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Surface State Decouples Normal Detachment and Slip Initiation in Grip-Optimized Rubber Contacts

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4 Keywords

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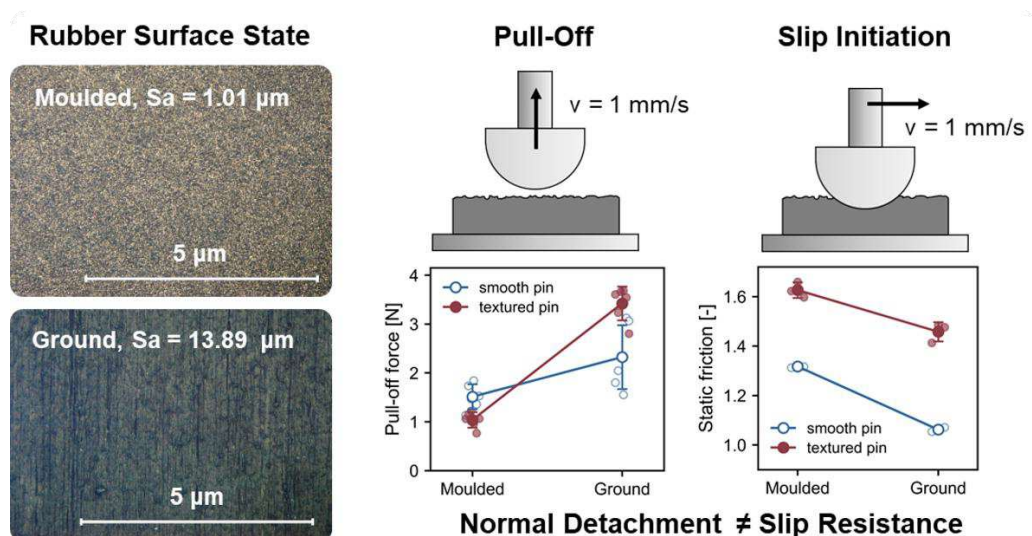
Abstract

Rubber surface condition can influence both normal detachment and resistance to tangential slip, but these responses are not necessarily governed by the same interfacial mechanisms. This study investigated how surface preparation of a grip-optimized climbing shoe rubber affects pull-off and slip initiation against smooth and textured rigid spherical counter-surfaces. The same rubber compound was tested in four surface states: the original moulded surface (P0), a cut surface exposing subsurface material (CUT), and surfaces ground with P100 or P60 abrasive paper. Normal detachment was characterized using maximum pull-off force and work of detachment, while tangential response was evaluated using static and steady sliding friction coefficients and the static-to-steady friction drop.

Surface preparation strongly altered both detachment and friction, but the responses were not directly coupled. The ground surfaces generally showed higher detachment resistance but lower static and steady sliding friction than P0, with the magnitude of these effects depending on counter-surface texture. CUT further emphasized this decoupling: despite having nearly the same arithmetic mean height (S_a) as P0, it produced markedly greater pull-off force and work of detachment, particularly against the smooth pin, while exhibiting lower static friction. This demonstrates that surface preparation affects the response through more than roughness amplitude alone.

Resistance to normal detachment therefore cannot be used alone to predict resistance to tangential slip. Pull-off and friction tests provide complementary information, and both rubber surface preparation and representative counter-surface texture should be controlled when evaluating climbing shoe rubber performance.

Graphical Abstract



1. Introduction

Many high-friction applications, including tyres, robotic grippers, and climbing shoes, rely on soft rubber contacts that must resist slip under limited normal load. In climbing, the quality of shoe–hold contact is directly relevant to performance: biomechanical studies show that skilled climbers effectively redistribute load away from the upper limbs, operate closer to the frictional limit of the contact, and thereby reduce physiological demand and improve movement economy [1–4].

From a tribological perspective, the resistance to the initiation of slip is described as static or breakloose friction. Rubber friction is commonly interpreted in terms of adhesive and hysteretic contributions [5], where the adhesive contribution originates from the attractive interactions in the real contact area [6] and hysteretic contribution originates from cyclic deformation of the rubber by surface asperities during sliding, producing viscoelastic energy losses [7]. As a result of material deformation caused by the tangential force, the contact area already begins to decrease during the initial displacement stage [8]. Barquins observed that, in viscoelastic rubbers, sliding does not initiate simultaneously over the entire contact area. Instead, a slip region first forms at the edge of the contact area and then gradually expands [9]. Thus, both adhesion and hysteresis are expected to affect the static friction force [10].

Adhesion in rubber and other soft-material contacts is commonly quantified using normal detachment experiments, in which a rigid probe is pressed against a compliant substrate and subsequently retracted while the normal force, displacement, and, where possible, contact radius are recorded [11,12]. For smooth elastic contacts, the Johnson–Kendall–Roberts (JKR) framework relates the pull-off force to the thermodynamic work of adhesion (W_{adh}), which is the reversible energy required to separate an interface per unit area [13]. However, this approach assumes elastic bodies, smooth surfaces and no viscoelastic dissipation or plastic damage. Studies on rubber adopting this approach for viscoelastic rubbers usually use very low retraction velocities, small loads and smooth surfaces to satisfy the main assumptions [14–16].

In rubber contacts, the measured work of adhesion is strongly rate dependent [17]. Gent and Schultz provided a classical interpretation of this behaviour, showing that the measured adhesion of viscoelastic materials can be described as a thermodynamic contribution multiplied by a rate- and temperature-dependent dissipation factor [18]. Such rate-dependent apparent adhesion energies are commonly described as effective works of adhesion [19].

In addition to the work of adhesion given by the JKR framework, work of detachment (W_{det}) can be used to evaluate the adhesive strength of an interface. Work of detachment is calculated as the area under the tensile region of the load-displacement curve acquired during the normal

detachment experiment [20]. This approach is often used for evaluating the adhesive strength of highly adhesive materials such as pressure-sensitive adhesives [20,21], where substantial viscoelastic dissipation during detachment is expected.

Persson et al. investigated adhesion between glass and three different tire tread rubbers using the JKR framework and did not find a simple relation between adhesion and sliding friction of these rubber compounds against a concrete block [22,23]. Later, Elkington et al. investigated the work of detachment of several grip-optimized climbing shoe rubbers against a steel ball together with frictional response of the rubbers against a granite pin and found a positive correlation between static friction and work of detachment at low load, which strongly weakened for frictional experiments with higher load [24]. However, mixed surface conditions of the tested rubbers in Elkington's study complicate separation of material-composition-related effects from rubber-surface condition effects on the detachment and frictional responses.

In the present study, we use a rubber compound commonly used in high-performance climbing shoes to investigate the relationship between normal detachment and slip initiation under climbing-relevant loading conditions. To isolate surface-preparation effects, the same rubber compound was tested in four distinct surface states: the original moulded surface, a cut surface exposing subsurface material, and two ground surfaces with progressively greater roughness. These conditions were evaluated against rigid spherical polyester pins with controlled smooth and textured surfaces. This design allows normal detachment and tangential slip initiation to be compared within the same material system and contact geometry, while also distinguishing the effects of surface roughness from broader changes associated with removal of the moulded surface layer.

2. Materials and Methods

2.1. Materials and Surface Preparation

2.1.1. Rubber Plate Specimens

Sheets of grip-optimized rubber, commercially known as Cat μ 1.5, were supplied by the Czech climbing shoe manufacturer RP Climbing s.r.o. (Mnichovo Hradiště, Czech Republic). The nominal thickness of all rubber sheets was 4 mm. Rubber hardness was measured using a type A durometer according to EN ISO 868:2003 [25], with a waiting time of 10 ± 1 s before reading. Based on five measurements, the hardness was 80.2 ± 0.9 Shore A.

Four rubber surface conditions were prepared for comparison. The unground moulded surface, denoted P0, was cleaned with an IPA-wetted cloth to remove possible low molecular weight surface contamination film. Two roughened surfaces, denoted P100 and P60, were prepared from the pristine rubber surface using a belt grinding device equipped with P100 or P60 abrasive paper, respectively. The P60 treatment produced a higher average surface roughness than P100, as confirmed by areal surface topography measurements.

