Electronic Supplementary Information (ESI) for Role of fingerprint-inspired relief structures in elastomeric slabs for detecting frictional differences arising from surface monolayers

Charles Dhong[1]*, Laure V. Kayser[1], Ryan Arroyo[1], Andrew Shin[1], Mickey Finn III[1], Andrew Kleinschmidt[1], Darren J. Lipomi[1]*

[1]*Department of NanoEngineering, University of California, San Diego, La Jolla, CA*

*Corresponding Authors: cbdhong@eng.ucsd.edu, dlipomi@eng.ucsd.edu

PDMS slab residue

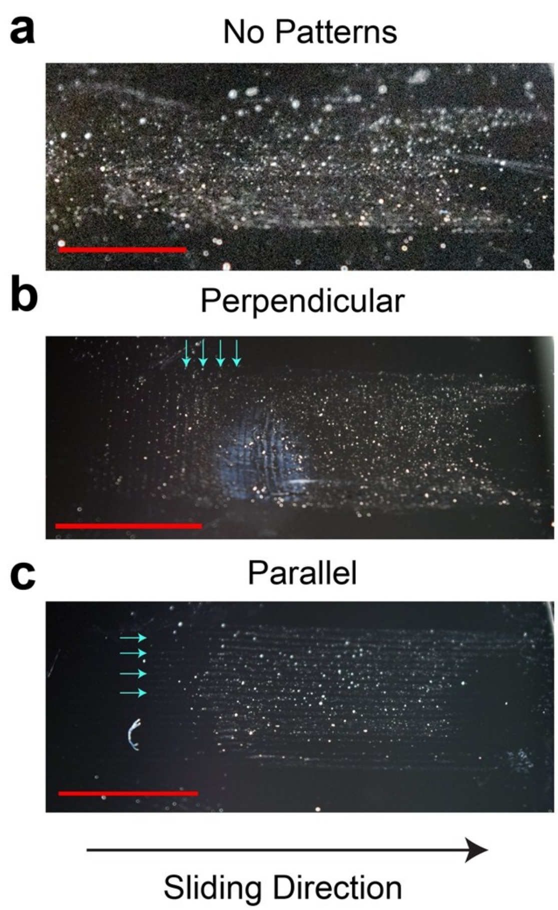


Figure S1: Residue pattern from testing of a single spot. (a) "No Ridges" (Flat) PDMS finger residue. (b) Perpendicular and (c) Parallel ridges on the PDMS block leave (highlighted by the blue arrows) distinct residue on bare FOTS-coated wafers after testing. Scale bar = 1 cm in all panels.

The PDMS slabs leave residue after testing and in particular, the PDMS slabs with relief structures leave a patterned residue which gives visual evidence that the contact of the PDMS slab to the silicon wafer is at the ridges only.

Force traces and cross-correlation analysis of force traces

Force traces and cross-correlation (explained below) are plotted together for various conditions.

A. **Force traces.** Every surface was tested at least 3 times at 3 different spots, for a total of 9 total tests. This was done for each type of PDMS slab ("no ridges", ridges "perpendicular" to motion, ridges "parallel" to motion) and under all 16 testing conditions (v = *1, 2.5, 7.5, 10* mm/s and M = *0, 25, 75, 100* g). In total, there are at least 864 individual force traces. M, applied mass, refers to mass in addition to a PDMS finger (~ 5 grams). In the testing configuration, the PDMS finger contributed 1 g downward force. Trials were done in random order to prevent bias, across multiple days.

Table S1: Testing conditions

PDMS slab	**Velocity** v *(mm/s)*	**Applied Mass** M (*g*)	**Surface**
No ridges, perpendicular, parallel	1, 2.5, 7.5, 10	0, 25, 75, 100	FOTS, SiOH

B. **Cross-correlations.** Cross-correlation is a common technique to compare whether two signals or traces (forces, concentrations, spectra, etc.) are similar. We use cross-correlation to quantify how similar or different the friction traces are under different conditions, from surface (FOTS vs SiOH), PDMS slab (flat finger, fingers with ridges parallel or perpendicular) and the substrate (flat wafers, wafers with obstacles). High cross-correlations between force traces on SiOH and FOTS would suggest the two surfaces generate similar friction forces, and thus would be difficult to distinguish. Conversely, low cross-correlations mean that the two surfaces generate distinct force traces.

We also cross-correlate different pulls of the same experiments (not an auto-correlation) to gauge the consistency of our experiments between runs. However, we note that a few conditions yielded low cross-correlations across multiple trials and spots, likely due to unstable stick-slip sliding. The correlation (about the mean force) between two friction traces ***a*** and ***b*** numerically calculated by:

$$Cross\ Correlation = \sum_t [(a(t) - \bar{a}) * (b(t - lag) - \bar{b})]$$

Representative force, internal cross-correlation and cross-correlation plots. Due to the large permutations of force traces and cross-correlations, only one representative plot, out of 9 per each condition For a given finger pattern ("no ridges", "perpendicular"," parallel), in the following plots, from left to right, top to bottom, three force traces on FOTS are shown. Then, three force traces on SiOH. The cross-correlation of the FOTS traces, the cross-correlation of the SiOH traces and finally the cross-correlation of SiOH and FOTS. The following titles can be translated as: Surface, pull speed, pull distance (always 4 mm for all tests), applied mass, ridges (if any), trial/spot #. For example FOTS1mms4mm25gparaspot1 is decomposed to: a parallel finger ridge (para), tested on a FOTS treated wafer (FOTS), at a pull velocity of 1 mm/s, with an additional mass of 25 g, trial 1. They are attached at the end of this document.

Correlations of Steady Slip Friction

Gueorguiev et al. postulated that the tactile cues primarily arise from steady sliding,[1] which occurs after the mock finger has begun bulk motion. As the motor applies a displacement on the mock finger, it may not immediately move – only portions of the mock finger will begin to slide or "slip". This portion is known as "partial slip". A representative force curve has been marked with the "partial slip" (between the green X and blue X) and "steady sliding" (blue X and red X) regime.

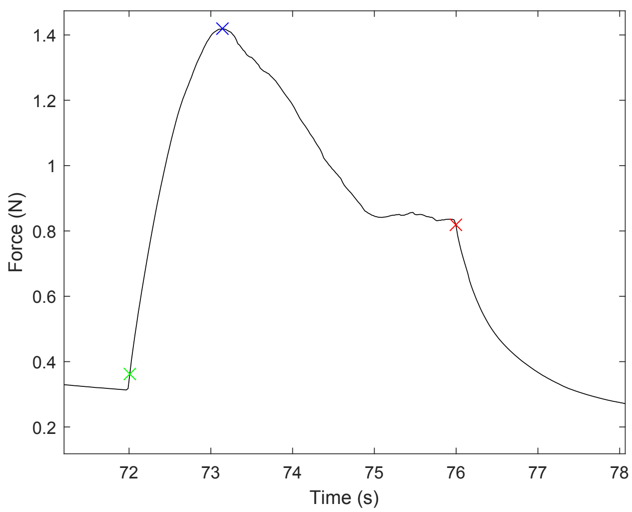


Figure S2: Friction trace segmented into partial slip and steady sliding. The green X represents the beginning of sliding, the blue X represents the transition of partial slip to full slip, or bulk motion of the finger, and the red X represents termination of the sliding event.

Comparing the cross-correlation at only the steady sliding regime yields the following discriminability matrices.

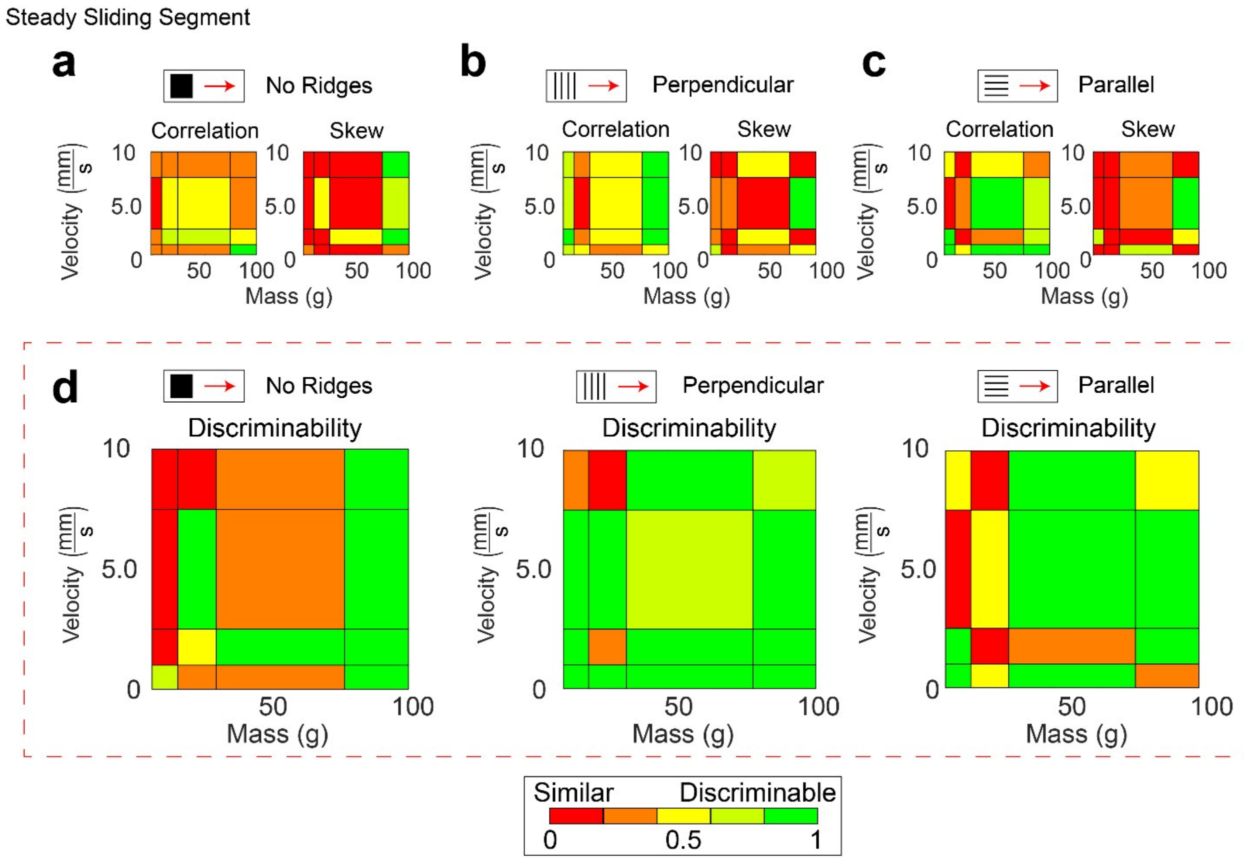


Figure S3: Discriminability matrices of the steady-sliding portion of friction traces. (a) Quantifying the cross-correlations between FOTS and SiOH friction traces. Two metrics used are the normalized area under the curve ('correlation') and the normalized symmetry ('skew') (b) for perpendicular ridges and (c) parallel ridges. (d) Discriminability matrix, which combines parametric values of 'correlation' and 'skew' into one matrix. In matrices, red indicates high similarity between force traces on FOTS and SiOH while green indicates low similarity (i.e., high discriminability).

