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The effectiveness of chalk as a friction modifier for finger pad contact with rocks of varying roughness

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Abstract

The application of chalk (magnesium carbonate) in rock climbing is common practice as climbers attempt to improve their grip by removing moisture from their hands with the aim of increasing friction at the finger pad-rock interface. This novel work investigated the effectiveness of chalk as a friction modifier on four different rocks (sandstone, granite, dark limestone and light limestone) typically found in areas of the UK where the sport of climbing is undertaken, with varying surface roughness. The static coefficient of friction was measured for dry and wet fingertip conditions with and without chalk, under normal ('grip') forces of 5, 10 and 15 N. Results showed that the effectiveness of chalk as a friction modifier is dependent on a number of factors such as moisture level and the gradient of the asperity at the rock surface, however, in general chalk applied to dry fingertips had a more positive effect on the static coefficient of friction than in simulated sweaty conditions. During lab tests, chalk was also seen to be beneficial by making the static coefficient of friction more consistent across most test conditions. The results of this study, and the explanation of friction mechanisms involved, provides guidance for the use of chalk with consideration of the type of rock which is being climbed.

Keywords

Friction, friction modifiers, rock climbing, surface roughness, tribology, chalk, magnesium carbonate, finger pad-rock interface, grip, climbing

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Introduction

Rock climbing is becoming an increasingly popular recreational and competitive sport, making its Olympic debut in Tokyo in 2020. Traditionally, rock climbing is an outdoor activity undertaken across a wide range of locations, climates, and rock types, but is now also a popular indoor activity on artificial 'holds' made from resin arranged on walls in climbing gyms. Climbers rely on their hands and feet to progress through a climbing route and the friction at the hand-hold interface plays a crucial role in rock climbing performance.[1]

Friction modifiers, such as chalk, are used by climbers with the belief that they improve grip on rock surfaces. The general thought amongst the climbing community is that chalk dries the hand from sweat and moisture which increases friction, but the use of chalk likely has a more complex effect. A decrease in moisture content of the surface of the fingertip pad can increase the coefficient of friction where the water is acting as a lubricant, but can also decrease it by reducing the stiffness and smoothness of the finger surface and therefore reducing the real contact area.[2,3] There is also potential for the chalk itself to act as a solid lubricant by forming an easily sheared third-body layer.

To date, from the small number of studies concerning finger pad-rock friction and the effect of chalk, conflicting conclusions have arisen. Li et al.[4] reported that chalk decreases the coefficient of friction, whereas both

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Amca et al.[5] and Fuss et al.[6] found the opposite. Other studies have observed no significant differences in friction coefficient with the use of chalk.[7,8] Chalk has also been linked to increased performance in rock climbing through its ability to sustain grip for a longer duration[7] and to perform more weight assisted pull-up repetitions.[9] Conflicting conclusions for the effect of water or moisture on finger pad-rock friction have also been made. Water has been shown to have no significant effect on friction[4] or to increase friction.[8] Both are contrary to the believed mechanism for the effectiveness of chalk. Other considered variables were temperature and humidity which were found to have no significant effect on coefficient of friction.[5]

There are two major mechanisms that enable friction between skin and a counter-surface. The first is adhesion, caused by attractive forces at the interface and thus the magnitude of this force is dependent on the real contact area at the nanoscale,[10] as opposed to the apparent contact area at the macroscale. The second mechanism is deformation,[11] which can be split into ploughing, and viscoelastic effects.[12] Energy is lost as heat due to the deformation or delay in recovery of the surfaces and underlying material. Depending on lubricant amounts and contact conditions friction can also be reduced by boundary, mixed or elasto-hydrodynamic lubrication.[13]

Finger friction is a complex interaction as skin exhibits varied frictional behaviour which may be influenced by many factors. Tomlinson et al.[14] covered many of these factors in their review: normal force, direction of motion, angle of contact, sliding speed, skin hydration, and from person to person (skin properties, geometry, topology). In dry conditions, coefficient of friction is generally independent of load, or shows a slight decrease with load.[14,15] In wet conditions coefficient of friction decreases with increasing load[15] and differences between wet and dry skin are more apparent than at lower normal loads.[15] Wear of finger pads can also significantly affect friction. Liu et al.[16] found that repeatedly rubbing a finger with sandpaper initially reduced the coefficient of friction against an acetal surface and this effect eventually plateaued.