A fourth surface condition, denoted CUT, was prepared by splitting the 4 mm rubber sheet approximately in half along a plane parallel to its surface, producing two layers of approximately 2 mm thickness. One layer was inverted so that the freshly exposed internal rubber surface became the testing surface. The two layers were then bonded together using cyanoacrylate adhesive to restore the original specimen thickness of approximately 4 mm. Because the CUT specimens contained an internal cyanoacrylate adhesive interface absent from the other conditions, some increase in effective stiffness was expected. Its influence was assessed from the measured indentation response during normal loading. At 45 N, the mean indentation depth was 0.277 ± 0.020 mm for CUT and 0.290 ± 0.033 mm for P0, corresponding to a difference of -4.6 %. This difference was comparable in magnitude to the variation observed among the other surface preparations, suggesting that the added stiffness from the reconstructed interface had only a minor effect on the effective normal compliance under the investigated loading conditions. The corresponding force-indentation curves and comparison of indentation depth among all rubber surface preparations are shown in **Fig. S18** (online).

For mechanical testing, all rubber sheets were bonded to PMMA support plates using cyanoacrylate adhesive. This ensured fixation of the specimens during both normal pull-off and tangential slip initiation experiments.

2.1.2. Rigid Pin Specimens

Rigid spherical polyester pins were supplied by the Czech climbing hold manufacturer AIX s.r.o. (Prague, Czech Republic). Two pin surface conditions were used: a smooth surface and a textured surface. Both pin types had the same nominal radius of 20 mm. The textured pin was designed to match the surface texture of a commercial grade climbing hold.

2.2. Surface Topography Characterization

The rubber and pin surfaces were characterized using a Keyence VHX-6000 optical microscope equipped with a 250 $\times$ magnification lens. Both pin surfaces (smooth and textured) were scanned close to the apex of the curvature. Each rubber surface was scanned on five independent locations. Representative height maps and pictures of the tested surfaces are shown in **Fig. 1**.

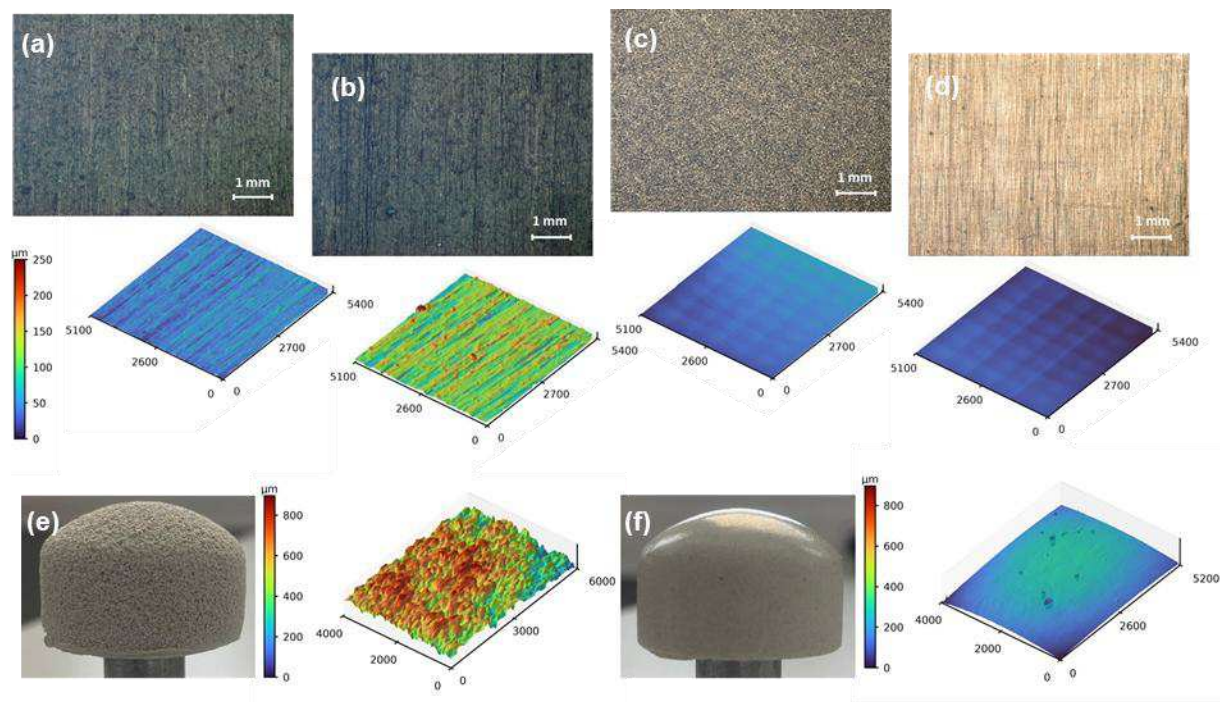


Fig. 1 Representative height maps and pictures of the tested surfaces: (a) P100, (b) P60, (c) P0, (d) CUT, (e) textured pin, and (f) smooth pin. The pin surfaces were scanned close to the top of the spherical pin. Colour bars indicate height.

Areal surface descriptors were calculated using the Keyence VHX software. For the rubber specimens, the evaluated region was selected as an approximately 4.8 mm $\times$ 4.8 mm square in the central part of the scanned area. For the pins, the evaluated region was selected as an approximately 4 mm $\times$ 4 mm square close to the top of the spherical surface. Arithmetical mean height (S_a) and root mean square height (S_q) were used as the primary roughness

descriptors. Gaussian filtering together with end-effect correction was applied before calculating the surface descriptors. Gaussian S-filter of 8 μm was used for all measurements to suppress short-wavelength measurement noise in form of isolated peaks. For the rubber specimens, a Gaussian L-filter of 0.8 mm was used to remove plane tilt from the roughness evaluation. For the spherical pins, a Gaussian L-filter of 2.5 mm was used to remove the nominal curvature of the pins from the roughness evaluation.

Evaluated surface areas together with wavelength filtering methods are reported in **Table 1**.

Table 1: Surface topography evaluation settings and evaluated areas for the rubber and pin specimens.

Specimen surface	Gaussian S-filter [μm]	Gaussian L-filter [mm]	Evaluated Area [mm^2]
Rough pin	8	2.5	16.02
Smooth pin	8	2.5	16.01
P0	8	0.8	23.03 ± 0.01
CUT	8	0.8	23.04 ± 0.02
P100	8	0.8	23.05 ± 0.02
P60	8	0.8	23.04 ± 0.01

Following the slip-initiation experiments, worn rubber surfaces were examined using an optical microscope at $1.5\times$ magnification equipped with a digital camera. Images were acquired for all four rubber surface conditions after sliding against both the smooth and textured pins. The wear track microscopy was used qualitatively to compare surface damage morphology between conditions. No quantitative wear analysis was performed.

2.3. Pull-off Experiment

2.3.1. Measurement Procedure

Pull-off experiments were performed using a universal mechanical tester UMT TriboLab (Bruker, USA) equipped with a DFH-5G load sensor (measuring range 0.5-50 N, force resolution 2.5 mN, and force acquisition frequency 1000 Hz). Experiments were performed under laboratory conditions at 24.2 $^{\circ}\text{C}$ and 30 % relative humidity.

The spherical polyester pin was mounted directly to the load cell to reduce the overall compliance of the loading system. Rubber specimens bonded to PMMA support plates were fixed to the lower module of the tester. Time (t), normal force (F_z), and vertical displacement (Z) were recorded during all phases of the experiment. Because of the direct pin

mounting and the relatively low applied normal load, the measured vertical displacement was treated as the pin-head displacement, with frame compliance assumed to be negligible compared with rubber deformation.

