Eectronic Supplementary Information

Materials and methods used for experiments in Section 2.1

Polydimethylsiloxane (PDMS, Sylgard-184, Dow Corning, Midland, MI) was cast into uniform 5 mm thick sheets using 10% cross-linker and cured at 100℃ for 48 hours before use. The sheets were bonded to actuator bases cast from a different silicone (RTV-4136M, Dow Corning, Midland, MI). To generate wrinkles at the exposed upper surface of the Sylgard sheet, a stiffness mismatch must be created between a thin stiffer superficial layer and softer bulk silicone. PDMS surfaces were stiffened by exposure to UV ozynolysis (UVO), which vitrifies the surface into a ~100 nm thin layer of silica [1]. The advantage of UVO treatment methods is the ability to create very thin and well bonded surface layers. To create uniform surface layers with minimal defects, the samples were positioned 2 cm from the UV source in an oxygen enriched reaction chamber of a Novascan PSD Pro 4 UVO cleaner (Novascan Technologies Inc., Ames, IA) and irradiated for ninety minutes. Irradiation for shorter periods of time creates thinner silica layers, however significant surface inhomogeneities also appeared.

Some samples were irradiated with the Sylgard sheet being flat (i.e. the actuator base was not pressurized during ozonolysis. These samples served as controls. Wrinkled samples were generated by irradiating under pressurized conditions so that the Sylgard sheet was stretched 30% along the short axis. The silica layer formed under these conditions were strain free under pressurized conditions, but upon reducing the pressure, the Sylgard retracted, thus compressing the silica layer and wrinkling it. Given the anisotropic strain along the actuator short axis, the neutral direction of the wrinkles was along the actuator long axis. To minimize Y-type defects in wrinkle wavelength, the pressurized samples were slowly depressurized over 12 hours; however, even under the most optimal conditions Y-type defects were exceedingly hard to completely avoid in PDMS samples. Samples were stored in air and at room temperature before use in blood experiments. The above procedure generated unidirectional wrinkles with a uniform wavelength of roughly 50 μm (see figure 1).

The blood contact chamber was designed to minimize non-PDMS (non-test) surface contact. This was accomplished by machining a polycarbonate chamber that sits onto the Sylgard silicone sheet and masks all but the thin rectangular part of the surface which expands under actuation. The volume of this chamber is 30 mL. Since standard surface/blood testing requires minimization of any blood/air surface area, a second Sylgard sample surface was placed on top of the polycarbonate chamber (Fig. 2). The three parts were placed under axial compression, and given the compressible nature of the silicone, a good seal was obtained between the polycarbonate and actuators without the need for any additional sealants that may

contaminate or leak into the blood-containing chamber. Valves located at the ends of the polycarbonate chamber allow easy filing of the reaction chamber with blood and purging of all air (see Fig. 2 where for demonstration purposes green colored fluid was used in place of blood). This design allowed testing of two surfaces during each blood contact experiments. Once the chamber was filled with 30 ml of ovine blood, the actuators were connected to the actuation circuit (see Fig. 2C). The blood was drawn 15 minutes prior to the contact experiments and kept from coagulating by a small amount of citric acid solution. A peristaltic pump (9000G series, New Era Pump Systems, Inc., Farmingdale, NY) was connected in series to the two actuators. During each half-cycle the pump moved 4 mL of water from one actuator chamber to the other, pressurizing one chamber and expanding its PDMS membrane while depressurizing the other and contracting its PDMS membrane making the surface wrinkle. This counter-pulsation allowed minimization of any hydrostatic pressure build-up in the actual blood chamber. It is noteworthy that the blood was never placed into the actual flow circuit, since it was separated from the water based circuit by the Sylgard test sheets. The actuation frequency was 0.4 Hz/cycle. The entire assembly was placed into a tissue culture incubator at 37℃ and actuation was carried out for 90 minutes or 2100 cycles.

Whole fresh ovine blood was collected by jugular venipuncture and anticoagulated with sodium citrate solution (10 mM/L). NIH guidelines for the care and use of laboratory animals were observed, and all animal procedures were approved by the Institutional Animal Care and Use Committee (IACUC) at the University of Pittsburgh.