These factors are all associated with the skin itself, but the counter-surface also has a significant effect on friction. Counter-surface roughness can have differing effects over different length scales.[15,17] As roughness is initially increased from a smooth surface, friction decreases as the contact area and adhesion decreases. A roughness magnitude is then reached at which point ploughing can start which increases friction and deformation becomes the dominant friction mechanism.[15] The exact nature of this relationship will depend on the shape of the asperity profile, as well as simply the magnitude of the roughness.

The material properties of the counter-surface can also have a significant effect,[18] caused by different surface energies and different deformation behaviours. Other external factors including temperature and humidity can also influence the interaction and influence the factors previously described. The introduction of lubricants or third bodies, such as sweat, grains of rock, and friction modifiers like chalk, can also affect the contact and makes the interaction complex.

Of all these factors, relatively few have been considered in previous studies,[4–8] all of which only made measurements at one load case. Climbers distribute weight through their hands and feet, applying differing loads, and a variety of hand grips are used, which means that friction dependent movement may happen with a range of normal loads through the skin of the hand. The effectiveness of chalk as a friction modifier should therefore be assessed at a range of loads. Almost all the previous studies measured the static coefficient which is appropriate as once a contact has slipped typically failure in climbing has occurred. The only exception to the choice of friction measurement was Carré et al.[8] who measured dynamic coefficient of friction.

A variety of surfaces have been tested previously, but none of the existing studies parameterised the roughness of the surfaces tested. Two rock samples of the same type can have substantially different surface roughness and so merely stating the rock type gives limited information on the possible roughness values. In some studies, rock surfaces were also modified to produce flat surfaces, which would have been likely to alter these from their natural state.[4,8] In these studies, loose rock particles were observed in testing, commonly referred to as 'scrittle' by climbers, which is encountered on poor quality rock or newly developed climbing routes. The influence of scrittle on climbing friction is an interesting topic, but may over-complicate investigations in this instance.

Of the existing studies, two controlled for the effect of changing skin moisture on the impact of friction modifier,[4,8] whilst other studies[5–7] did not, due to the reasoning for the use of chalk being to combat the effect of sweat lubricating the contact. Amca et al.[5] were the only team to investigate the effect of temperature and humidity, but found no significant correlation with friction coefficient. The aim of this work was to assess the effectiveness of chalk as a friction modifier in a range of situations, to extend the knowledge in this area by assessing different loads and by quantifying roughness of rock surfaces in a more comprehensive manner.

Methodology

Test method

A set of experiments was designed to assess the effectiveness of chalk when the finger pad moisture level, applied load or rock type is varied. Ethical approval was obtained from the Ethics Committee at The University of Sheffield (number 047646). A female participant, aged 21, with rock climbing experience was recruited for testing and the test apparatus was designed to allow the participant control over the required normal load during friction tests. The participant consented through the signing of participant consent form 1107239. The rocks were fixed to a metal plate using an epoxy and mounted onto a six-axis HE6X6 force plate with AMTI Net Force software attached. Labview was then used for data acquisition to record normal and shear force reactions as shown in Figure 1.

Friction properties can vary between climbers which is the reason one participant was selected for testing to enable a trend in the friction to be identified across the varying rocks. The participant was asked to wash and dry their hands with mild foam hand wash[19] for 20 s prior to and in between testing. The participant was asked to wait for 30 s after drying their hands to ensure that their fingers were completely dry. To minimise their effects on moisture and friction, efforts were made to ensure variability in room temperature and humidity was minimised during testing. Measurements of temperature varied from 23.5°C to 27°C and room humidity varied from 34.2% to 47.4 %.

The participant was instructed to place their wrist on a support 5 mm above the surface of the rock while carrying out testing which maintained an approximate contact angle of 25°, which ensured near-constant contact area between the finger pad and rock to minimise the effect of deformation as a friction mechanism due to the viscoelastic behaviour of the finger. The middle finger of the participant's dominant hand was used for testing. The proximal interphalangeal joint of the middle finger was maintained at full extension with the index finger stabilising the distal interphalangeal joint for stable loading and for the comfort of the participant.