Each measurement consisted of three consecutive phases: indentation, stabilization, and pull-off (**Fig. 2**). During indentation, the pin was pressed into the rubber surface at a constant vertical velocity of 0.1 mm/s until a normal force of 45 N was reached. The stabilization phase was force-controlled at 45 N and lasted 1 s. During the pull-off phase, the pin was retracted at a constant velocity of 1 mm/s until full separation of the two surfaces.

For each rubber-surface and pin-surface condition, six repetitions were performed at independent fresh surface locations. One smooth pin and one textured pin were used throughout the experiments. The pin was cleaned between repeated measurements to reduce contamination: the smooth pin was wiped with a dry cloth, whereas the textured pin was cleaned by gentle dry brushing.

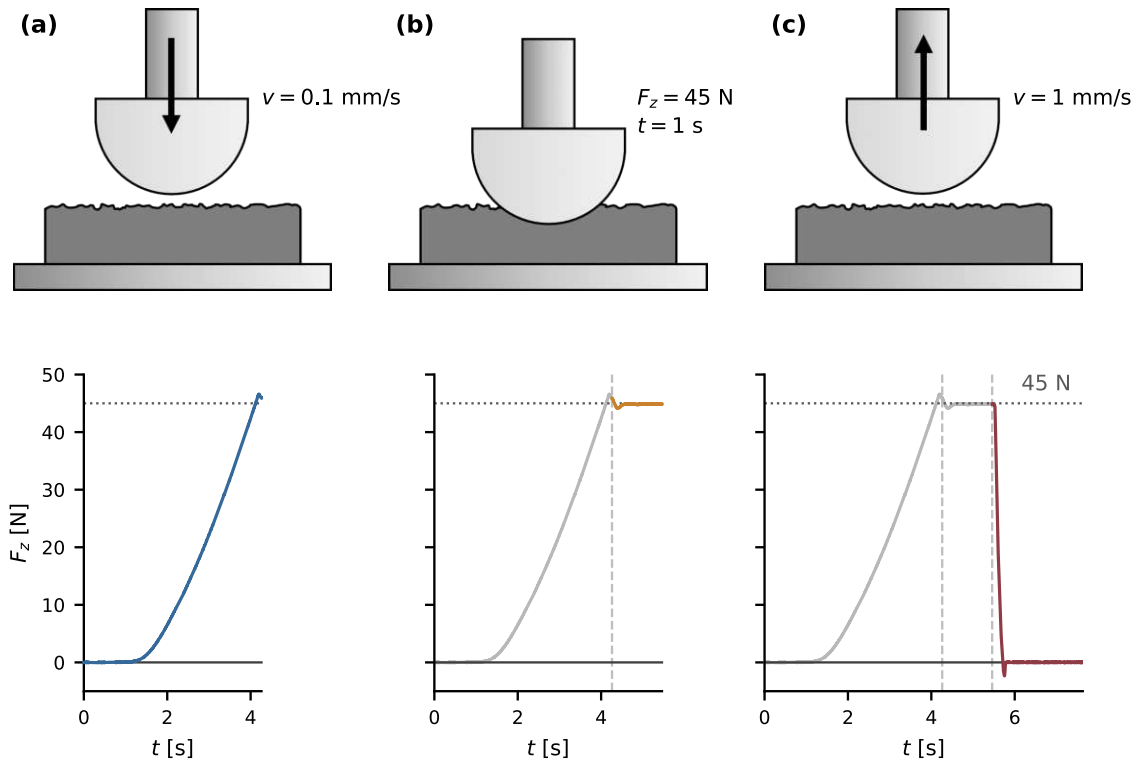


Fig. 2 Pull-off measurement sequence. Schematic representation and corresponding normal-force response during (a) indentation, (b) stabilization at the target normal load, and (c) pull-off.

2.3.2. Data Processing

Raw Bruker UMT data were processed as multi-step files, with each measurement cycle consisting of indentation, stabilization, and pull-off phases. For each cycle, the normal-force baseline was estimated from the initial unloaded part of the indentation step and subtracted from all phases of the same cycle.

The first-contact coordinate was determined from the initial indentation response. A Hertz-inspired relation,

$$F_z = A \cdot (Z - Z_0)^{\frac{3}{2}} \quad (1)$$

was fitted to the early loading region, with the exponent fixed at 1.5 and $A > 0$. The fitted contact coordinate Z_0 was then used to define the contact-relative displacement (δ) for the indentation, stabilization, and pull-off phases of the corresponding cycle as

$$\delta = Z - Z_0. \quad (2)$$

Because the normal force and vertical displacement channels were sampled at different effective rates, the original displacement updates were identified from the stepwise Z signal and linearly interpolated onto the force timestamps. This produced a time-matched displacement coordinate without smoothing or otherwise modifying the measured force signal.

The maximum pull-off force (F_p) was defined as the magnitude of the minimum baseline-corrected normal force during retraction. The tensile part of the pull-off curve was identified around this minimum using a noise-based force threshold with a persistence criterion, which excluded small negative baseline fluctuations before and after the true detachment event. The work of detachment (W_{det}) was calculated by integrating the baseline-corrected tensile force over the corresponding displacement interval and was reported as a positive quantity.

$$W_{\text{det}} = \left| \int F_z d\delta \right| \quad (3)$$

Pull-off results are reported as mean $\pm$ standard deviation across the six repetitions for each rubber-surface and pin-surface combination. Details of the tensile part of processed pull-off cycles for all rubber and pin conditions are shown in supplementary figures **Fig. S1-S8** (online).

A representative processed pull-off cycle with the evaluated F_p and W_{det} is shown in **Fig. 3**.

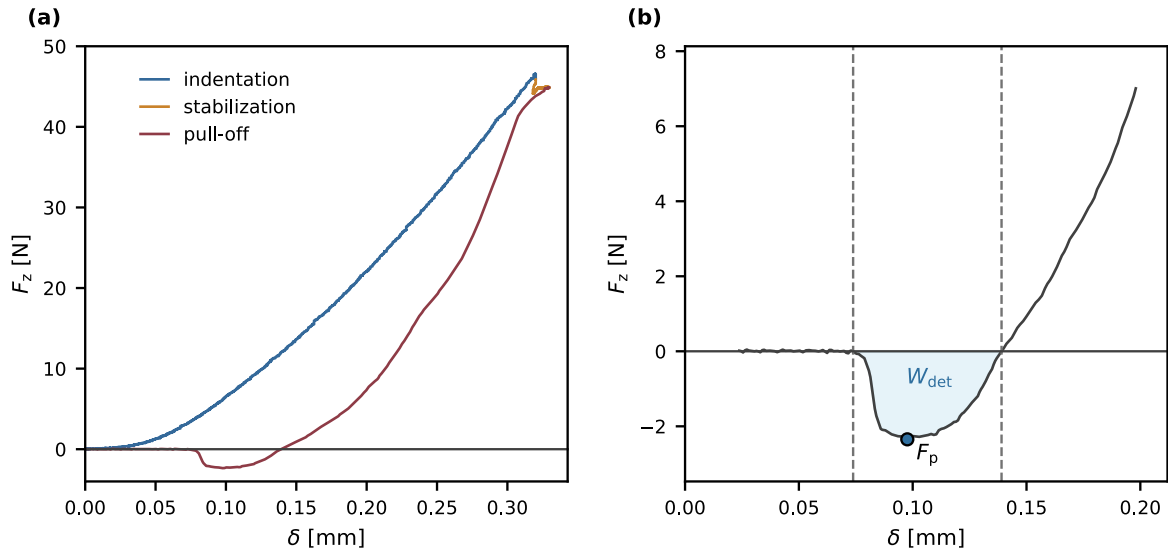


Fig. 3 Representative pull-off cycle shown as $F_z(\delta)$: (a) full indentation-stabilization-pull-off cycle and (b) detail of the tensile pull-off region used to determine the maximum pull-off force and work of detachment.