We see that the mock finger with ridges generally increase discriminability, even when only considering the steady-sliding portion of the friction traces. We would expect that a subset of the friction traces would still recapitulate the general trends of the entire friction trace, although the increased discriminability of mock fingers with ridges occurs under slightly different masses and velocities. The increased discriminability from mock fingers with ridges as compared with mock fingers without ridges may appear to be less dramatic than comparing against the full friction trace. We note that, however, visually the parameter space from M=0 to 25g and v = 1 to 2.5 mm/s occupies a small portion of the plot but represents a quarter of the parameter space tested.

Model Details

The parameters for the model, other than the applied mass and velocity are, are as follows:

Table S2: Model parameters

Parameter	Value	Notes
Modulus of finger, E	100E3 Pa	Effective elastic modulus of entire finger, not individual layers
Spring constant (force sensor), k	1.384E4 N/m	-
Spring constant between fingers, k_{shear}	9000 N/m	Burridge-Knopoff, depends on finger as $k_{shear} = E * thickness * \frac{height}{width}$
Friction parameter, A	0.005 (FOTS), 0.015 (SiOH)	Directly taken from literature values, OTS in place of FOTS
Friction parameter, B	2*A	See above
Slip length, d_c	20E-7 m	-
Travel distance	4 mm	-
Finger dimensions, l x h x w	1 cm x 1 cm x 1 cm	Approximate region for fingertip, (not an entire finger), the only portion in contact with surface

FFT Analysis

We took the relative position data from several conditions and plotted the Fourier transforms to identify any trends that might explain the discriminability. We did not see any clear trends that could explain the changes in discriminability from the FFT alone.

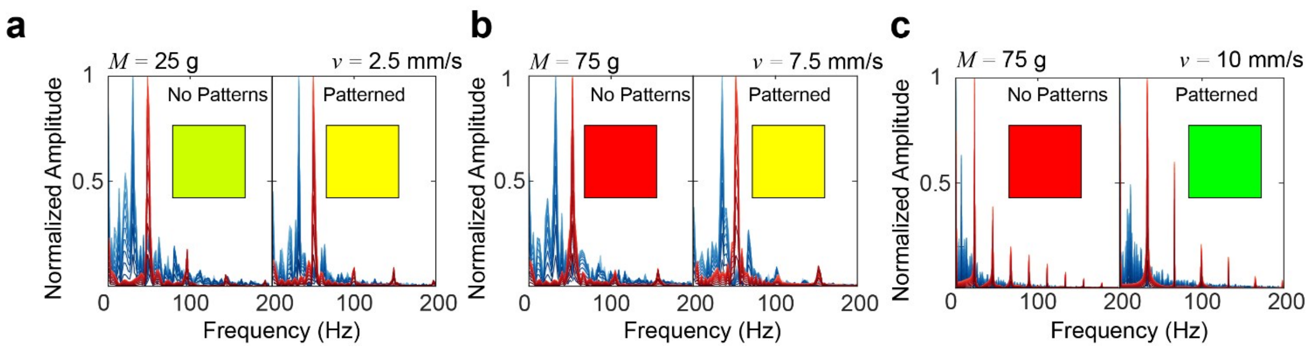


Figure S3. FFT of position. Color represents changes in discriminability matrix from experiments.

Complete Strain Outputs for all Blocks

For clarity in the main text, not all portions of the finger were visualized in the main text. These are provided below.

Mechanoreceptor Outputs

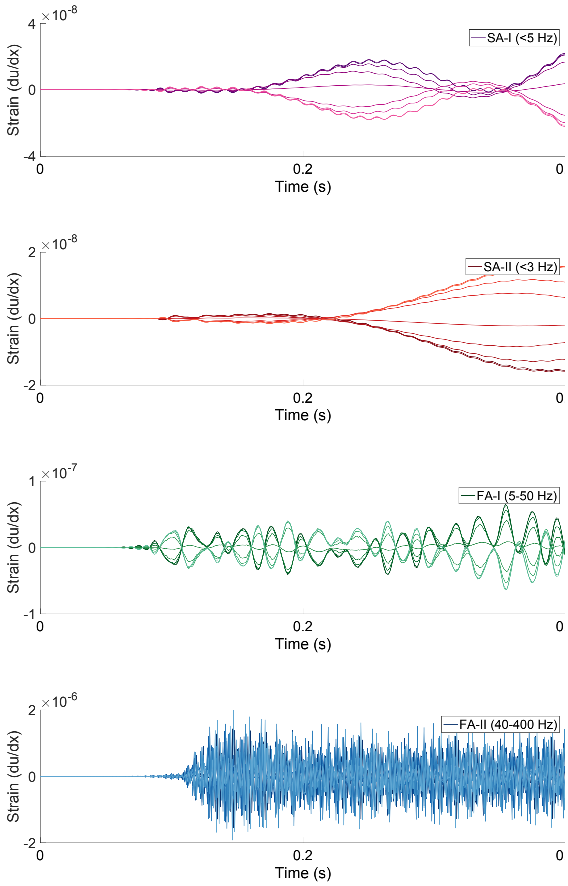


Figure S4. No "Ridges", on smooth FOTS

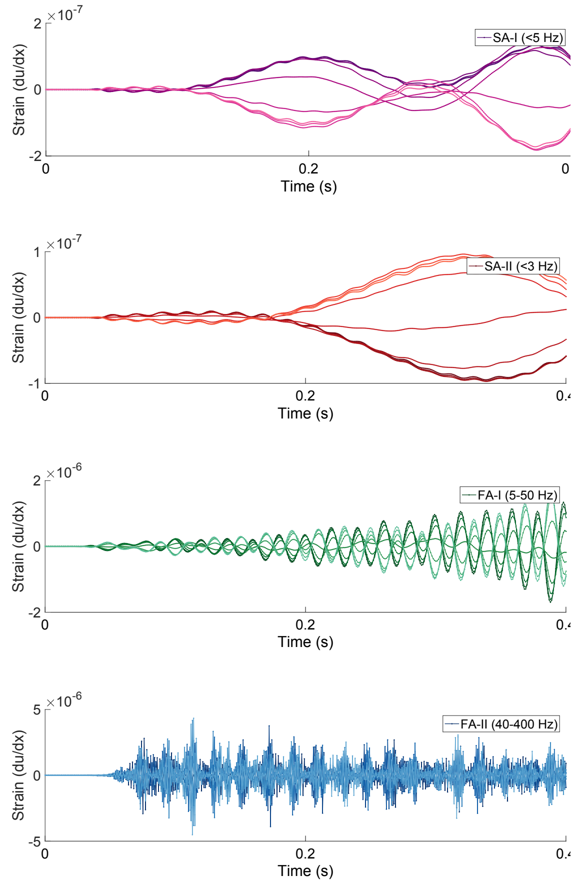


Figure S5.No "Ridges", on smooth SiOH

Table S3:Normalization Constants for Strain

	Flat FOTS	Flat SiOH	Perp. FOTS	Flat Bump (FOTS)	Perp. Bump (FOTS)	Perp. SiOH
SA-I	1.60E-8	9.70E-8	9.14E-9	9.72E-9	4.86E-9	4.98E-8
SA-II	2.21E-8	1.82E-7	1.17E-8	1.23E-8	3.47E-8	8.38E-8
FA-I	6.49E-8	1.73E-6	2.44E-8	3.95E-8	7.06E-8	1.62E-7
FA-II	1.99E-6	4.51E-6	4.92E-6	3.89E-6	3.37E-6	1.84E-6

Table S4: Tabulated Cross-Correlation

	No Ridges on FOTS vs SiOH (Fig 4E)	Perp. FOTS vs SiOH (Fig 4F)	No Ridges on Bump vs Smooth (Fig 4G)	Perp. with Bump vs Smooth (Fig 4H)
SA-I	1.18×10^{-11}	1.14×10^{-12}	1.47×10^{-10}	1.34×10^{-11}
SA-II	2.39×10^{-11}	3.26×10^{-12}	2.57×10^{-10}	3.65×10^{-11}
FA-I	8.29×10^{-11}	1.24×10^{-11}	2.35×10^{-9}	1.06×10^{-10}
FA-II	8.00×10^{-8}	5.08×10^{-8}	6.28×10^{-8}	8.46×10^{-8}

Autocorrelations	*Finger*	
Surface	**No Ridges**	**Perpendicular**
Flat FOTS	6.66×10^{-4}	4.30×10^{-4}
Flat SiOH	2.4×10^{-3}	1.4×10^{-3}
Bump on FOTS	6.20×10^{-4}	3.83×10^{-4}

Table S2 tabulates the cross-correlation (summed here) of the strain on each finger as it encounters different surfaces. A high cross-correlation indicates a similarity between the two surfaces (e.g FOTS and SiOH), while a low cross-correlation indicates that they are different. For brevity, a sum of the cross correlation across lag is tabulated, but cross correlations are shown below.

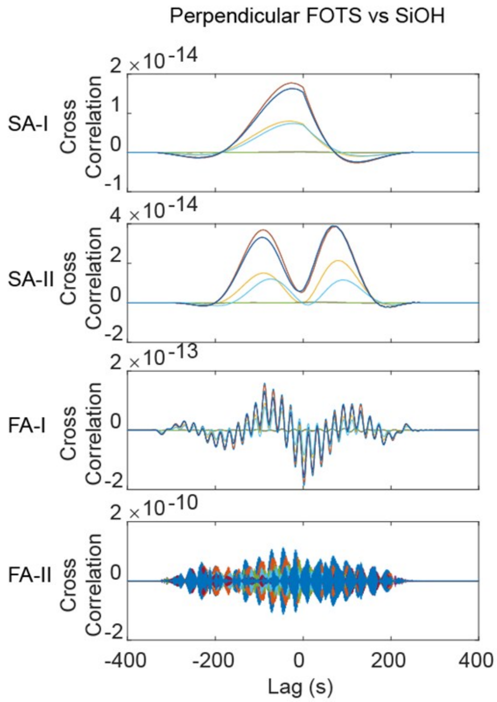


Figure S6. Cross-correlations strains, filtered by mechanoreceptors, of fingers with ridges "perpendicular" sliding on FOTS and SiOH.