The participant was asked to apply a constant normal force of 5, 10 and 15 N onto the rock, whilst steadily increasing shear force towards the palm of the hand until slip started. The shear force reaction was then defined as the friction force. The application of forces during testing was aided by live readings displayed on a screen, a method adapted from previous work.[2,8,17] The middle finger was selected as previous studies have shown that in open hand and open hand crimps, where failure is the most friction dependent, the largest load is applied by the middle finger.[20–22] Furthermore, the middle finger performed the most consistently in similar experimental set-ups.[8] From experience, the slip direction away from the palm of the hand is also the most common in climbing.

The forces were selected as they were representative of the loads naturally applied in climbing situations. The forces in climbing scenarios can vary depending on whether the climber is hanging on one hand or has their weight distributed evenly through feet and hands. The upper limit of this experiment was 15 N which was selected to be applicable for most climbing scenarios and was also the load limit that was comfortable for the participant to apply and maintain until slip occurred, allowing repeatability within the testing.

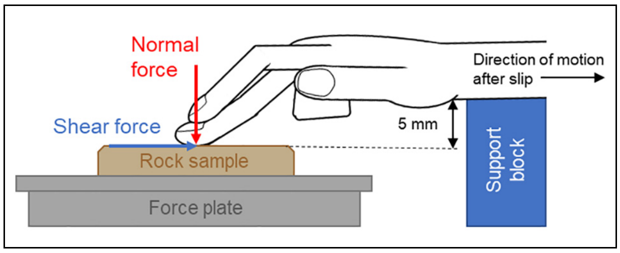

Figure 1. Experimental set-up with rock attached to the force plate.

Additional testing was conducted to investigate how different moisture levels affect friction. A second participant was selected due to the original participant being unavailable. This stand-alone testing saw the participant moisten their finger for varying durations by pressing it into a damp paper towel, allowing for controlled moisture absorption prior to repeating friction tests at one load on a single rock. The participant for this test was male, aged 29, with rock climbing experience and consented through the signing of participant consent form 1107239.

Test samples

Four different rocks types typically found in rock climbing sites in the United Kingdom were obtained for testing: sandstone (sedimentary), granite (igneous), dark limestone (sedimentary), and light limestone (sedimentary), as shown in Figure 2.

To avoid the loose grains of rock observed in other studies interfering with other mechanisms,[5,8] the rock samples were examined by eye to identify any naturally flat regions for use in the test programme to avoid the need to machine the sample before testing. Rock samples were set in epoxy such that the flat testing region was as close to parallel with the test plate as possible.

The surface roughness was the variable of interest between the samples within this work. Surface roughness measurements (Table 1) were therefore conducted using a non-contact, focus-variation type, 3D profilometer (Bruker Alicona Infinite Focus SL; MeasureSuite 5.3) over an area of 16.75 mm × 16.75 mm, comparable with the size of a finger pad. Areal measurements were taken as opposed to linear profile measurements (e.g. R_a) to give a more complete assessment of the surface. The areal mean surface roughness, S_a, is given by equation (1).

$$S_a = \frac{1}{A}\iint |z(x,y)|dxdy \tag{1}$$

The areal root mean squared (RMS) surface roughness, S_q, is given by equation (2).

