An Interaction-Aware, Perceptual Model for Non-Linear Elastic Objects - Supplementary Material

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1 FEM simulation setup

For the finite element method simulation we use the commercial software Abaqus [http://www.3ds.com/ 2015] with implicit integration scheme. For Spec2Fab [Chen et al. 2013] the provided simulation library, materials and settings were used.

Material model For each material the force-displacement curves for uniaxial compression were extracted and converted to nominal stress-strain curves. Next, using this data the following hyperelastic material models were analyzed: Mooney-Rivlin, Ogden 3th order model and Reduced polynomial models from 1st to 6th order [Dorfmann and Muhr]. After the analysis unstable material models were excluded and from the remaining models the model best explaining experimental data with minimal degree was used. For silicon materials we used Reduced-polynomial model of 4th degree. Objet materials were simulated using Reduced-polynomial model of 2nd degree.

Model setup For all simulations in Abaqus quadratic tetrahedral elements with hybrid formulation were used to accommodate for nearly incompressible materials such as silicons. The rubber duck model was simulated using 22803 elements. The stand of the model was fixed to simulate that it was glued to its base and ground was added to represent the contact of the model with its base. The octopus model was simulated using 3282 elements. Only half of the model was modeled in the software. The other half was represented using symmetric boundary condition. The contact of the octopus with ground was modeled using a high friction coefficient to represent the interaction between rubber and a wooden plate. The seahorse model was discretized using 7429 elements. Only half of the model was used for simulation as the used materials (Ecoflex 00-30, Dragon skin 30, TangoBlack+) were soft enough to not affect the rest of the model. For the remaining two materials (flexible resin, TPU 92A-1) due to the lack of material samples we directly measured the interaction with a uniaxial device, instead of simulating it.

Interaction simulation To represent the human interaction with an object a spherical indenter with diameter of 1.5 cm was used. In all Abaqus simulation we modeled this indenter as a rigid body made from aluminum. During the simulation we extracted the reaction forces of the indenter to recover the force required to deform each specimen. The overall time duration of the simulation was set to 2 seconds to account for the human interaction speed.

2 Used materials

Figure 1 contains extracted force-displacement data for all our models. The silicon ducks [https://www.thingiverse.com/thing:139894 2015] were casted using different mixtures of silicons. All used silicons were purchased at [http://www.kaupo.de/ 2015]. For the base silicon material we have selected materials with different shore hardness [ASTM 2010]: Dragon skin 30, Dragon skin 10, Ecoflex 00-50, and Ecoflex 00-30. The different mixtures as well as naming convention are shown in Table 1. All of the octopus toys were produced on Objet Connex 500 printer. As base materials we have used TangoBlack+ and VeroClear. For the six in-between digital materials we selected RGD8725, FLX9095, FLX9070, FLX9060, FLX9050, and FLX 9040. Seahorse models [http://www.thingiverse.com/thing:561147 2015] were fabricated using different techniques. Two seahorses were casted from silicon using Dragon skin 30 and Exoflex 00-30. One seahorse was printed on Objet Connex 500 using TangoBlack+ materials. Penultimate seahorse was printed on Ember printer using flexible resin. The last seahorse was produced using a laser printer with TPU 92A-1 material.

ID	Silicon mixture
A	100% Dragon skin 30
B	50% Dragon skin 30 + 50% Ecoflex 00-30
C	100% Dragon skin 10
D	50% Dragon skin 10 + 50% Ecoflex 00-50
E	100% Ecoflex 00-50
F	87.5% 100% Ecoflex 00-50 + 12.5% Ecoflex 00-30
G	75% 100% Ecoflex 00-50 + 25% Ecoflex 00-30
H	50% 100% Ecoflex 00-50 + 50% Ecoflex 00-30
I	100% Ecoflex 00-30

Table 1: *Silicon mixture with their corresponding IDs.*

3 Peak-force histograms

Figure 1 shows on the left shows the force applied by all participants on a block during the psychophysical study. On the right the corresponding peak-force histogram stored in our database is shown.