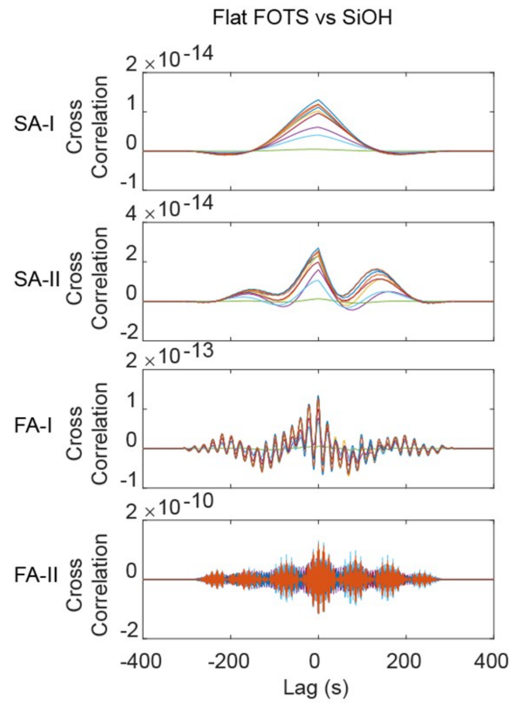
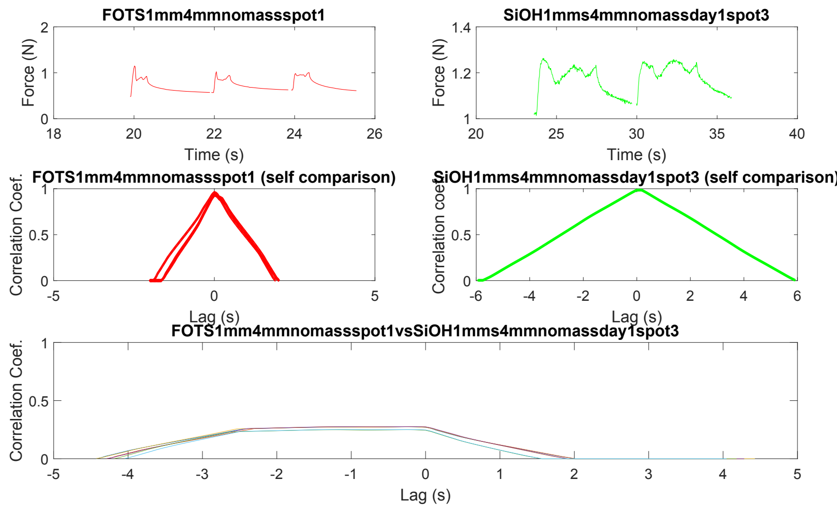


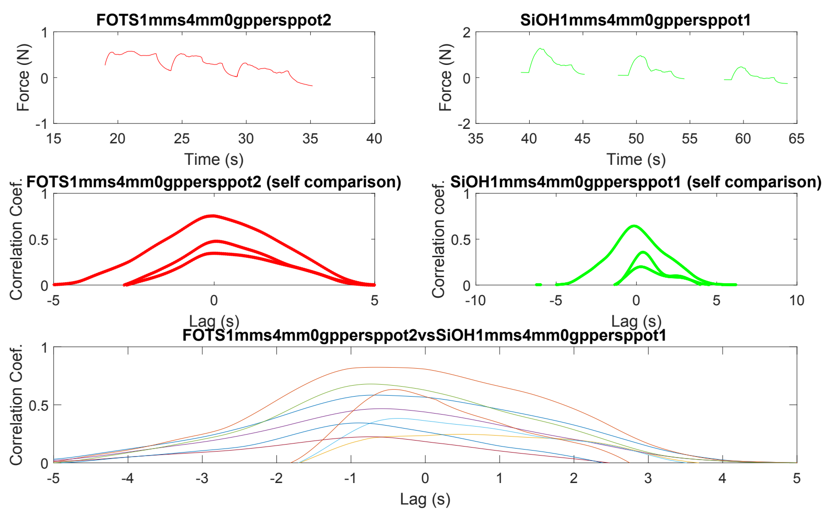
Figure S7. Cross-correlations strains, filtered by mechanoreceptors, of fingers without ridges sliding on FOTS and SiOH.

Friction traces and correlations of PDMS slabs

No Ridges



Perpendicular



Parallel

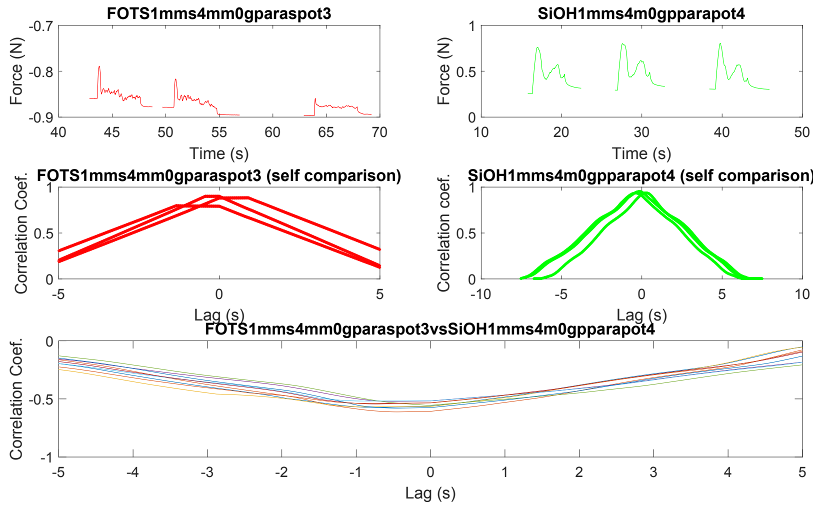
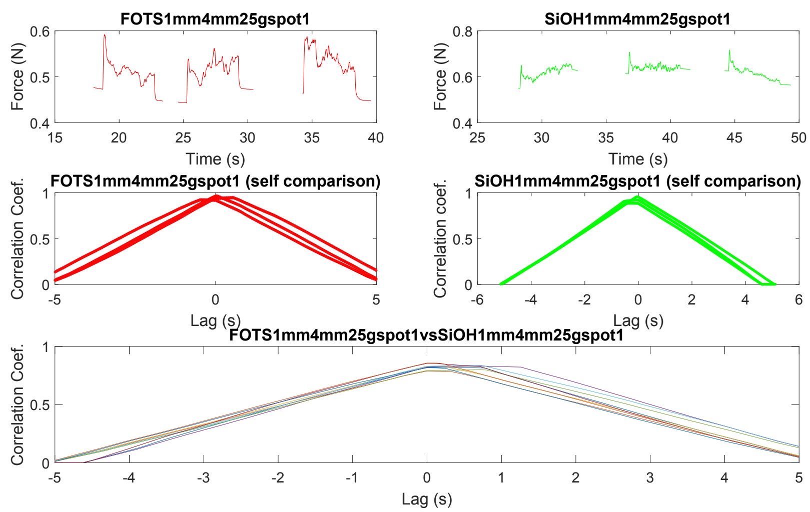
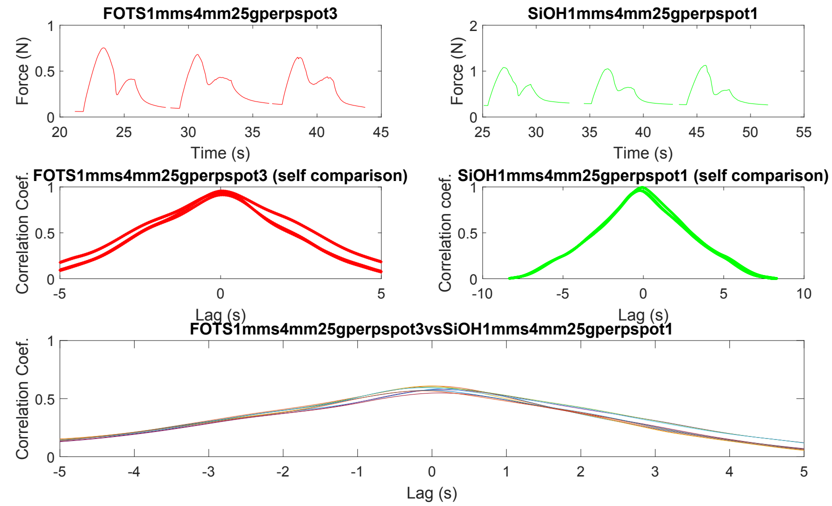


Figure S8: *v = 1 mm/s, M = 0 g*

No Ridges



Perpendicular



Parallel

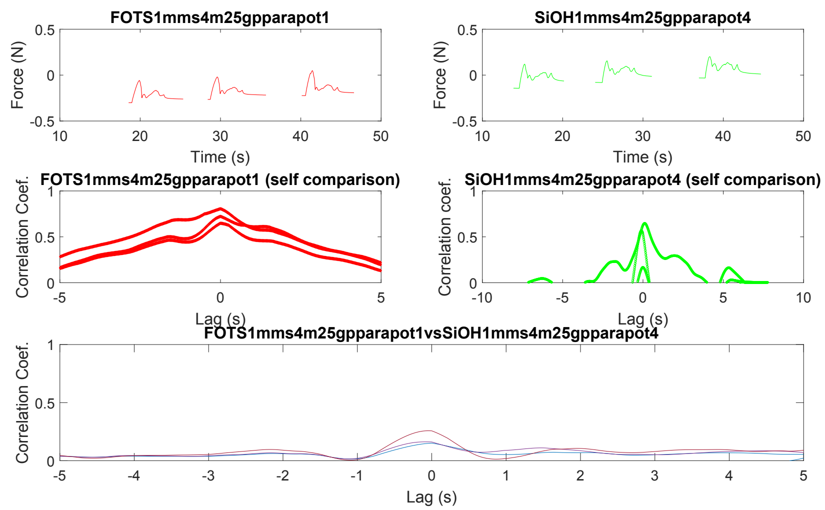
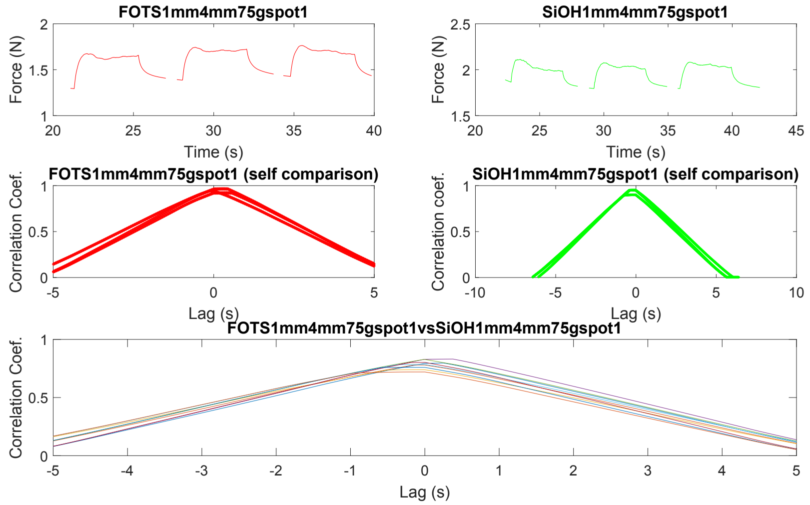
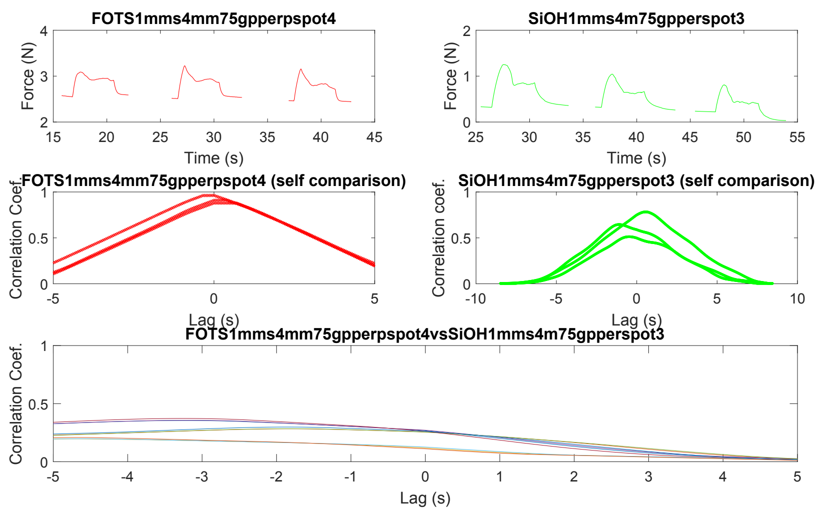