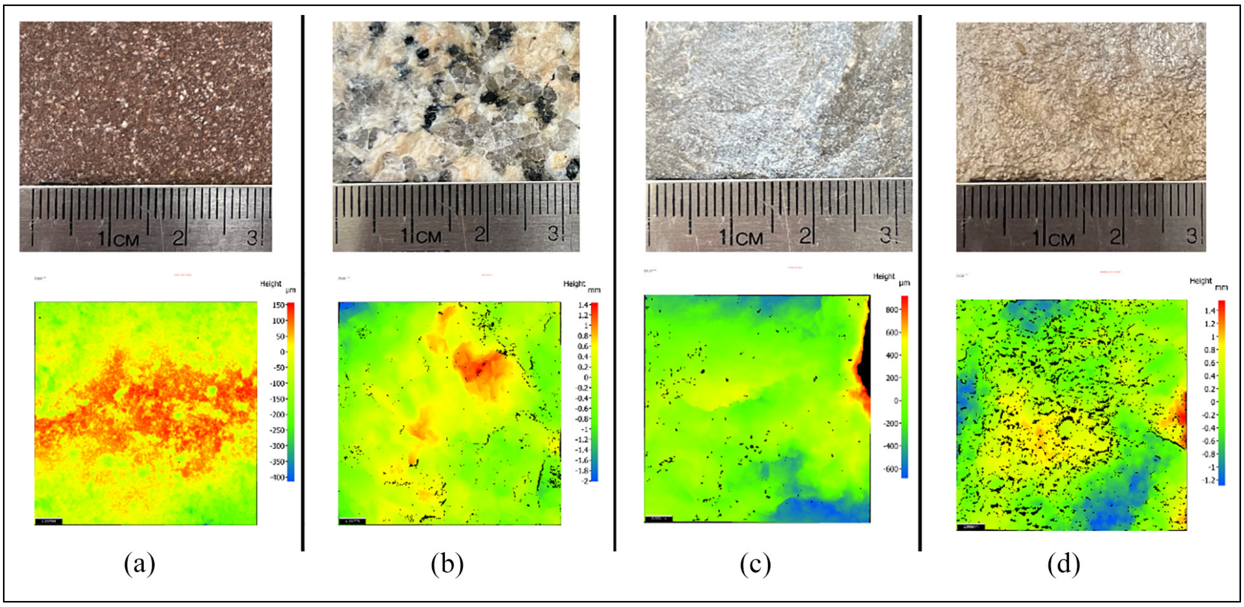

Figure 2. Images of the rock samples used in testing and Alicona surface height maps of: (a) sandstone, (b) granite, (c) dark limestone and (d) light limestone.

Table 1. Surface measurements of the rock samples.

Surface measurements	Sandstone	Granite	Dark limestone	Light limestone
Mean roughness, S_a (μm)	59	413	184	395
RMS roughness, S_q (μm)	73	505	237	498
Skew, S_{sk}	−0.55	−0.26	−0.10	−0.05
Kurtosis, S_{ku}	3.0	2.9	3.5	2.7
RMS gradient, S_{dq}	0.6	1.3	0.7	1.0
Approximate grain size (mm)	0.15	1.00	0.10	0.60

$$S_q = \sqrt{\frac{1}{A}\iint |z^2(x,y)|dxdy} \quad (2)$$

Skew, S_{sk}, is given by equation (3).

$$S_{sk} = \frac{1}{S_q{}^3}\left[\frac{1}{A}\iint |z^3(x,y)|dxdy\right] \quad (3)$$

Kurtosis, S_{ku}, is given by equation (4).

$$S_{sk} = \frac{1}{S_q{}^4}\left[\frac{1}{A}\iint |z^4(x,y)|dxdy\right] \quad (4)$$

Root mean-square (RMS) gradient, S_{dq}, is given by equation (5).

$$S_{dq} = \sqrt{\frac{1}{A}\iint \left[\left(\frac{\partial z(x,y)^2}{\partial x}\right) + \left(\frac{\partial z(x,y)^2}{\partial y}\right)\right] dxdy} \quad (5)$$

An estimate of grain size was measured through observation using the optical microscope images and analysed using the MeasureSuite 5.3 software, where the diameter of the grain was measured. Grains were identified as complete areas with visible defined edges such as the example of light limestone shown in Figure 3. Multiple measurements were taken, and the mean average was used to approximate the grain size to allow a comparison of the four rocks.

The primary roughness measurements (S_a and S_q) indicate that the granite had the highest surface roughness of the rock samples, and sandstone the lowest. The kurtosis and skewness of the rocks can be further analysed to understand and categorise the patterns of the peaks and valleys. Skewness measures the symmetry of the profile around the mean plane. All samples had a negative skewness which indicates deep valleys and short peaks. A positive value indicates the opposite, shallow valleys and tall peaks. Kurtosis measures the sharpness of the surface. A value above three indicates sharp peaks and troughs (sandstone and dark limestone), and below three indicates more rounded features (granite and light limestone). Granite had the highest RMS gradient of the surfaces followed by light limestone, dark limestone and sandstone. Approximate grain size, measured as the average diameter of the