References

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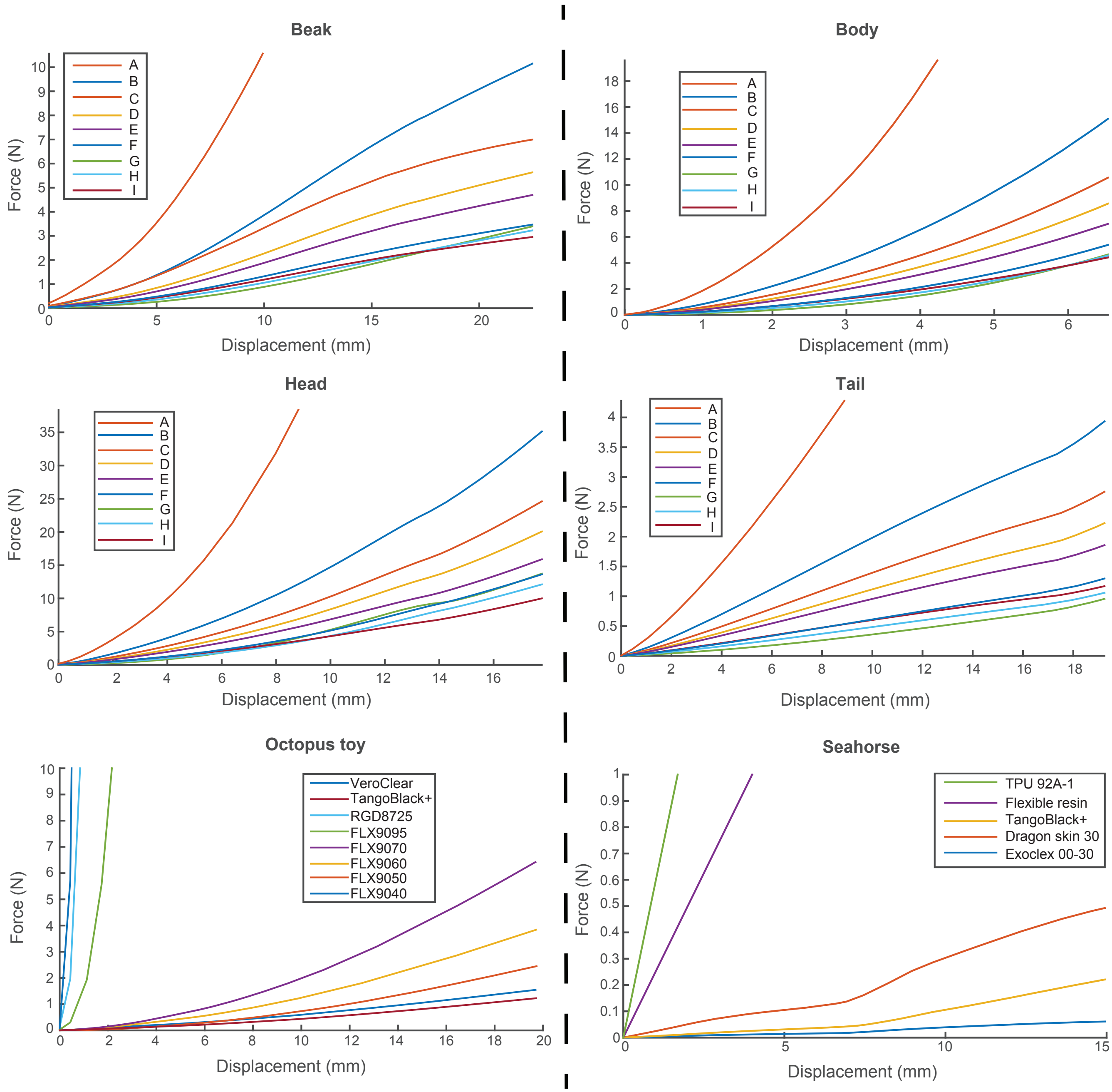

Figure 1: *Force-displacement data recovered for interaction with all fabricated objects.*

