin indentation $p - p_0$ and normal skin force f. This forms the output of our nonlinear durometer (Figure 1, right).

We can use our nonlinear durometer to measure various parts of the human body (hand, belly, face, back, etc.), and man-made soft objects (mattress, chair, shoe). A precision camera setup can be used instead of the millimeter paper. For example, one can affix an inexpensive augmented reality (AR) barcode onto the force meter, and track it with a camera using the widely available AR Toolkit [1]. By repeating this process for many locations on the human face or body, we can build a map of the nonlinear stiffness of the human body. A similar experiment has been performed in [2], but only for linear relationships between indentation and force. Our experiment (Figure 1) demonstrates that linear materials are not sufficient. As an application, from such individual (force, indentation) curves and an FEM simulation model one can then optimize nonlinear elastic strain-stress material relationships.

Figure 3: **AR tracking marker.**

In addition to measuring normal forces and displacements (indentations), one can also measure displacements under tangential forces, and capture the entire deformed shape in the vicinity of the probe, as opposed to only 1D normal displacements. One possibility is to do this using precise (arrays of) cameras. Another is to use a 6-DoF haptic device, such as the Haption Virtuose 6D device. One can replace the tip of the device with a suitable probe, and bring the device in contact with the skin. Then, one can command the device to produce some fixed force (capped at some maximum safe value), all the while the vision equipment measures the displacements.
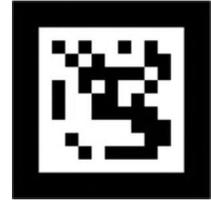
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