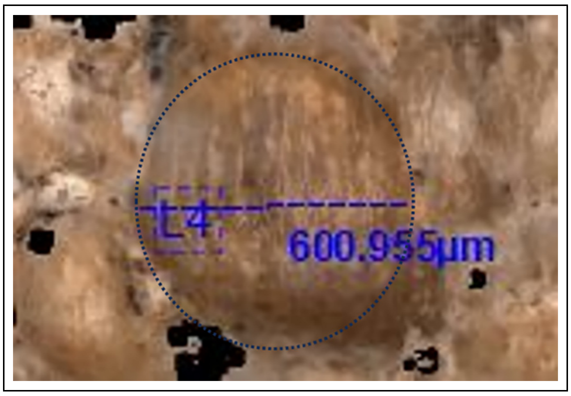

Figure 3. Example of grain diameter measurement, shown on light limestone.

grains, followed a similar order, but with the position of sandstone and dark limestone swapped.

The roughness measurements are counterintuitive for the granite and light limestone as it can clearly be seen with a visual inspection that the two rocks are very different. Further exploration of the surface data, splitting it into roughness and waviness shows the mean waviness to again be similar for each rock (granite 384.27 and light limestone 376.14). The parameter which separates the two rocks are the skewness and kurtosis in the waviness measurements.

The chalk selected for testing was a commercially available rock-climbing chalk consisting of 100% magnesium carbonate. The method of applying the friction modifier was standardised across all tests to ensure consistency. Hands were dipped into the chalk bag and the chalk was then crushed and distributed by the thumb rubbing against the middle finger 10 times, testing then commenced immediately. It was decided not to test liquid chalk in this study due to the high likelihood that rosin deposits (an ingredient in almost all liquid chalk) which would be difficult to clean from the surface of the rocks and affect other tests (necessarily conducted on the same surface for comparison).

Moisture was defined as 'wet' or 'dry' within the tests, to create the 'wet' finger condition a procedure was developed to ensure consistency. A paper towel was dampened with room temperature water, the participant was asked to press their finger into the towel for 3 s, after washing and drying their hands as described in section 'Test method'. The participant was then asked to wipe off excess moisture with their thumb and conduct the test immediately. A commercially available moisture detector (MoistSense) was used to assess the hydration of the skin through measuring the change in capacitance when in direct contact with the skin.[2] The moisture level is presented as a scaled reading from 0 to 99.

Test conditions

To create a full combination of variables to test the effect of chalk as a friction modifier in different situations, the test schedule shown in Table 2 was created. In between the tests the rocks were cleaned with compressed air and a rock-climbing brush to remove any remaining debris from the previous test. This protocol replicates climbing conditions in a more controlled manner, as climbers will often blow the dust off rather than using compressed air. Rock samples were tested successively, but within samples the order in which tests were performed was randomised to ensure a different order of wet/dry/chalk/no chalk each time. This method gave a balance between practicality and improving reliability of results through reducing bias from the participant. Each test was repeated five times.

Data analysis method

Data was recorded from the force plate for each test and was processed using MATLAB 2023a to find the shear force at slip. Figure 4 shows an example of an output graph from the force plate. The point at which the finger slipped is circled. This region was identified by finding the maximum recorded shear force for each test. This maximum shear force was divided by the normal load at the corresponding instance in time to give the static coefficient of friction.

Statistical analysis. Statistical analysis was performed using R Studio 4.2.2. Where appropriate normality and variance of the data was assessed using Shapiro–Wilks and Levene tests, respectively. Significant differences in the data were assessed using one-way analysis of variance (ANOVA) or Friedmans test where significance was assessed as a p-value < 0.05. Where significant, a post-hoc T-test or Wilcoxons test with Bonferroni correction was used to provide paired analysis between the groups.

Repeated measures correlation was used to calculate the correlation coefficient (r_{rm}) to assess the strength of the relationships between RMS S_q, S_{dq} and grain size compared with the mean static coefficient of friction under wet and dry conditions with and without chalk for each load.

Results

The mean static coefficient of friction (CoF) results and standard error ($SE = /\sqrt{n}$, where σ is the standard deviation and n is the sample size) of finger pad-rock friction tests for each rock in wet and dry conditions, with and without chalk for the three loads tested are shown in Figure 5. Significant differences in the mean static CoF were observed in 9 out of 12 groups studied (Table 3). This analysis of the results gives an overview of all testing but is difficult to discuss in isolation. In the following sections the results without the addition of chalk are first discussed, followed by those with the addition of chalk.