Figure S9: *v = 1 mm/s, M = 25 g*

No Ridges



Perpendicular



Parallel

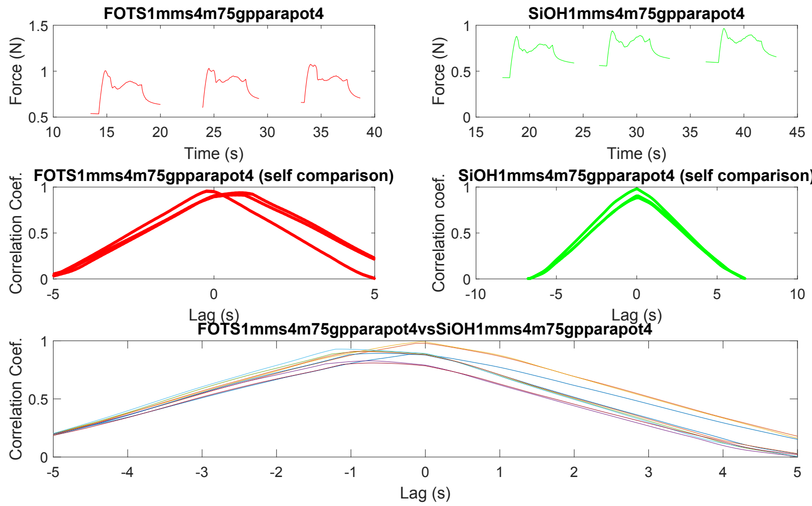
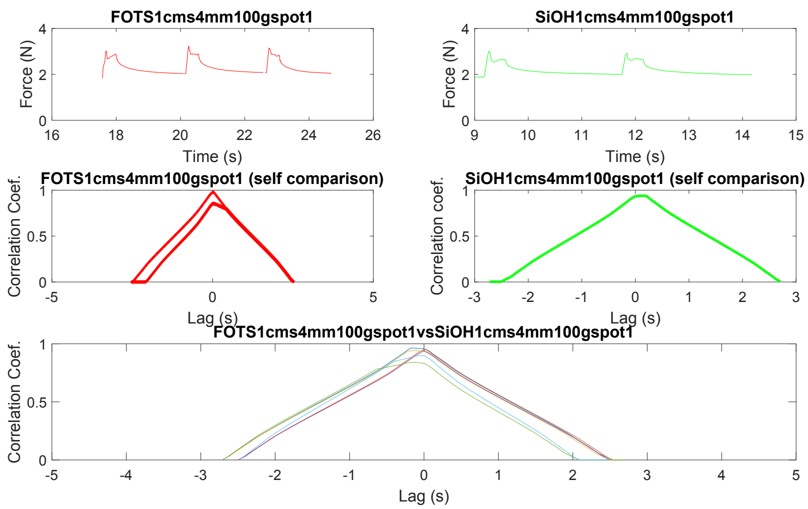
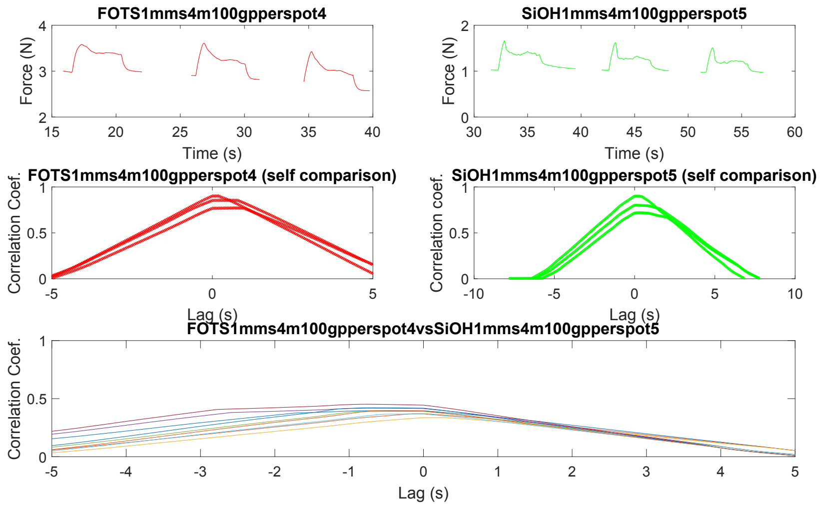


Figure S10: *v = 1 mm/s, M = 75 g*

No Ridges



Perpendicular



Parallel

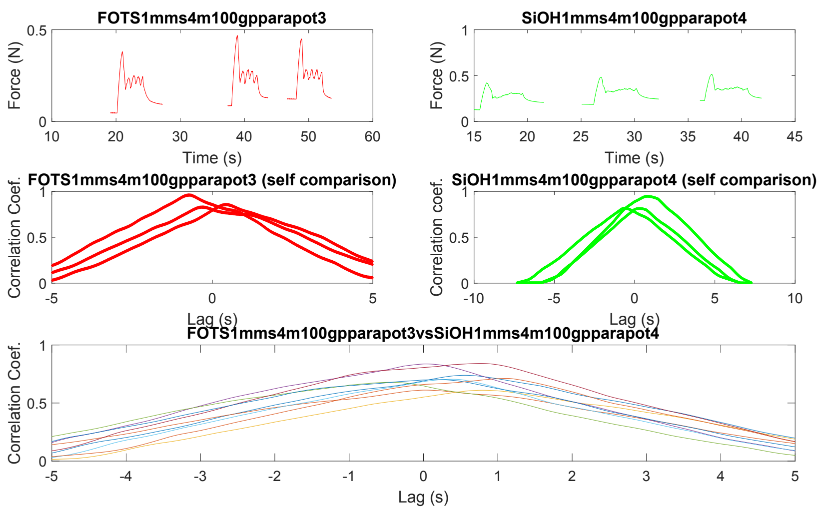
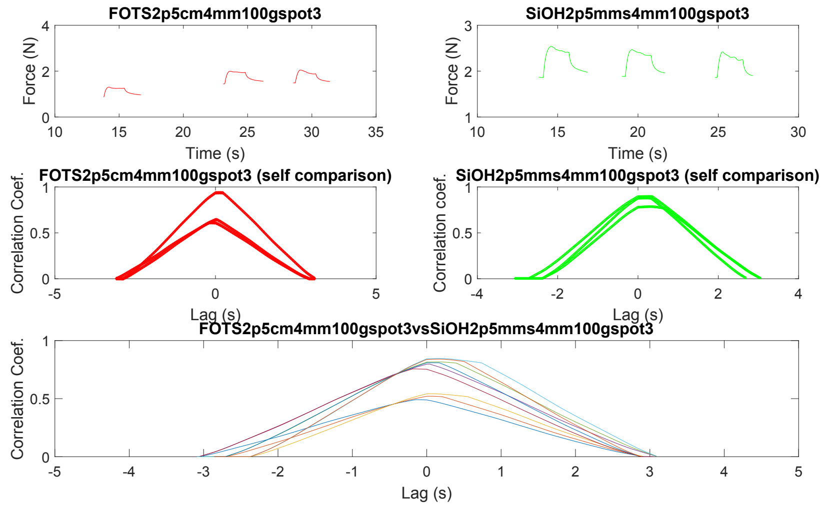
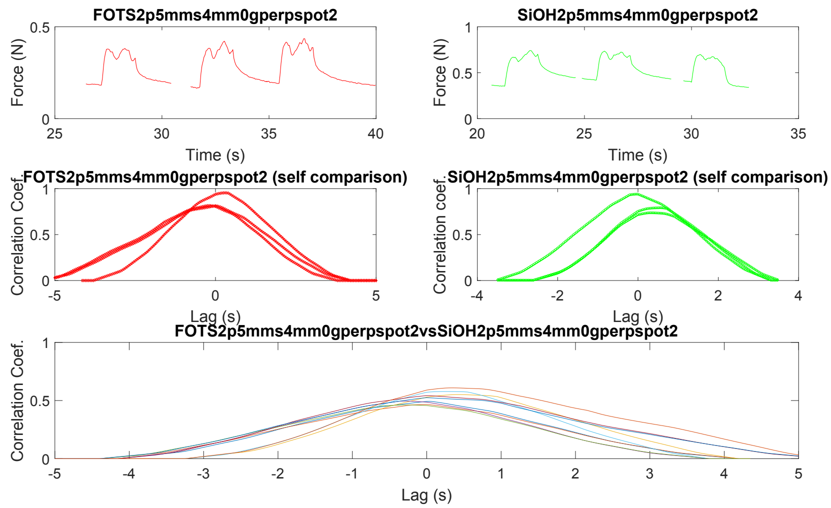


Figure S11: *v = 1 mm/s, M = 100 g*

No Ridges



Perpendicular



Parallel

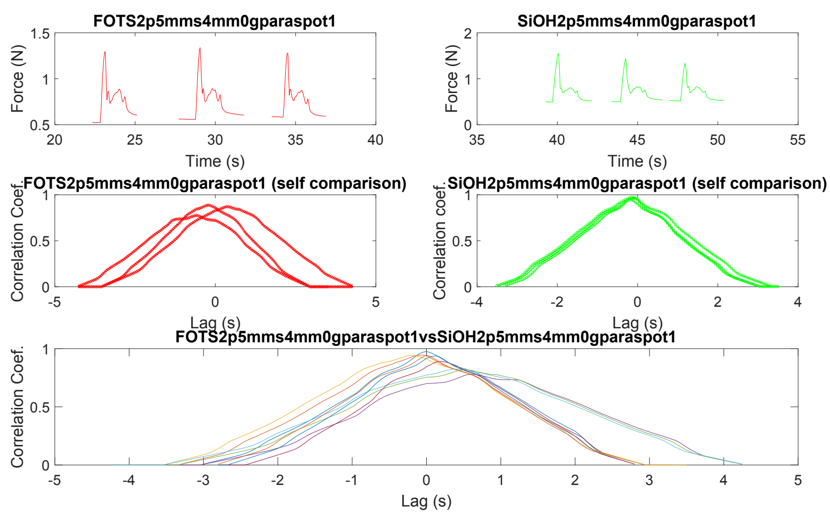
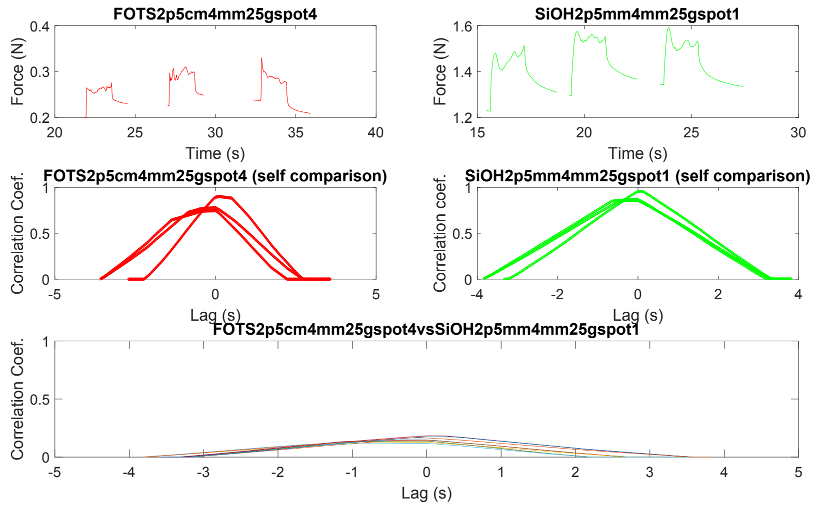
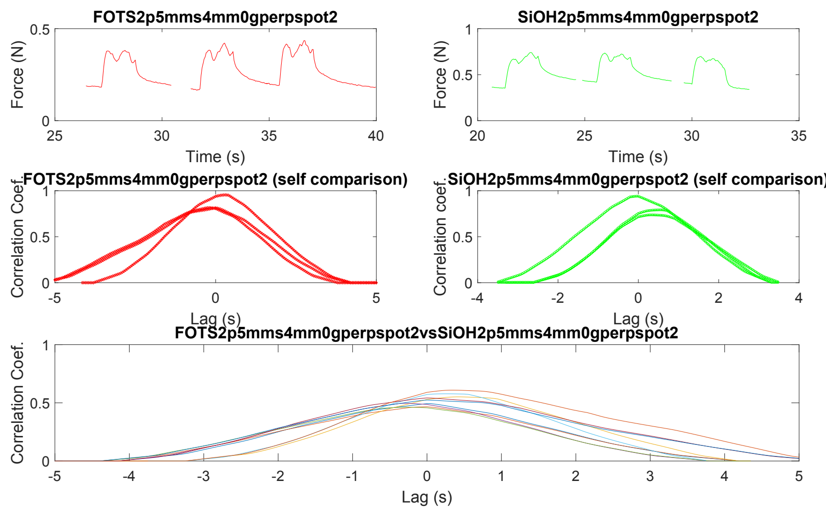