2.4. Slip Initiation Experiment

2.4.1. Measurement Procedure

Slip initiation experiments were performed using UMT TriboLab (Bruker) with a setup similar to that used for the pull-off experiments. For the slip initiation experiments the tester was equipped with a DFH-100G load sensor and a suspension module. The load sensor had a measuring range of 10-1000 N and a force resolution of 50 mN.

Each measurement cycle consisted of normal loading, stabilization, and lateral-motion phases. The pin was first pressed against the rubber surface at a vertical velocity of 0.3 mm/s until a normal force of 50 N was reached. The stabilization phase was force-controlled at 50 N and lasted 1 s. After stabilization, the upper module carrying the pin was moved laterally over approximately 15 mm at a nominal constant velocity of 1 mm/s. For P100 and P60, sliding was perpendicular to the grinding grooves. For CUT it was perpendicular to the cutting direction.

The higher nominal vertical loading velocity used in the slip initiation experiment was chosen to obtain a contact-loading timescale comparable to the pull-off experiment, where the pin was mounted directly to the load cell and indented at 0.1 mm/s. In the slip initiation setup, part of the imposed vertical motion was absorbed by deformation of the suspension module and the load-sensor assembly before contributing to the actual indentation of the rubber contact. The nominal 0.3 mm/s loading speed therefore compensated for this additional system

compliance resulting in a corrected pin velocity of 0.103 ± 0.012 mm/s across the experiments. The measurement sequence and representative force response during lateral motion are shown in **Fig. 4**.

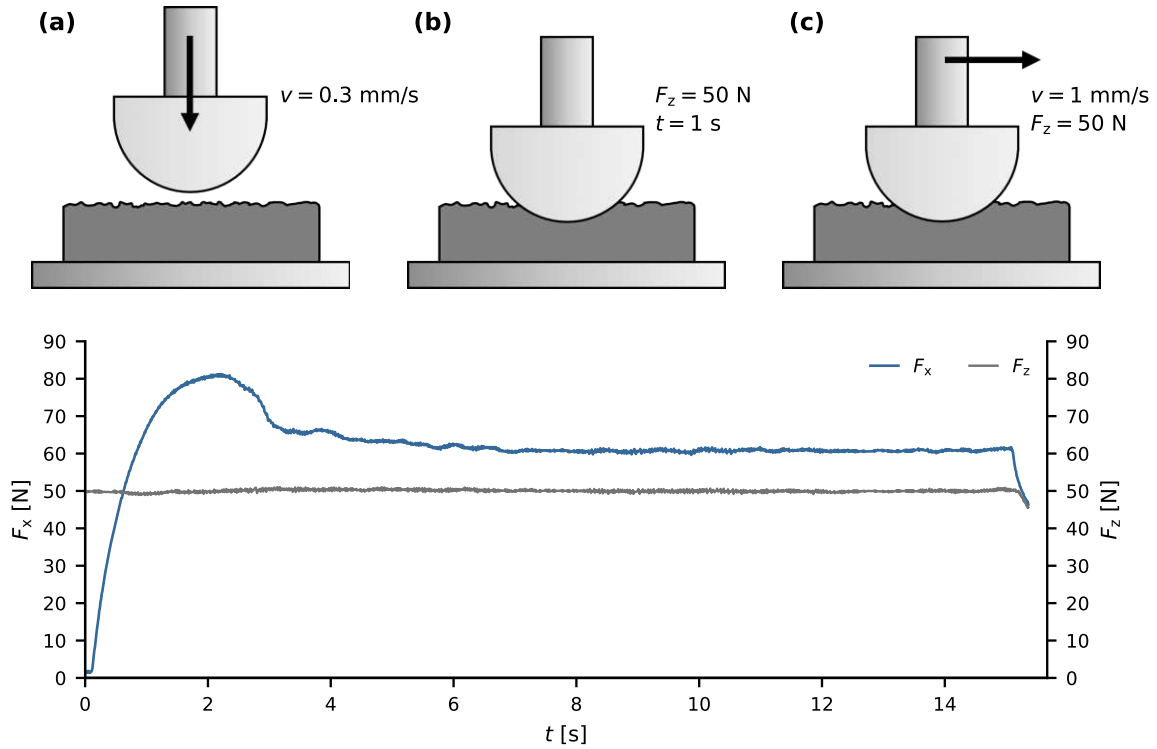


Fig. 4 Schematic representation of the slip initiation experiment and representative force response during lateral motion: **(a)** indentation, **(b)** stabilization at the target normal load, and **(c)** lateral motion. The lower graph shows the tangential force (F_x) and normal force (F_z) during the lateral-motion phase.

During all phases, time, tangential force (F_x), normal force, vertical displacement, and horizontal displacement (X) were recorded. For each rubber-surface and pin-surface condition, three repeated measurements were performed at independent fresh surface locations. The pin surface was cleaned between repeated measurements using the same procedure as in the pull-off experiments.

Before the slip initiation measurements, the compliance of the test system was characterized in both the normal and tangential directions. This was done by pressing a rigid steel indenter against the lower frame in the corresponding direction. The resulting calibration data were used for system-compliance correction.

2.4.2. Data Processing

Raw Bruker UMT data were processed as multi-step files, with each slip initiation cycle consisting of normal loading, stabilization, and lateral-motion phases. The lateral-motion phase was used for friction analysis. The friction coefficient was calculated from the measured tangential and normal forces as

$$\mu = \frac{|F_x|}{F_z}. \quad (4)$$

The horizontal displacement coordinate was corrected for system compliance using the tangential compliance calibration obtained before the experiments. The deceleration region of the lateral motion step was removed before evaluating friction parameters. The friction coefficient signal was then mildly smoothed using a Savitzky-Golay filter with a 31-point window and second-order polynomial for the purpose of identifying the static peak and friction-curve regions.

The static friction coefficient (μ_s) was defined as the maximum of the smoothed friction curve during the lateral motion. The pre-peak region was defined from the start of lateral motion to this static peak. A terminal steady sliding friction level was estimated from the final 8 mm of the retained curve. A terminal level band was then defined around this value using the larger of the within-cycle terminal noise level and the between-cycle repeatability of the terminal friction level. The beginning of steady sliding was identified as the first post-peak point where the smoothed friction coefficient returned to this band. The steady sliding friction coefficient (μ_d) was calculated as the median friction coefficient within the steady sliding region and the static-to-steady friction drop ($\Delta\mu$) was then calculated as

$$\Delta\mu = \mu_s - \mu_d. \quad (5)$$

Slip-initiation results are reported as mean $\pm$ standard deviation across the retained repetitions for each condition. For the CUT condition against the smooth pin, only cycle 3 was retained for analysis. Cycle 1 was excluded because unevenness of the specimen surface affected the sliding response, while cycle 2 exhibited anomalous slip behaviour, possibly due to contamination. Consequently, no standard deviation was calculated for this condition. Individual processed slip initiation cycles for all rubber and pin conditions are shown in supplementary figures **Fig. S9-S16** (online).

The definition of frictional parameters is illustrated on a representative slip initiation curve in **Fig. 5**.