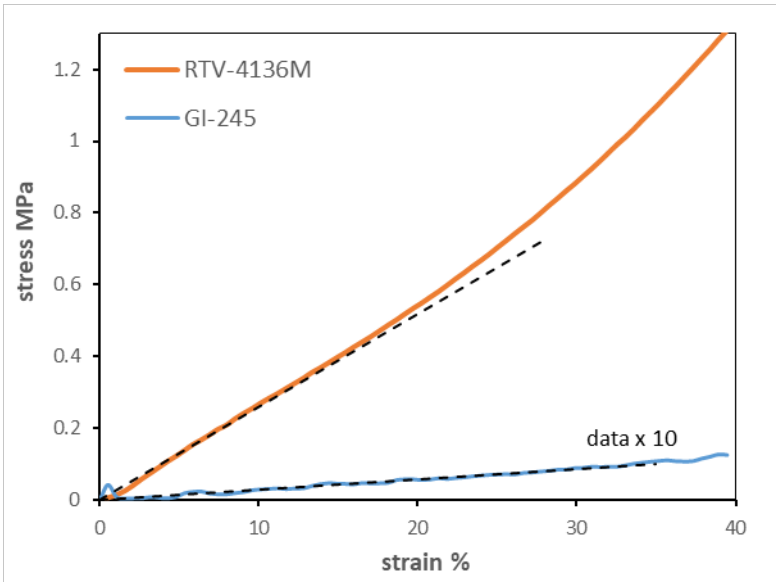
For the static PDMS control samples, the surface thromobotic deposition was assessed by a simple rocking test [33]after being cut and placed in a test tube (BD Vacutainer, with no additives). The test tube was filled with 5 mL of ovine blood and gently rocked for 90 minutes at 37℃ on a hematology mixer (Fisher Scientific, Pittsburgh, PA).

At the completion of actuation or incubation for the static samples, the blood was carefully removed and the surfaces washed 10 times with normal saline. The elastomeric sheets were then cut into 1 cm^2 samples. For samples recovered from the pneumatic device, we took care to take samples at least 1 cm away from the short-axis boundaries where substantial bi-axial strain exists. Samples then underwent post-processing for the characterization]. In detail, the blood contacted PDMS surfaces were rinsed with DPBS (10 times) to remove any non-adherent blood contents. Samples were then immersed in a 2.5% glutaraldehyde solution of DPBS for 2 h at 4℃ to fix the surface adherent platelets and then serially dehydrated with solutions of increasing ethanol content. Each sample surface was observed by scanning electron microscopy (SEM; JSM-6330F, JEOL USA, Inc., Peabody, MA) after sputter coating with gold/palladium. Deposited platelets on each surface were also quantified by a lactate dehydrogenase (LDH) assay with an

LDH Cytotoxicity Detection Kit (Clontech Laboratories, Inc. Mountain View, CA) after the blood contact.

Materials and methods used for experiments in Section 2.2

To study a range of wavelengths, multiple bilayers were constructed using GI-245 (Silicones, Inc., High Point, NC) as the softer thicker layer and RTV-4136M/Xiameter (Dow Corning, Midland, MI) as the thinner stiffer layer. Bulk samples of each fully cured silicone were tested using standard dog-bone tensile testing to obtain the stress strain results shown below. The corresponding Young's moduli, obtained by fitting the small-strain behavior, are : $E_s = 29$ kPa (GI-245) and $E_m = 2.6$ MPa (RTV-4136M). The RTV-4136M was dissolved into hexane at a weight loading ranging from 20-25%, and the solution was spread as a few μm thin wet film onto clear acrylic plates (McMaster-Carr, Elmhurst, IL) using a wire-wound rod with 0.0025 inch wire diameter and an automatic spreader (Paul N. Gardner Company, Pompano Beach, FL). After solvent evaporation and curing for 24 hours at room temperature, a 750 µm layer of GI-245 silicone (10:1 polymer:crosslinker ratio) was spread directly onto the cured film using a precision knife edge spreader (Paul N. Gardner Company, Pompano Beach, FL). Curing of this layer resulted in a flat bilayer with a smooth surface. Simultaneously, a second film of GI-245 silicone was cured onto a separate acrylic sheet, released, and prestretched to a strain of 30-40% using a custom-built uniaxial stretching jig. The flat bilayer was then placed onto the prestretched layer with a thin "bonding" layer of uncured GI-245 in between so that the bilayer and the prestretched sheet made contact. Upon curing the bonding and releasing the prestretch, the surface film of RTV-4136M developed strong wrinkles whose wavelength could be tuned via the thickness of the RTV-4136M film. This layered sheet was then rolled into a cylinder 10 cm in length and 6 mm in diameter, using a custom built holding apparatus, allowing precise juxtaposition of the free boundaries, which were sutured together using 6-0 polypropylene suture (Covidien, Dublin, Ireland). The suture line was sealed externally with an ultra-thin coat of GI-245 silicone to provide a water tight suture line. The resulting cylinders expanded excessively at physiological pressures of ~150 mm Hg). To reduce the expansion, they were dip-coated with a layer of GI-380 silicone.



Stress vs strain of the materials used for the luminal film (RTV-4136M) and the main material of the wall (GI-245). The dashed black lines indicate fits to the low-strain data. Note that the stress for the latter have been scaled up by a factor of 10 for clarity.