Figure S12: *v = 2.5 mm/s, M = 0 g*

No Ridges



Perpendicular



Parallel

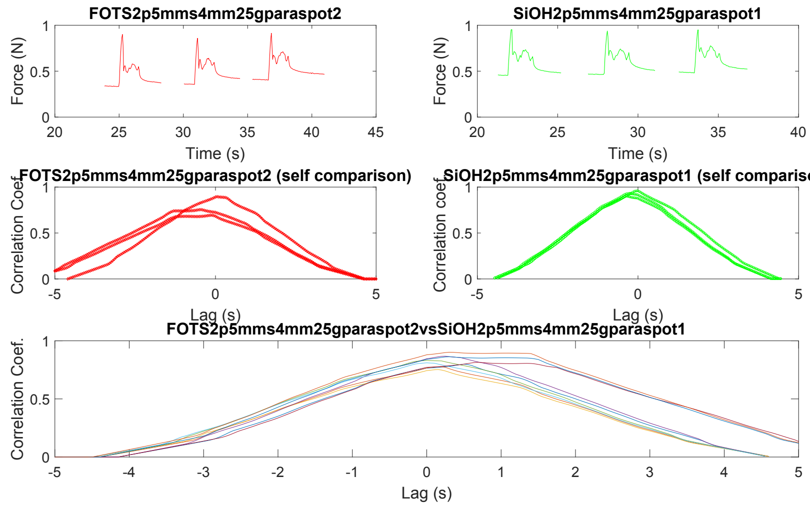
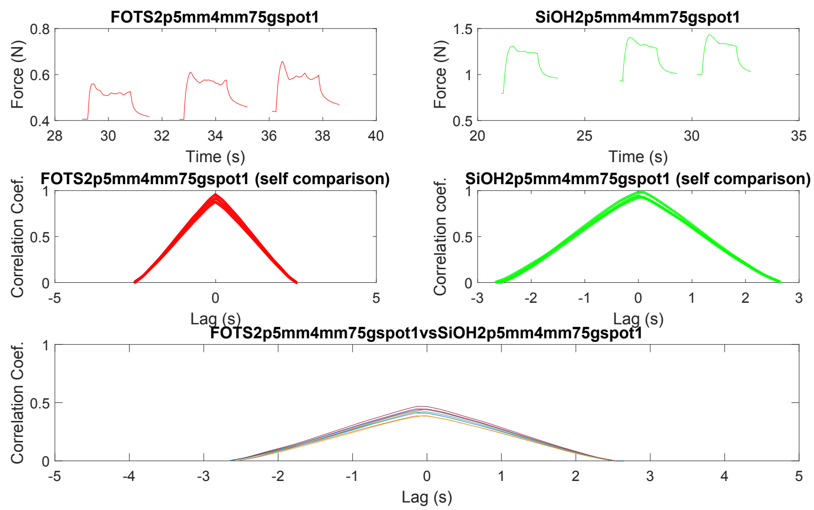


Figure S13: *v = 2.5 mm/s, M = 25 g*

No Ridges



Perpendicular

Parallel

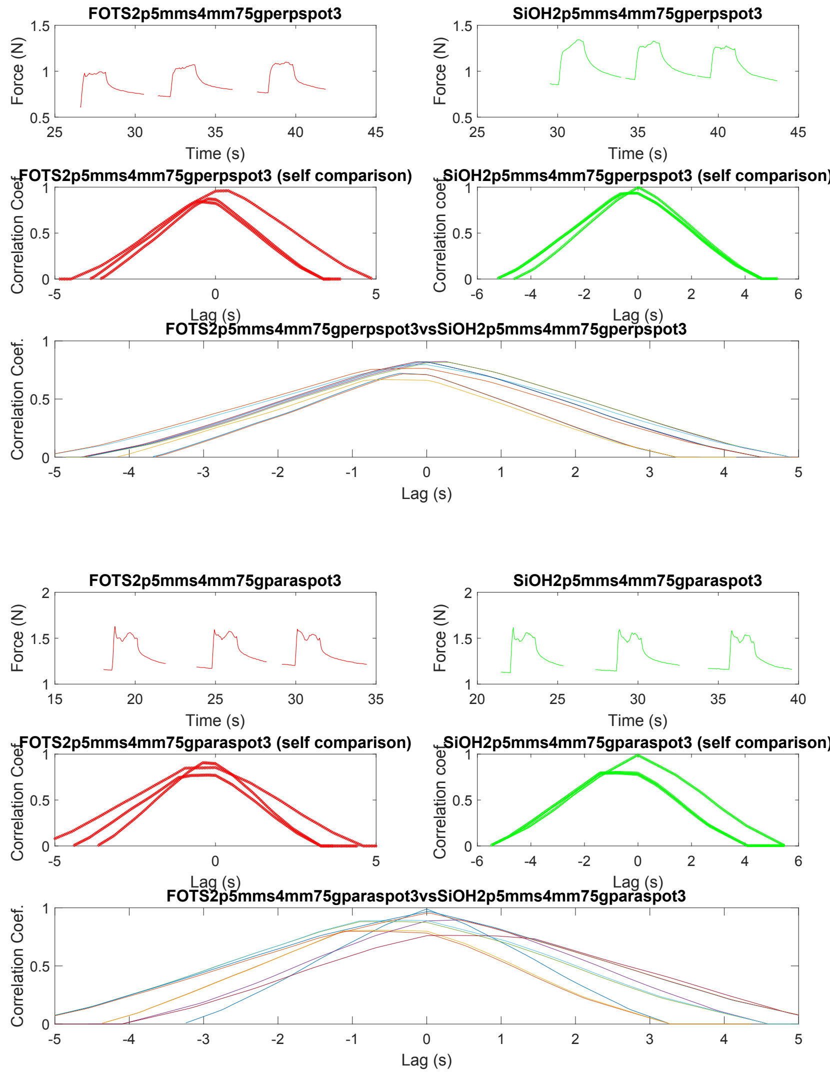
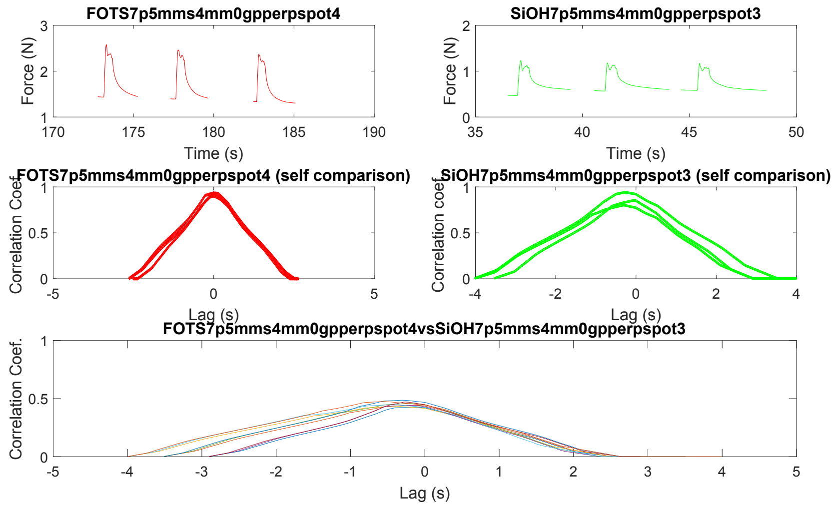
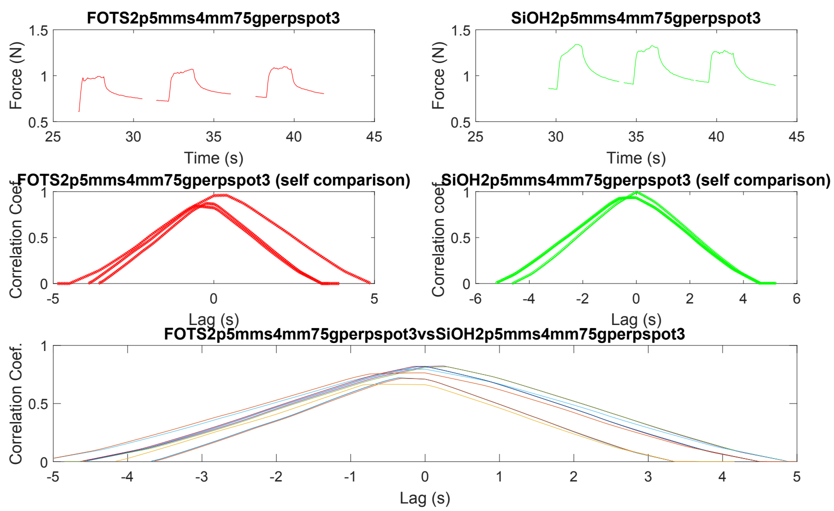