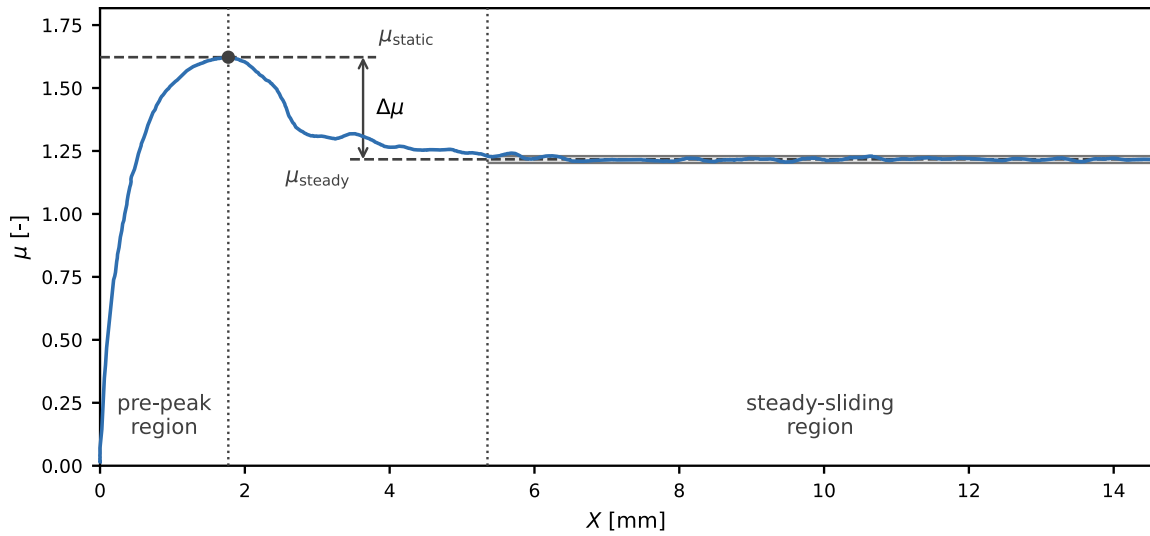


Fig. 5 Representative slip initiation curve shown as $\mu(X)$ with the pre-peak and steady sliding region borders marked with dotted lines. The horizontal band within the steady sliding region indicates the terminal friction-level band used to identify steady sliding.

2.5. Loading and Kinematic Conditions

The slip initiation experiments were performed at a normal force of approximately 50 N. Using the corrected indentation depth and the nominal radius of the spherical pin, the nominal geometry-based Hertz contact area during lateral motion was estimated to be $21.3 \pm 3.0 \text{ mm}^2$ on average. This corresponds to an equivalent circular contact radius of approximately 2.6 mm and an average nominal contact pressure of $2.39 \pm 0.34 \text{ MPa}$ across the investigated surface conditions.

The nominal pressure was higher than the average pressures usually assumed for a larger shoe-hold contact but remains representative of localized loading on small footholds. Elkington et al. used 30 and 60 N loads in climbing rubber sliding tests and related these to an estimated total shoe contact area of 10 to 20 cm^2 for a 75 kg climber, corresponding to nominal pressures of approximately 0.37 - 0.74 MPa [24]. The present mean pressure of 2.39 MPa would instead correspond, for a 75 kg climber, to supporting the full body weight on an area of approximately 3.14 cm^2 , equivalent to a circular contact diameter of about 2 cm. If only half of the body weight were carried by one foothold, the corresponding area (1.57 cm^2) would be equivalent to a circular diameter of about 1.4 cm. Therefore, the present contact does

not represent the average pressure over a whole shoe sole or a large smearing contact. Instead, it approximates the contact pressure that may occur when load is transferred through a small foothold, an edge, or a limited contact region of a larger hold.

The kinematic conditions were chosen to represent controlled rather than impact-like loading. In the pull-off experiments, the pin was mounted directly to the load cell and indented at 0.1 mm/s. In the slip initiation setup, the nominal vertical loading speed was increased to 0.3 mm/s to compensate for deformation of the suspension and load-sensor assembly. After correction for system compliance, the real pin velocity during slip initiation loading was 0.103 ± 0.012 mm/s, comparable to the pull-off loading velocity of 0.1 mm/s. The time from first contact to onset of lateral motion was 3.90 ± 0.22 s in the slip initiation experiments. Although shoe–hold contact times during climbing are expected to vary strongly with route style, movement type, and climber strategy, available time–motion data indicate that contact durations during bouldering occur on the order of seconds. For example, White and Olsen reported an average hold-gripping time of 7.9 ± 1.3 s in elite competitive bouldering [26].

During the lateral-motion phase, the contact was already normally loaded and the tangential force developed over a shorter timescale. The time required to reach 95% of the static friction force was 1.33 ± 0.18 s on average, while the static peak itself was reached after 2.02 ± 0.44 s. Quaine et al. showed that, during a controlled postural transition, expert climbers redistributed vertical and horizontal forces among the remaining holds after releasing one hand while maintaining nearly unchanged body posture. Their force traces indicate that this redistribution occurs over a timescale in order of one second [27]. The lateral force-development timescale in the present slip initiation experiments is therefore of the same order as deliberate force redistribution during controlled climbing movement.

3. Results

3.1. Surface Topography of the Measured Contacts

Optical surface measurements showed that P0 and CUT had similarly low areal roughness, whereas grinding produced progressively rougher surfaces. The moulded P0 surface had $Sa = 1.01 \pm 0.09 \mu\text{m}$ and $Sq = 1.26 \pm 0.11 \mu\text{m}$, while CUT showed $Sa = 1.02 \pm 0.07 \mu\text{m}$ and $Sq = 1.29 \pm 0.11 \mu\text{m}$. Grinding with P100 increased the roughness to $Sa = 6.88 \pm 0.89 \mu\text{m}$ and $Sq = 9.00 \pm 1.23 \mu\text{m}$, whereas P60 produced the roughest surface, with $Sa = 13.89 \pm 1.56 \mu\text{m}$ and $Sq = 18.46 \pm 2.33 \mu\text{m}$. Thus, P0 and CUT exhibited nearly identical roughness amplitudes, while P100 and P60 formed progressively rougher surface states.

The two spherical pin surfaces substantially differed in roughness. The smooth pin had $Sa = 2.72 \mu\text{m}$ and $Sq = 10.42 \mu\text{m}$, whereas the textured pin showed $Sa = 67.69 \mu\text{m}$ and $Sq = 86.55 \mu\text{m}$. The areal roughness parameters of all evaluated surfaces are summarized in **Tab. 2**.

Table 2: Areal roughness parameters of the evaluated surface regions. Number of evaluated locations (n).

Specimen surface	Sa [μm]	Sq [μm]
Textured pin (n = 1)	67.69	86.55
Smooth pin (n = 1)	2.72	10.42
P0 (n = 5)	1.01 ± 0.09	1.26 ± 0.11
CUT (n = 5)	1.02 ± 0.07	1.29 ± 0.11
P100 (n = 5)	6.88 ± 0.89	9.00 ± 1.23
P60 (n = 5)	13.89 ± 1.56	18.46 ± 2.33

3.2. Pull-off response

Pull-off characteristics were evaluated using the maximum pull-off force, shown in **Fig. 6a**, and the work of detachment obtained by integrating the tensile part of the retraction curve (**Fig. 6b**).

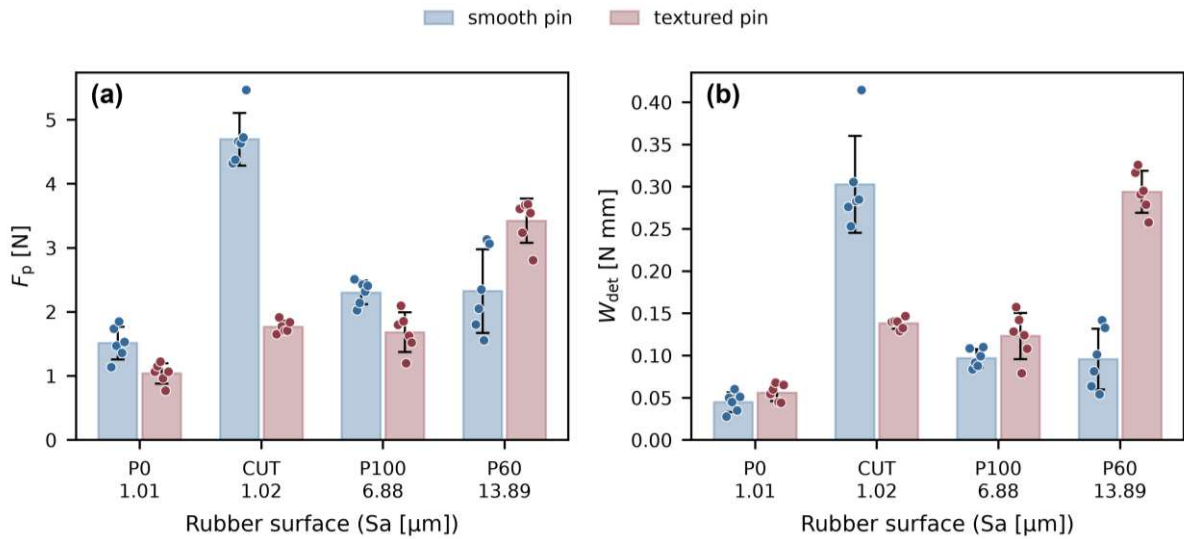


Fig. 6 Pull-off characteristics for rubber surface preparations ordered by increasing surface roughness. **(a)** Maximum pull-off force (F_p); **(b)** work of detachment (W_{det}). Bars show condition means, symbols show individual repetitions, and error bars indicate standard deviations. The values below the preparation labels indicate the measured S_a in μm . Colour distinguishes the smooth and textured pins.