During pressure testing and OCT characterization of the luminal surface, the silicone grafts were sealed at one end and inflated and deflated with water using a syringe pump while measuring pressure. Given that care was taken to assemble all test cylinders in the same manner, the range of volumes needed to achieve these settings was fairly consistent. Cylinders on average had an initial zero pressure volume of 2 mL, the desired low pressure (60-80 mm Hg) was achieved with an additional volume of 0.5-1 mL, and the desired high pressure (150-180 mm Hg) with an additional 2 - 3 mL. The syringe pumps were then programed to deliver 2-3 ml of volume during each actuation in a cyclic manner at a rate of 10 mL/min, making for an actuation frequency of 0.05-0.1 Hz. Simultaneously an OCT catheter was swept through the graft. We were therefore able to calibrate the pressure and volume at which the lumen wrinkled and unwrinkled.

After calibration of each graft, blood tests were conducted. Both free ends of the cylindrical graft were sutured closed using 6-0 polypropylene suture. A 5fr vascular access catheter (Bard, Murray Hill, New Jersey) was sutured at one end to allow access for blood flow via a syringe pump (Harvard Apparatus, Cambridge, MA). The distal tip of the catheter was placed 1 mm from the cylinder end. The access line was split two ways into the syringe pump to drive fluid flow and to connect a digital pressure transducer (Blood Pressure Analyzer 400, Digi-Med, Inc, Louisville, KY). Fresh whole blood was collected after informed consent from a healthy human donor (age 35, male) who had refrained from taking any platelet

altering medications 14 days prior to collection in accordance with Institutional Review Board guidelines. The blood was used immediately in the actuation experiments, following anti-coagulation with 3 units/cc heparin sulfate. Multiple cylinders with the same wavelength were tested N= 2 for flat surfaces, N= 3 for a wavelength of 1000 μm, N= 3 for a wavelength of 250 μm, and N= 4 for a wavelength of 80 μm. In each case, the pump/cylinder system was placed into an incubator at 37℃ and actuated for 90 minutes. A flat surface of $TiAl_6V_4$ alloy was also exposed to blood as a reference to crosscheck the LDH assay data against data obtained previously in our lab[34]. This sample is included in Fig. 5.

At the end of the experiments, the cylinder ends were cut, blood was carefully drained, and the cylinders were bisected in half along the long axis creating two equal hemi-cylinders. This allowed easy access to the internal surfaces for the washing and processing as described above for platelet density measurement with LDH assay. The samples for the two hemi-cylinders were processed separately because it is well known that suture lines introduce a strong nidus for thrombus formation and platelet adhesion. Indeed, our data presented in Fig. 5B (combined data sets) and 5C (sutureless hemi-cylinders only) bear out this fact, where we see a greater amount of platelet adhesion when the suture line is included in the analysis. Importantly, despite the increased overall platelet adhesion around the suture line, the effect of topographic actuation as well as the trend of decreased platelet deposition with greater curvature actuation was maintained. In all cases the data reached statistical significance with $p < 0.05$ or even $p < 0.01$ using a one-way ANOVA test followed by a post-hoc Tukey procedure.

Statistical Model

The statistical model in the main text can be made more quantitative by selecting a specific form for the distribution function: $P(\ell_{ec}) = \frac{1}{L}\exp\left(-\frac{\ell_{ec}}{L}\right)$. As per this distribution, patches range from the most flexible ($\ell_{ec} \to 0$) to most rigid ($\ell_{ec} \to \infty$). The mean value of the elastocapillary length is $\langle \ell_{ec} \rangle = L$. Since patches with $\kappa_f \ell_{ec} < 1$ remain adhered, the fraction, f, of patches remaining adhered after a cycle of actuation can be calculated

$$f = \int_0^{\lambda} P(\ell_{ec}) d\ell_{ec} = 1 - e^{-\frac{\lambda}{L}}$$

where we utilized the limits $\kappa_i = 0$ and $\kappa_f \propto 1/\lambda$. The above relation can be used to find a simple relationship between the fraction of adhered platelets for a given wavelength for comparison with experiments. By assuming that the majority of patches will have an average electrocapillary length greater than the wavelength ($\frac{\lambda}{L} < 1$) and therefor de-adhere, we can study the tail of our distribution function, simplify the above relation by expanding the exponential to second order, and thereby obtain an algebraic relation between fraction of remaining patches and wavelength:

$$f \sim \frac{\lambda}{L} \to \rho = \rho_o \frac{\lambda}{L}$$

where the fraction of remaining adhered platelets is defined as the ratio of final to initial platelet densities, ρ and ρ_0 respectively. Assuming that initial platelet density (ρ_o) and the average electrocapillary length (L) are intrinsic properties of the experimental system, the above relation predicts that the residual adherer platelet patch density should increase linearly with wavelength. Thus for the three experimental wavelengths of Fig. 5C, 1000 μm, 250 μm and 80 μm, this simple statistical model suggests that the platelet adsorption should be in the ratio 1:0.25:0.08. The experimentally-observed ratios (1:0.51:0.2, from Fig. 5C) show a similar trend but are weaker than predicted, though it captures the trend nicely.