Figure S14: *v = 2.5 mm/s, M = 75 g*

No Ridges



Perpendicular



Parallel

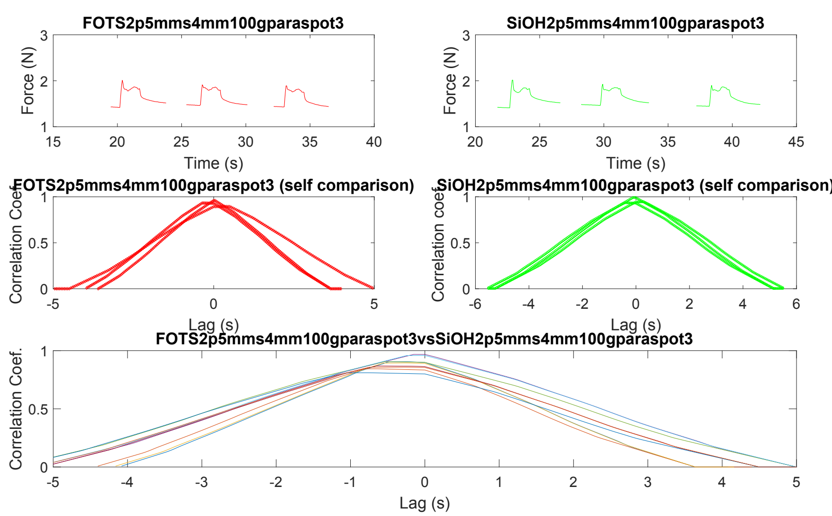
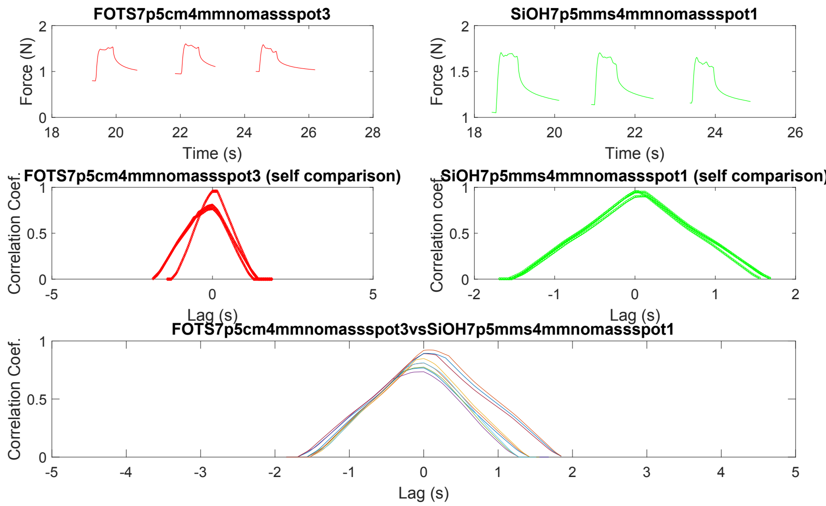
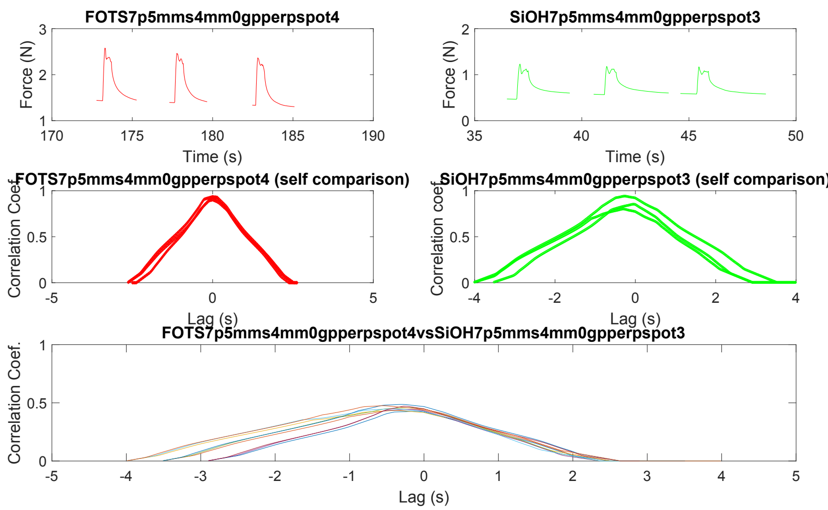


Figure S15: *v = 2.5 mm/s, M = 100 g*

No Ridges



Perpendicular



Parallel

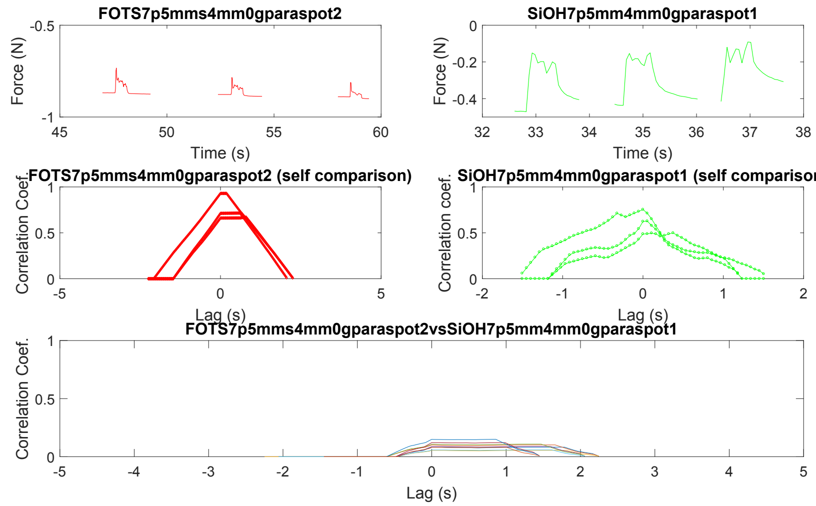
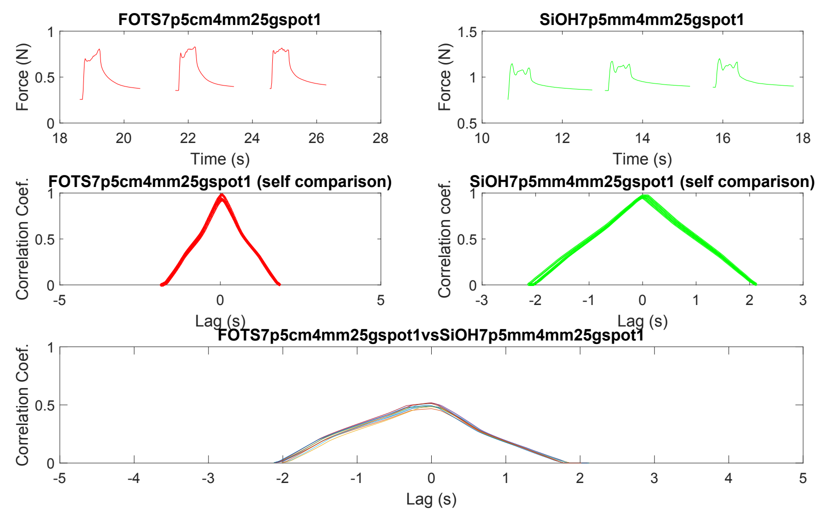
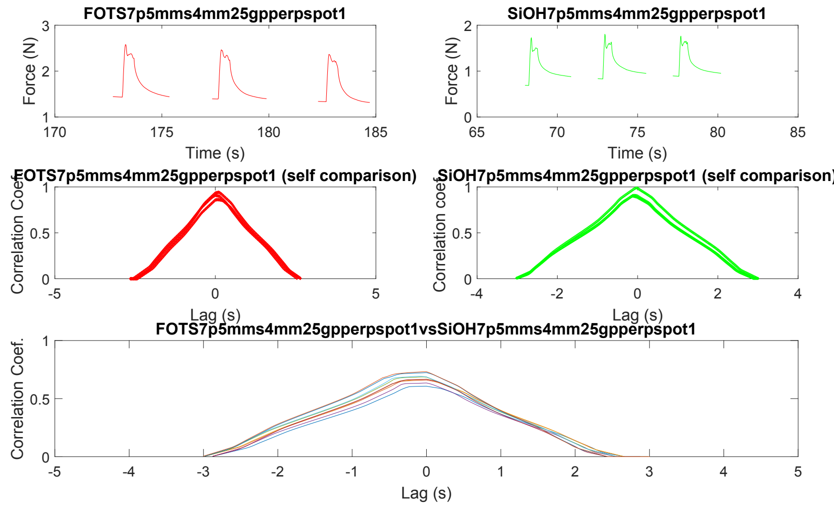


Figure S16: *v = 7.5 mm/s, M = 0 g*

No Ridges



Perpendicular



Parallel

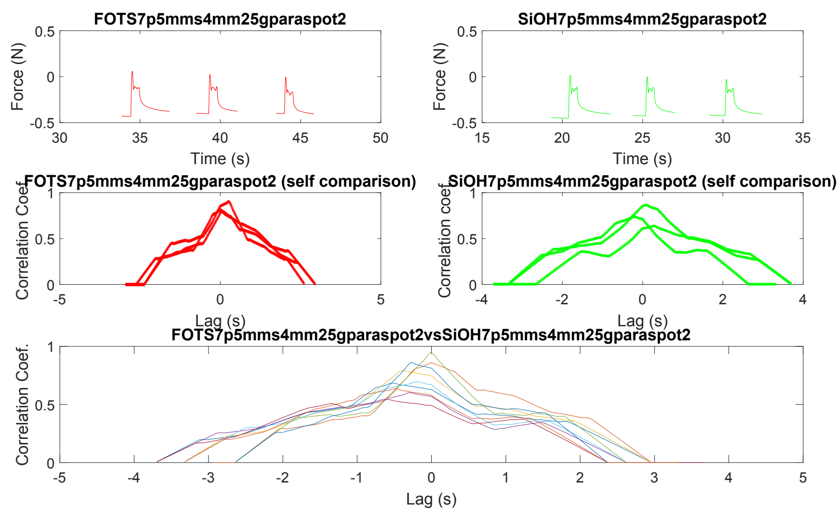
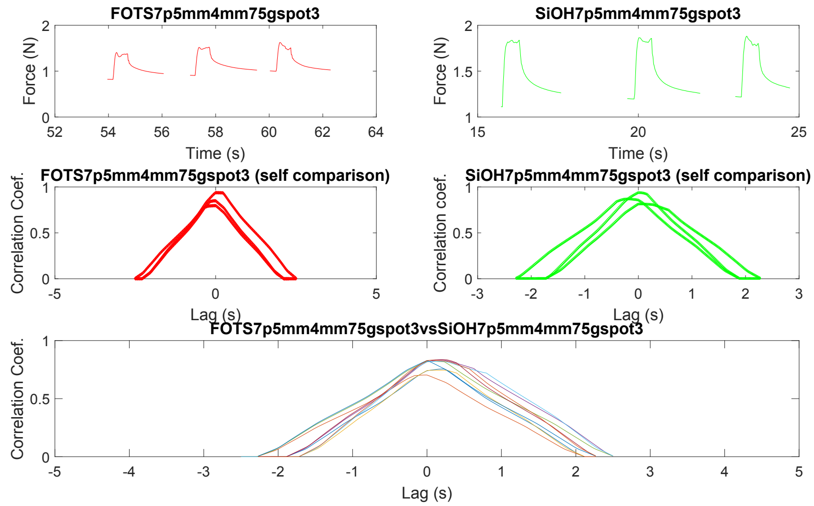
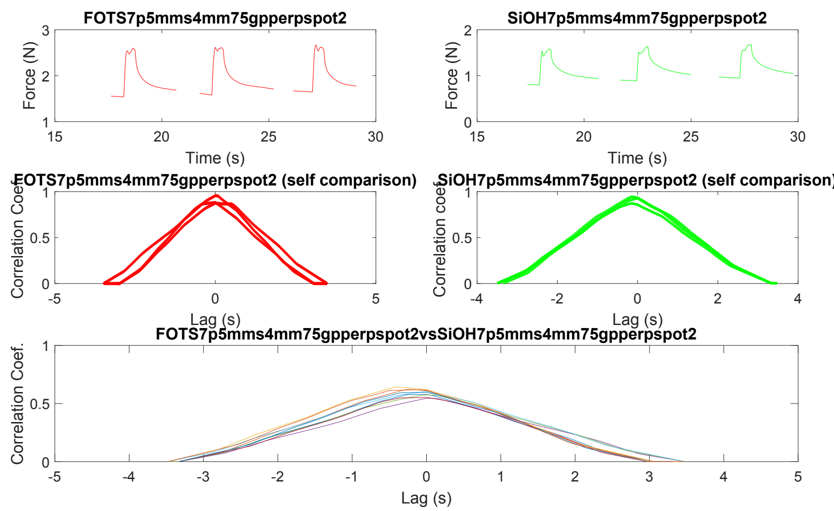