Rubber surface preparation strongly influenced the maximum pull-off force, with the effect depending on the counter-surface texture (**Fig. 6a**). Against the smooth pin, F_p increased from 1.51 ± 0.26 N for P0 to 2.30 ± 0.18 N and 2.32 ± 0.65 N for P100 and P60, respectively. CUT produced a substantially larger pull-off force (4.70 ± 0.41 N), approximately 3.1 times higher than P0. Against the textured pin, the ranking differed: F_p increased from 1.04 ± 0.16 N for P0 to 1.68 ± 0.31 N for P100 and 1.76 ± 0.10 N for CUT, while the highest value was obtained for P60 (3.42 ± 0.34 N).

The work of detachment also varied with rubber surface preparation, but its response was not identical to that of the maximum pull-off force (**Fig. 6b**). Against the smooth pin, W_{det} was 0.045 ± 0.012 N·mm for P0 and approximately doubled for P100 (0.097 ± 0.011 N·mm) and P60 (0.096 ± 0.036 N·mm). CUT produced the highest value (0.303 ± 0.057 N·mm), approximately 6.8 times that of P0. Against the textured pin, W_{det} increased progressively from P0 (0.056 ± 0.010 N·mm) through P100 (0.123 ± 0.027 N·mm) and CUT (0.138 ± 0.006 N·mm) to P60 (0.294 ± 0.025 N·mm). Consequently, the textured pin produced greater W_{det} than the smooth pin for P0, P100, and P60, whereas the opposite was observed for CUT.

Particularly notable is the contrast between P0 and CUT. Despite their nearly identical areal roughness ($S_a = 1.01$ and $1.02 \mu\text{m}$, respectively), CUT exhibited approximately three times higher F_p and almost seven times higher W_{det} against the smooth pin.

3.3. Slip initiation response

Slip initiation was characterized using the static friction coefficient and the steady sliding friction coefficient (**Fig. 7a, b**). In addition, the static-to-steady friction drop was used as a descriptive measure of the prominence of the static peak relative to the subsequent steady sliding level (**Fig. 7c**). The static friction coefficient represents the maximum tangential resistance reached before macroscopic sliding. In soft contacts, this peak reflects the state of the interface formed during normal loading, stationary contact, and the pre-slip phase [10,28,29]. The steady sliding coefficient provides a reference friction level after sustained sliding has been established.

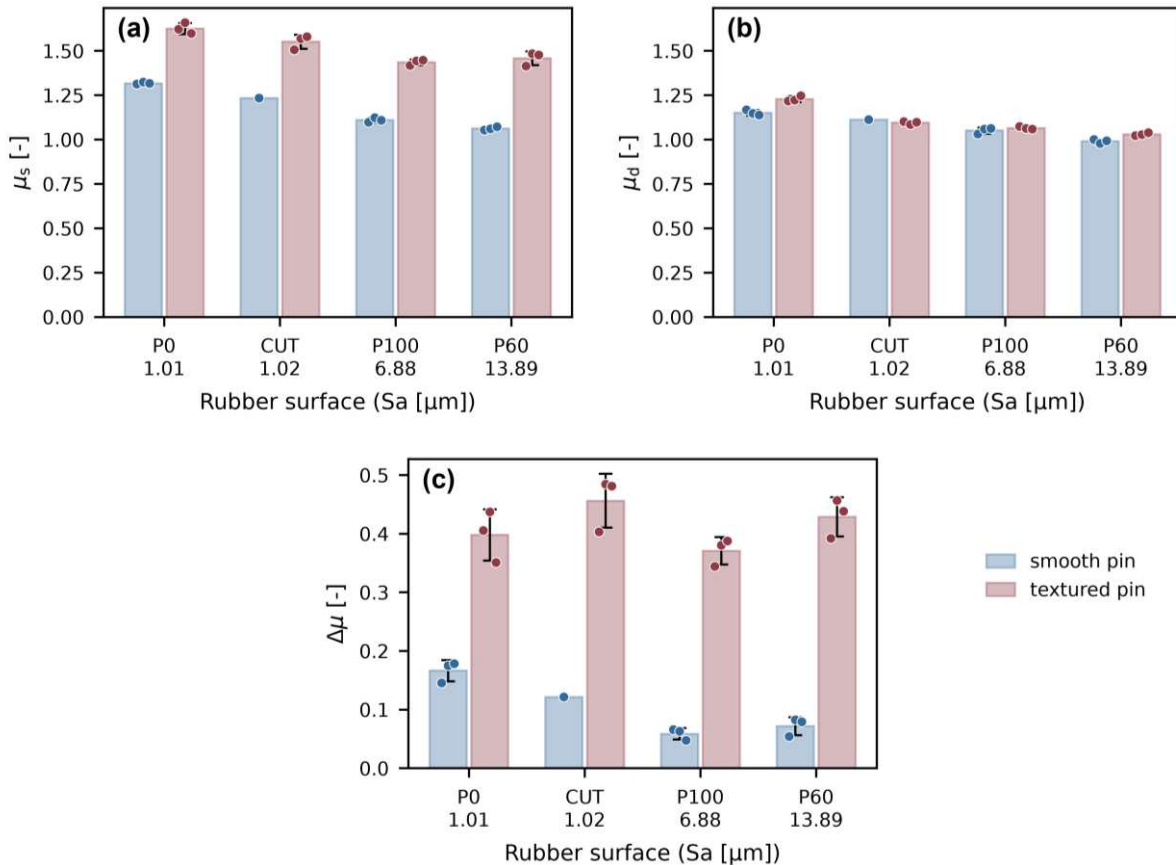


Fig. 7 Slip initiation characteristics for rubber surface preparations ordered by increasing surface roughness. **(a)** Static friction coefficient (μ_s), **(b)** steady sliding friction coefficient (μ_d), **(c)** static-to-steady friction drop ($\Delta\mu$). Bars show condition means, symbols show individual repetitions, and error bars indicate standard deviations. The values below the preparation labels indicate the measured S_a in μm . Colour distinguishes the smooth and textured pins. For CUT against the smooth pin, only one retained measurement is shown; therefore, no error bar is reported.

Rubber surface preparation influenced both static and steady sliding friction, with the magnitude of the differences depending on the pin surface condition. Against the smooth pin, P0 exhibited the highest static friction coefficient ($\mu_s = 1.318 \pm 0.005$). CUT showed an intermediate value of 1.234. Lower values were measured for the ground surfaces, with $\mu_s = 1.110 \pm 0.013$ for P100 and 1.062 ± 0.009 for P60. Steady sliding friction followed a similar overall trend, decreasing from $\mu_d = 1.151 \pm 0.015$ for P0 to 1.112 for CUT, 1.051 ± 0.017 for P100, and 0.990 ± 0.011 for P60.

Against the textured pin, P0 again exhibited the highest static friction coefficient ($\mu_s = 1.626 \pm 0.031$), followed by CUT at 1.551 ± 0.040 . The ground surfaces produced lower and similar static coefficients, with $\mu_s = 1.436 \pm 0.016$ for P100 and 1.458 ± 0.039 for P60. Differences among the rubber surface preparations were less pronounced during steady sliding. The coefficient decreased from $\mu_d = 1.228 \pm 0.016$ for P0 to 1.095 ± 0.009 for CUT, 1.065 ± 0.008 for P100, and 1.029 ± 0.008 for P60.