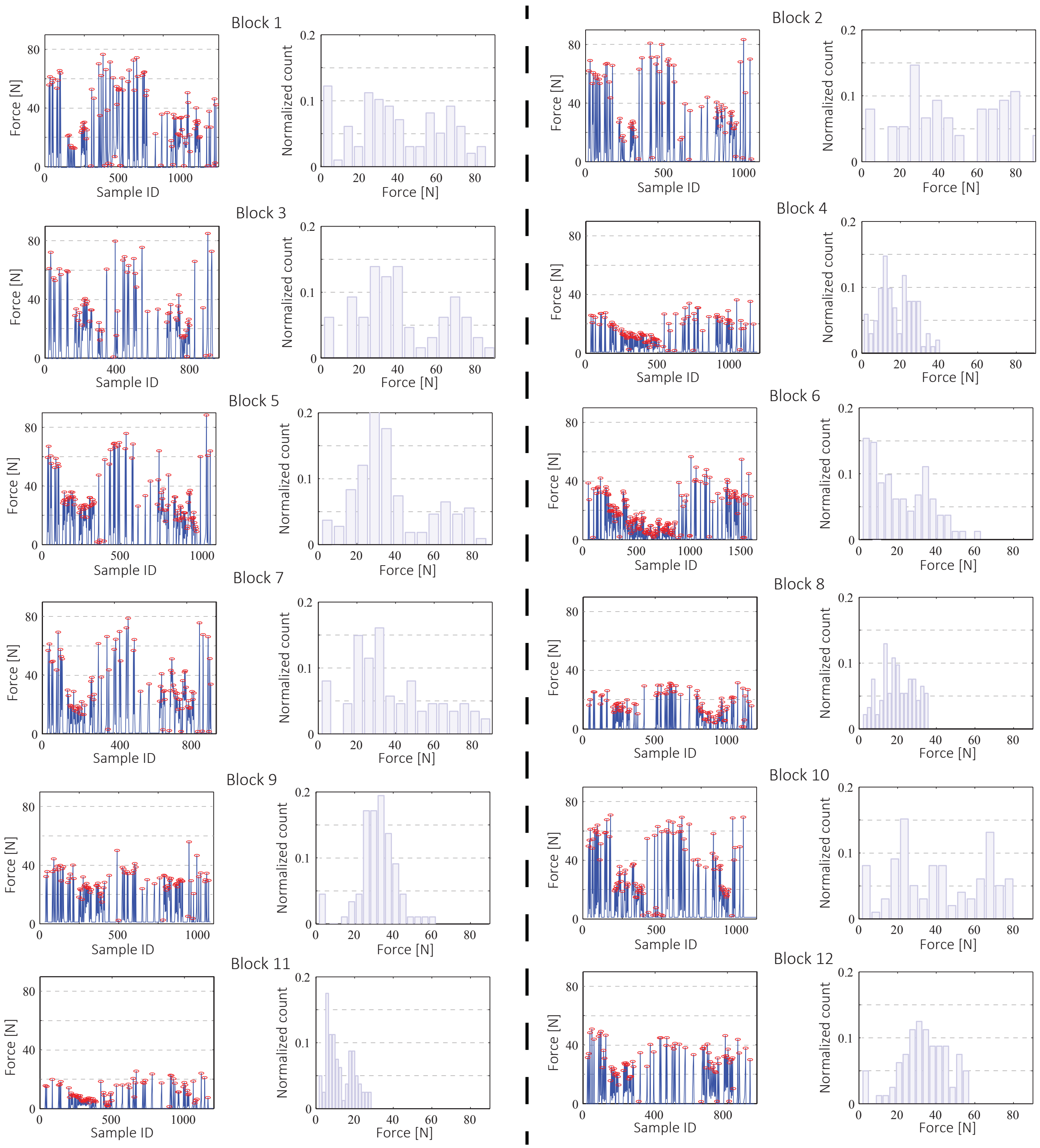

Figure 2: *Left: peak-force data recovered for each block during psychophysical experiment. Right: histograms stored in our database.*