Figure S17: *v = 7.5 mm/s, M = 25 g*

No Ridges



Perpendicular



Parallel

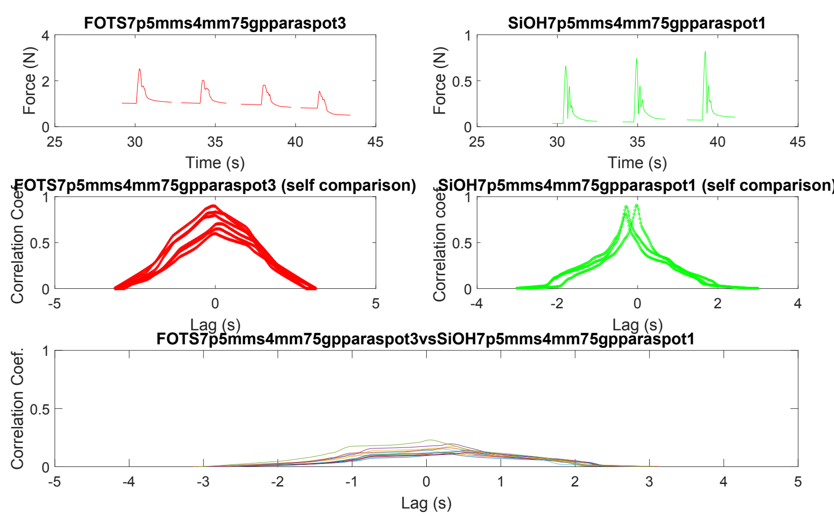
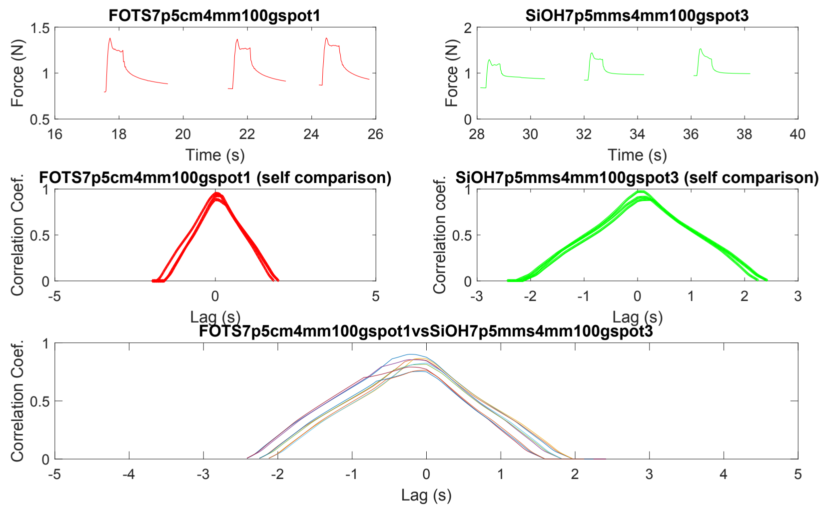
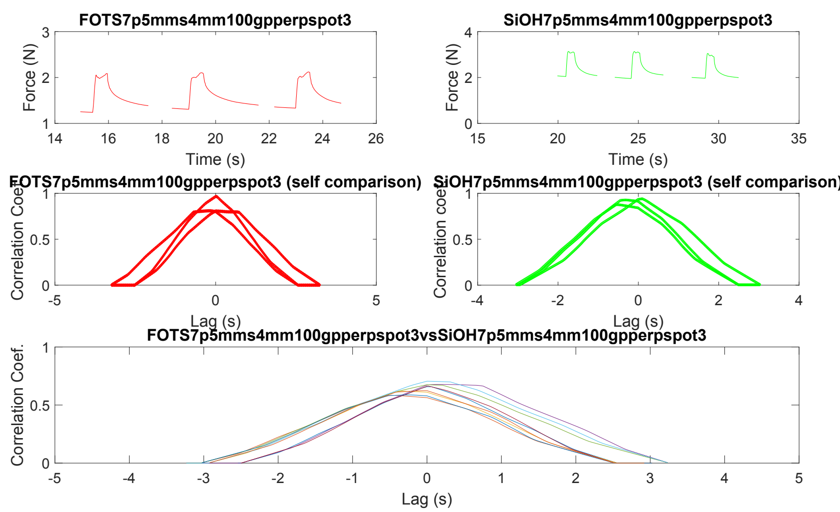


Figure S18: *v = 7.5 mm/s, M = 75 g*

No Ridges



Perpendicular



Parallel

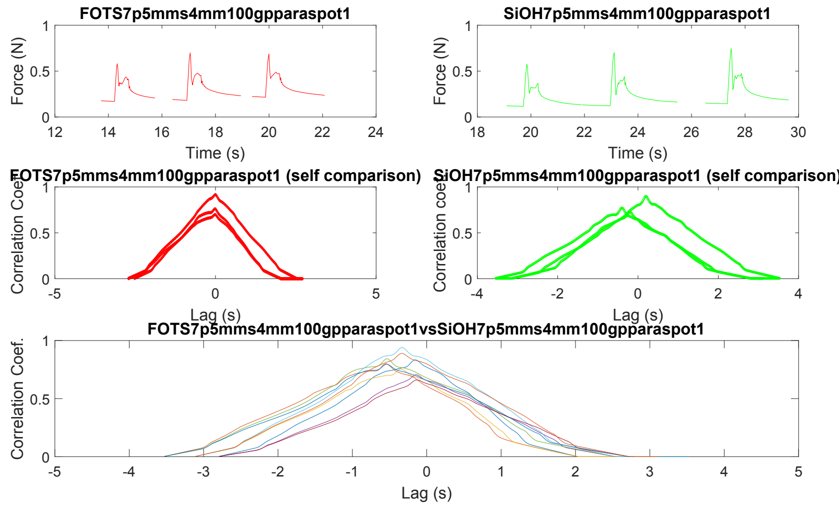
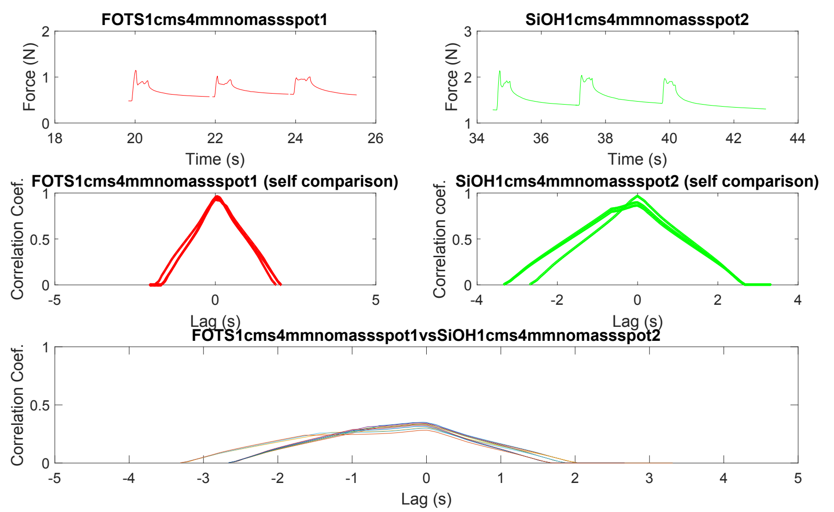
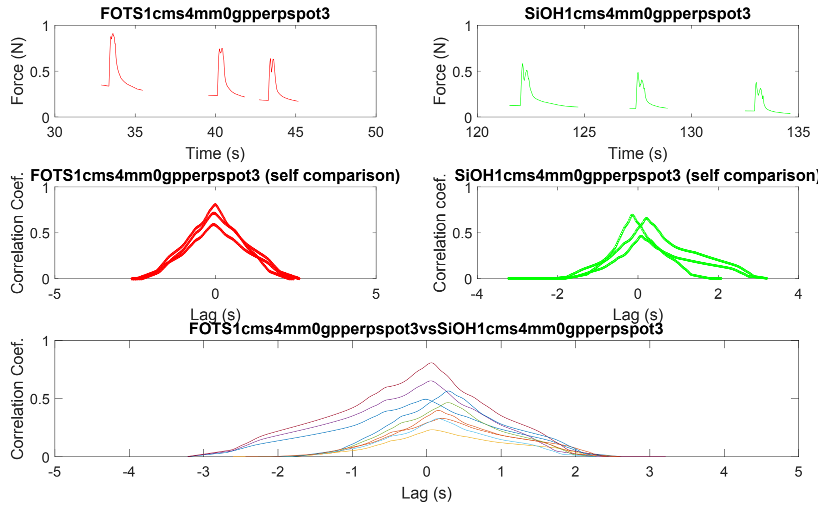