The static-to-steady friction drop depended strongly on the pin surface condition (**Fig. 7c**). Against the smooth pin, $\Delta\mu$ was largest for P0 (0.166 ± 0.018), followed by CUT (0.121), whereas substantially smaller values were measured for P100 (0.059 ± 0.010) and P60 (0.072 ± 0.015). Against the textured pin, $\Delta\mu$ was substantially larger for all rubber surface preparations, with values of 0.398 ± 0.044 for P0, 0.456 ± 0.046 for CUT, 0.371 ± 0.024 for P100, and 0.429 ± 0.033 for P60. CUT therefore exhibited the largest mean static-to-steady friction drop against the textured pin.

3.4. Cross-comparison of Normal Detachment Response and Friction

The cross-comparison showed no simple correspondence between normal detachment resistance and static friction. Conditions with higher maximum pull-off force or work of detachment did not consistently exhibit higher μ_s . This was particularly evident for P60 against the textured pin and CUT against the smooth pin, both of which showed high detachment resistance while retaining lower static friction than P0. The relationship is summarized in **Fig. 8**, where μ_s is plotted against F_p and W_{det} for each rubber surface preparation and pin surface condition.

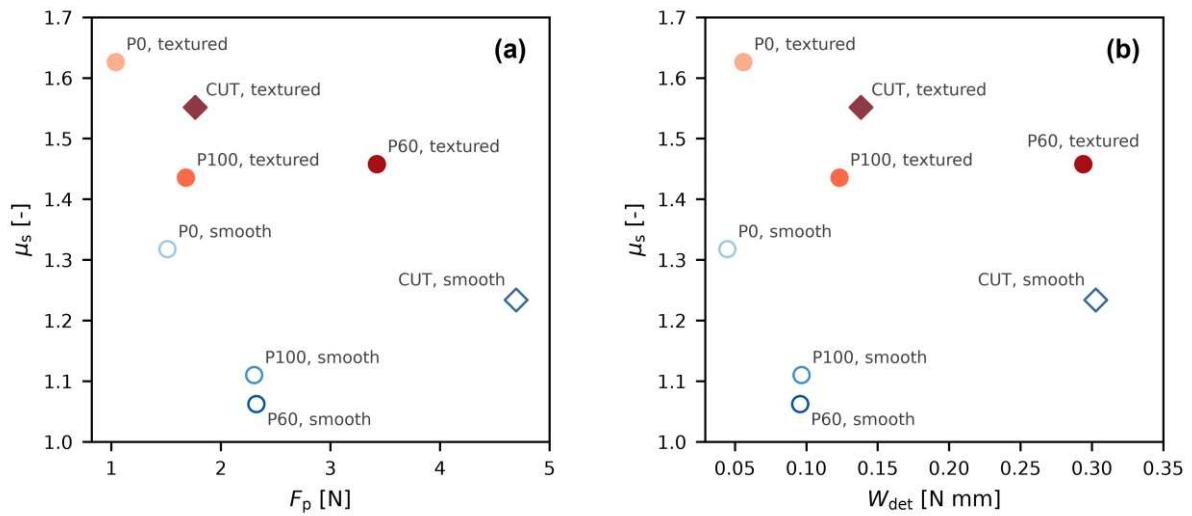


Fig. 8 Cross-comparison of normal detachment characteristics and static friction. Static friction coefficient plotted against (a) maximum pull-off force and (b) work of detachment using condition mean values. Labels identify rubber surface preparation and pin surface condition.

4. Discussion

4.1. Decoupling of Normal Detachment and Tangential Slip Initiation

In the investigated model contact between climbing shoe rubber and an artificial hold surface, changes in rubber surface state affected normal detachment and tangential slip initiation differently. Relative to the moulded P0 surface, both ground conditions exhibited higher maximum pull-off forces and work of detachment but lower static and steady sliding friction against both counter-surfaces. The CUT condition further emphasized this decoupling. Against the smooth pin, CUT produced the highest maximum pull-off force and work of detachment, while its static friction coefficient remained lower than that of P0. Against the textured pin, P60 showed the strongest detachment response while again exhibiting lower static friction than P0. Thus, surface states providing greater resistance to normal separation did not necessarily provide greater resistance to the initiation of tangential sliding.

Studies of normal detachment indicate that pull-off response is governed by propagation of opening crack across the interface [17,30]. Tangential response under compressive loading, however, depends not only on the processes at the contact zone boundary but also on the processes in the contact area [16,31]. Changes in rubber surface state can therefore make normal separation more dissipative while simultaneously reducing the coherent real contact area available to sustain tangential shear.

4.2. Mechanisms of Detachment

The comparison of maximum pull-off force and work of detachment indicates that the two parameters capture different aspects of the separation process. While F_p reflects the maximum tensile resistance reached during pull-off, W_{det} also incorporates the displacement over which this resistance is sustained. The different responses of these parameters to counter-surface texture therefore suggest that surface topography influences not only the peak resistance to separation, but also the progression of interfacial failure.

Surface roughness on the rigid counterpart can influence adhesive detachment through competing mechanisms. Classical rough-contact models predict that roughness generally suppresses macroscopic adhesion because only part of the nominal interface reaches sufficiently small separation for adhesive interactions to take place, while elastic energy must be stored in the compliant solid to conform to the rigid topography. This stored deformation energy can reduce the effective adhesion and the macroscopic pull-off force, even when the intrinsic interfacial interaction remains unchanged [32,33].

More recent studies show that introducing roughness to the rigid surface can also lead to an increase in the detachment resistance measured during unloading. When substantial contact has first been established under compression, surface features can introduce elastic instabilities and spatially heterogeneous crack propagation during retraction. In studies using periodically wavy surfaces, Guduru and Kesari have shown that fluctuations in stored elastic energy can substantially increase the apparent pull-off force and generate adhesion hysteresis even in elastic contacts [34–36]. Extending this concept to randomly rough surfaces, Sanner et al. combined simulations and experiments to show that contact-line pinning and the associated elastic instabilities can make an important contribution to adhesion hysteresis in real contacts [37]. These mechanisms provide a plausible explanation for the higher W_{det} observed against the textured pin for P0, P100, and P60.

The P60 condition may additionally involve mechanical interlocking. Its combination of a highly roughened rubber surface with the textured pin provides a strong opportunity for large

rubber asperities to penetrate surface cavities during loading and stationary contact. Such geometrical engagement could increase resistance during subsequent separation and may contribute to the particularly high F_p and W_{det} measured for this condition [38].

CUT exhibited a distinctly different detachment response from P0 despite having almost identical S_a . In particular, CUT showed substantially higher F_p and W_{det} , especially against the smooth pin. Because this difference occurred without a corresponding increase in S_a , it cannot be explained by roughness amplitude alone. One possible explanation is that removal of the moulded surface layer exposed subsurface rubber with different interfacial properties. In compounded elastomers, the surface layer can differ from the bulk because low molecular weight constituents, such as processing oils, waxes or vulcanization agents, may migrate toward the surface [39]. Removal or modification of this layer has been shown to alter rubber adhesion [40]. Grinding may produce a similar effect by progressively removing this outer layer, while simultaneously altering the surface topography. The CUT condition therefore supports the hypothesis that the increased detachment resistance observed after surface removal may arise partly from exposure of a more adhesive subsurface material, rather than from roughness changes alone.

4.3. Mechanisms of Slip Initiation

The slip-initiation response indicates that friction in the present soft contact cannot be explained by changes in real contact area alone. Surface preparation altered both the static peak and the steady sliding level, but the magnitude and direction of these changes depended on the counter-surface texture and on whether the interface was stationary or continuously renewed during sliding. This suggests that adhesive shear, viscoelastic deformation, geometrical interlocking, and wear related processes contributed in different proportions across the investigated conditions.