Figure S19: *v = 7.5 mm/s, M = 100 g*

No Ridges



Perpendicular



Parallel

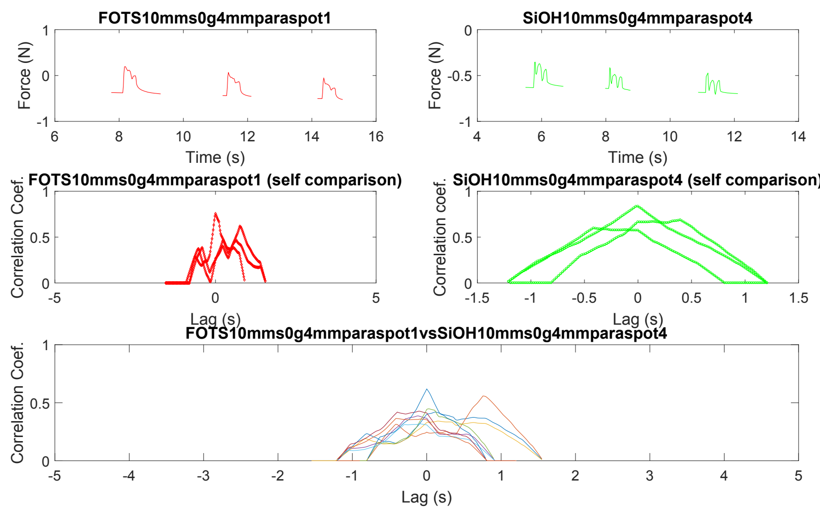


Figure S20: *v = 10 mm/s, M = 0 g*

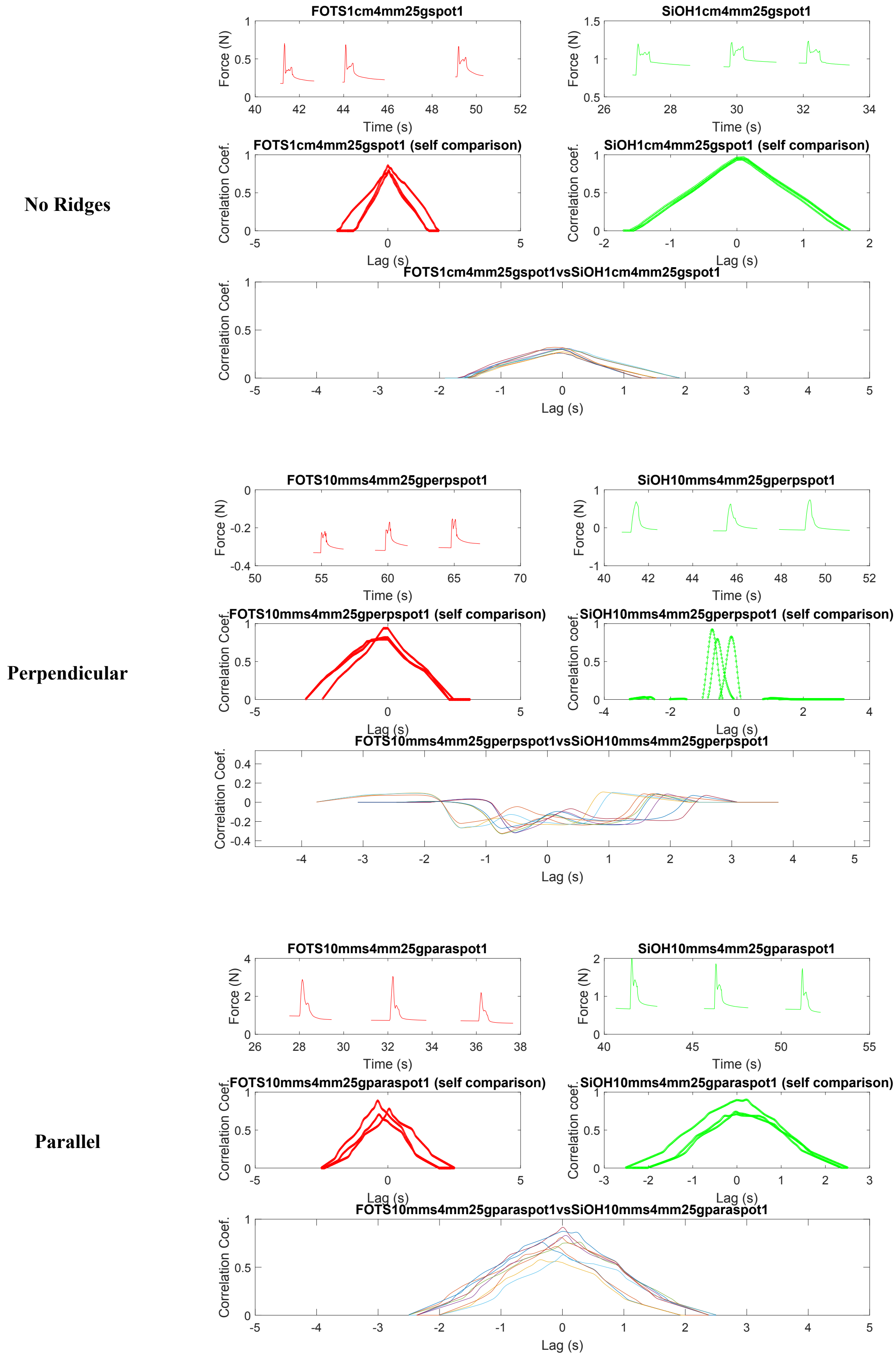
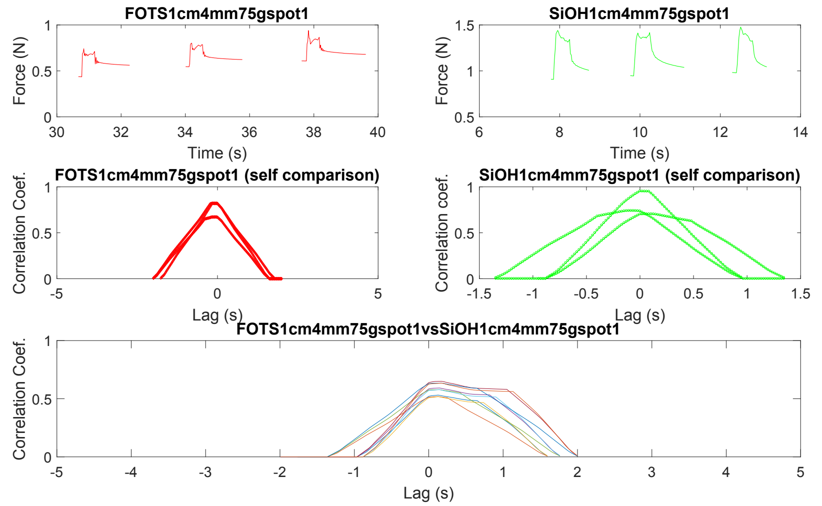
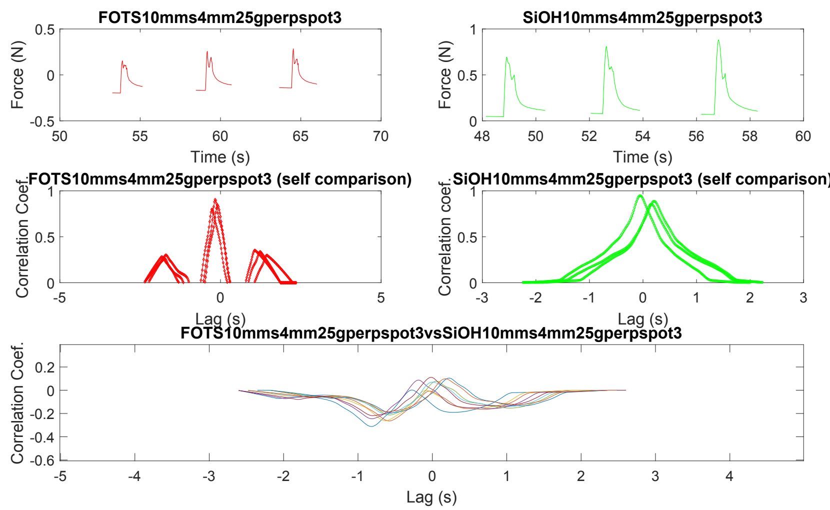


Figure S21: *v = 10 mm/s, M = 25 g*

No Ridges



Perpendicular



Parallel

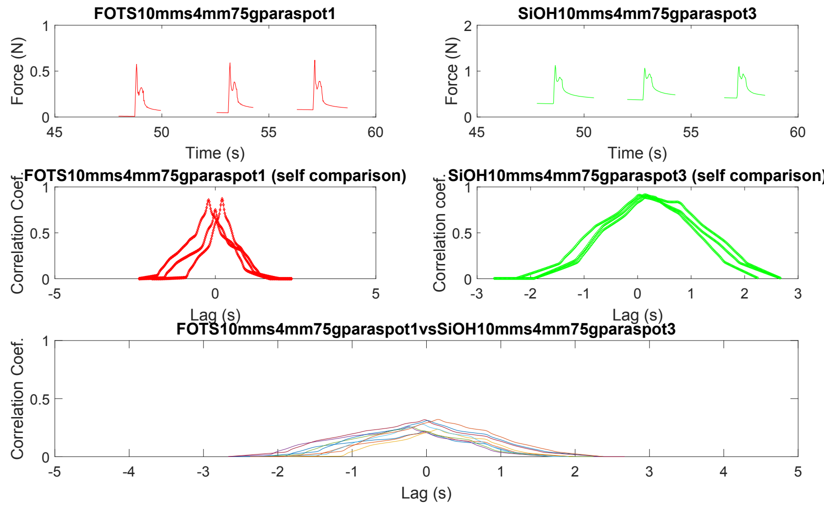
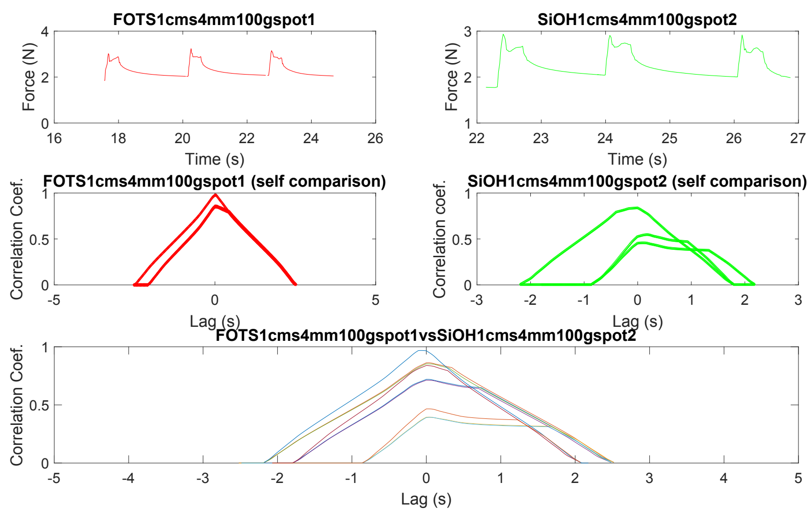
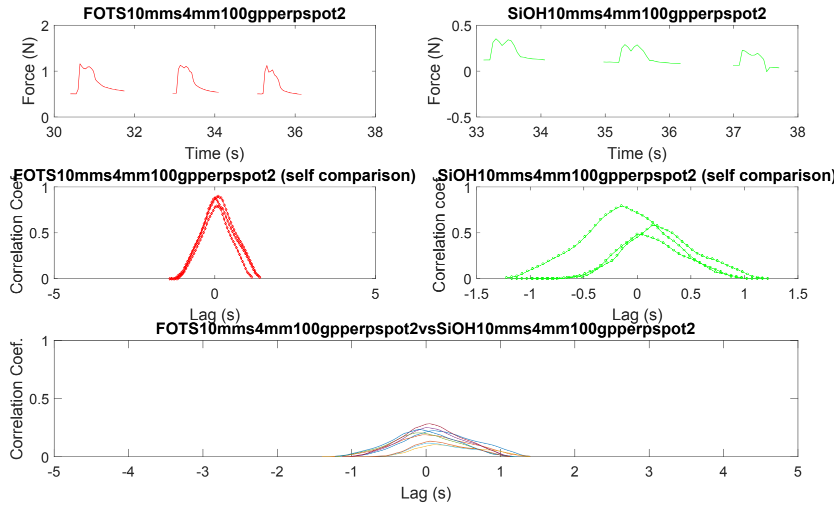


Figure S22: *v = 10 mm/s, M = 75 g*

No Ridges



Perpendicular



Parallel

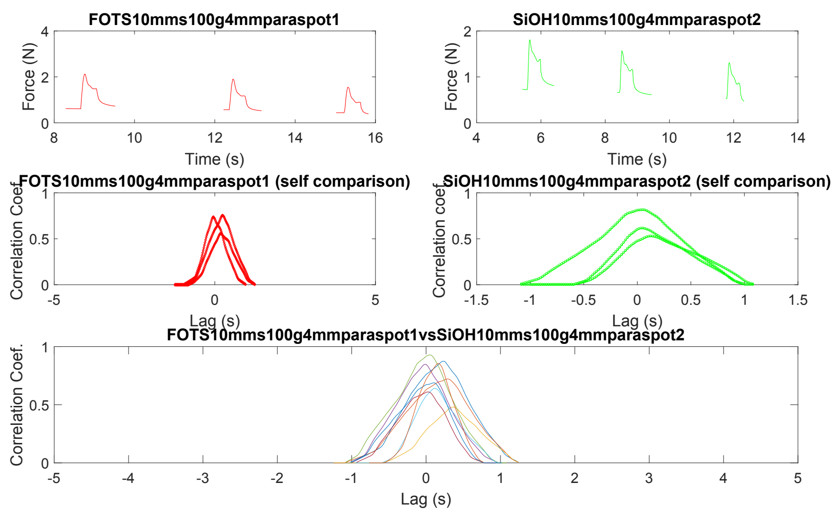


Figure S23: *v = 10 mm/s, M = 100 g*

1. Gueorguiev, D.; Bochereau, S.; Mouraux, A.; Hayward, V.; Thonnard, J.-L., Touch uses frictional cues to discriminate flat materials. *Scientific reports* **2016,** *6*.