Increased rubber surface roughness is generally expected to reduce real contact area and thereby decrease the adhesive contribution to friction [41–43]. This interpretation is consistent with the overall reduction in friction after grinding. However, the slight increase in μ_s from P100 to P60 against the textured pin cannot be explained by contact-area reduction alone. The roughest rubber surface may additionally engage with cavities of the textured counter-surface during loading and stationary contact, increasing resistance to slip initiation through geometrical interlocking. Such an effect would be less developed during sustained sliding, when the residence time of individual rubber regions at particular counter-surface

features is substantially shorter. This is consistent with the monotonic decrease in steady sliding friction from P0 to P100 and P60. The smooth counter-surface provides substantially less opportunity for such geometrical interlocking resulting in a simple decreasing trend in both static and steady sliding friction with increasing rubber roughness (**Fig. 7a, b**). Similar trend was also observed in our previous study of nitrile rubber sliding on a smooth epoxy surface [44].

Post-test wear morphology provides qualitative support for a stronger asperity-interaction component against the textured counter-surface. Across the investigated rubber surface states, sliding against the textured pin produced more pronounced directional grooving and local surface disruption than sliding against the smooth pin (**Fig. S17**, online). Directional scoring and grooving of rubber surfaces are commonly associated with abrasive interaction, in which counter-surface asperities induce local deformation, ploughing, or cutting of the rubber [45]. Such asperity interactions can also contribute to friction through viscoelastic deformation of the rubber by the roughness features [5]. The observed morphology is therefore consistent with a stronger mechanical and deformation-related contribution to friction against the textured pin. However, the microscopy provides only qualitative evidence and does not allow the interfacial, viscoelastic, and wear-related contributions to tangential resistance to be separated quantitatively.

The comparison between P0 and CUT provides additional insight into the role of the near-surface material state. Despite their similar roughness amplitudes, CUT exhibited lower static friction against both counter-surfaces. As proposed for the detachment response, removal of the moulded surface layer may expose subsurface rubber with different mechanical and interfacial properties. A more compliant near-surface material could alter local deformation around counter-surface asperities and thereby modify the relative contributions of interfacial shear, viscoelastic deformation, and ploughing to friction. However, the wear scars of P0 and CUT did not show a clear qualitative difference, so the lower friction of CUT cannot presently be attributed to a visibly reduced abrasive interaction.

The pronounced difference between static and steady sliding friction against the textured pin further emphasizes the importance of contact development before macroscopic sliding. During normal loading and stationary contact, the rubber progressively conforms to the counter-surface and develops interfacial junctions. Once sliding begins, the shorter interaction time with individual asperities limits this conformity [46], contributing to the reduction from μ_s to μ_d . The consistently larger $\Delta\mu$ against the textured pin therefore suggests that the rough counter-surface promotes stronger development of the interface during the stationary and

pre-slip phases, followed by a larger reduction in resistance when the interface is continuously renewed during sliding.

5. Limitations and future outlook

Several limitations should be considered when interpreting the present results. Although all rubber specimens originated from the same production batch, the study investigated only one climbing shoe rubber compound, four prepared surface states, and two specific polyester counter-surfaces. The experiments were also conducted under one set of normal loads, loading times, pull-off and sliding velocities, and dry laboratory conditions. This controlled design allowed the effect of surface preparation to be examined without variability between rubber compounds, but it limits direct generalization to other climbing shoe materials, hold materials, environmental conditions, and loading histories. Future studies should therefore examine whether the observed decoupling between normal detachment and tangential slip initiation persists across rubbers with different stiffness, viscoelastic response, formulation, and surface chemistry. Systematic variation of normal load, stationary contact time, pull-off velocity, sliding velocity, temperature, and humidity would additionally clarify the range of conditions over which the observed trends remain valid.

Surface preparation should not be interpreted as a purely geometrical modification of rubber roughness. Grinding removes the moulded surface layer while simultaneously changing the surface topography, and the CUT condition similarly exposes subsurface material without producing the large increase in S_a associated with grinding. The markedly different detachment and friction responses of P0 and CUT despite their almost identical S_a values demonstrate that this scalar roughness parameter alone is insufficient to characterize the relevant surface state. Differences may additionally arise from other topographical characteristics, surface chemistry, and mechanical properties of the near-surface rubber. Because these properties were not measured directly, their individual contributions cannot be separated in the present study. This is particularly relevant because moulded rubber surfaces may differ from the underlying material in cure state and mechanical properties as a consequence of thermal and processing gradients during vulcanization [47,48]. The P0, CUT, P100, and P60 conditions should therefore be regarded as distinct surface states rather than as a simple series of increasing roughness.

The proposed mechanisms underlying the measured responses were not verified by direct observation or independent measurement of the contact interface. Mechanical interlocking, progressive conformity during stationary contact, reduction of conformity after sliding begins,

contact-line pinning, and spatially heterogeneous crack propagation therefore remain plausible interpretations of the force and displacement measurements rather than directly demonstrated mechanisms. Post-test optical microscopy showed more pronounced directional grooving and local surface disruption after sliding against the textured pin, providing qualitative support for stronger asperity interaction. However, these images do not allow the interfacial, viscoelastic, and wear-related contributions to friction to be quantified separately.

Finally, the use of fresh rubber locations means that the study primarily describes the initial response of prepared climbing shoe rubber surfaces. In practical use, the rubber surface changes through repeated loading, wear, and contamination. These processes are expected to change both normal detachment and tangential friction, therefore further analysis of wear and contamination effects seems like a next logical step. Local contact conditions between rubber and counter-surface, governing the frictional response, are greatly influenced by the design of the climbing shoe. Subsequent validation using complete shoe–hold contacts would establish how the mechanisms identified in the controlled spherical contact translate to application-scale climbing conditions.

6. Conclusions and Implications for Climbing shoe Rubber Performance Testing

This study investigated how the surface state of a climbing shoe rubber affects normal detachment and tangential slip initiation against smooth and textured rigid polyester counter-surfaces. The same rubber compound, contact geometry, and closely matched loading timescales were used in both types of experiment. Under the investigated conditions, surface preparation strongly affected both responses, but it did not affect them in the same direction. The main findings can be summarized as follows:

- Normal detachment resistance and resistance to tangential slip are not directly coupled. Surface states producing greater maximum pull-off force and work of detachment did not necessarily exhibit greater static friction. This was evident both for P60 against the textured pin and for CUT against the smooth pin. Pull-off testing and slip-initiation testing should therefore be regarded as complementary rather than interchangeable measures of climbing shoe rubber performance.

- The influence of rubber surface state depends strongly on the counter-surface texture. The textured pin altered both the detachment response and the transition from static contact to steady sliding. In particular, the static-to-steady friction drop was substantially larger against the textured pin for all rubber surface states, while the effect of texture on detachment depended

on the rubber surface preparation. Performance rankings obtained against smooth counter-surfaces therefore should not be assumed to remain unchanged for rough climbing-hold surfaces.

- Surface preparation affects the response through more than roughness amplitude alone. P0 and CUT had almost identical Sa values but showed markedly different detachment behaviour and different static friction. The relevant rubber surface condition must therefore be considered as a broader surface state that may include detailed topography as well as mechanical and interfacial properties of the near-surface material. Rubber surface preparation should consequently be controlled and reported when comparing climbing shoe compounds, and characterization based on Sa alone may be insufficient.

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7. Statements and Declarations

7.1. Data Availability

The data that support the findings of this study are openly available in the Zenodo repository at <https://doi.org/10.5281/zenodo.22671100>.

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7.3. Author Contributions

M. Ž. and D. R. conceived the idea and designed the experiments. M. Ž. performed the experiments and analysed the data. M. Ž. and D. R. wrote the original draft of the manuscript. M. V. and M. H. administrated the project, secured the funding, and supervised the study.

7.4. Competing interests

The authors declare that they have no known competing financial interest or personal relationship that could have appeared to influence the work reported in this paper.

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