Table 2. Test schedule showing the combinations of variables for three loads on each of the four rocks in wet/dry conditions with or without chalk.

Rock type	Test conditions (all tested at 5, 10 and 15 N)
Sandstone	Dry Dry with chalk Wet Wet with chalk
Granite	Dry Dry with chalk Wet Wet with chalk
Dark limestone	Dry Dry with chalk Wet Wet with chalk
Light limestone	Dry Dry with chalk Wet Wet with chalk

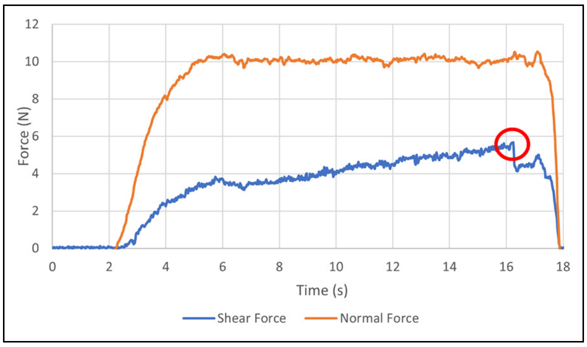

Figure 4. Example of output data of the force plate with the finger slip time point circled.

Table 3. *p*-Value results of one-way ANOVA or Friedmans test for comparisons between load and mean static CoF.

Rock type	5 N	10 N	15 N
Sandstone	NS	NS	NS
Granite	< 0.001	< 0.001	0.014
Dark limestone	< 0.001	< 0.001	NS
Light limestone	< 0.001	< 0.001	< 0.001

Significance indicated by a *p*-value < 0.05. *p*-values smaller than 0.001 or greater than 0.05 are indicated by < 0.001 or NS, respectively.

Without chalk

Load. Previous studies have shown both no load dependence and negative load dependence on CoF with skin,[15] both of which are seen here. Friction is independent of load for sandstone, but generally reduces with increasing load for wet and dry cases for the other rocks with the slight exception of dark limestone. In general, load had a smaller effect on CoF than other variables in the tests without chalk. One exception to this was the dark limestone with wet finger conditions. In the 5 N load case the wet condition increased the CoF compared to the dry condition, however, there was a smaller increase at 10 N and a reduction at 15 N. This difference in results is likely due to a combination of increased finger moisture improving plasticity of the finger and friction at low loads as the increased plasticity is limited by the increasing contact area reaching a plateau.

Roughness. Figure 6 shows how three rock surface parameters affected the CoF in both dry and wet conditions. There was a general trend of increasing CoF across most parameters although there were obvious exceptions to this trend. Of the surface measurements, both grain size (Figure 6(c) correlation coefficient of $r_{rm} =$ 0.61 and 0.54 and p-value = 0.06 and 0.11 for dry and wet conditions, respectively) and RMS gradient Sdq RMS gradient S_{dq} (Figure 6(b) correlation coefficient of r_{rm} = 0.60 and 0.58, and p-value = 0.07 and 0.08 for dry and wet conditions, respectively) showed stronger relationships in the wet and dry condition compared with to RMS surface roughness S_q (Figure 6(a) correlation coefficient of r_{rm} = 0.36 and 0.54 and p-value = 0.30 and 0.11 for dry and wet conditions, respectively). Average roughness S_a showed a similar relationship to S_q, and skewness S_{sk} and kurtosis S_{ku} showed no clear trends.

The fact that RMS gradient is more closely linked with CoF suggests that the dominant mechanism is likely ploughing, as sharper asperity angles result in a greater amount of ploughing. These sharper asperities also dig further into the skin, increasing both deformation and contact area, creating higher ploughing and adhesion in a similar way to the effect of increasing load depicted by Figure 9(c). Relationships with other surface roughness parameters are likely masked by additional contributing factors, like surface energy, hydrophobicity and porosity of the rock samples. Changes in moisture content of the skin also affect the topology of fingerprint ridges. More hydrated skin has wider ridges, which will interact slightly differently with the (constant within the testing time) rock topology.

The strong link between CoF and grain size partially supports this theory, but it is also probable these trends are affected by other surface properties such as surface energy or chemistry which were not measured this study.

Moisture. Table 4 gives a summary of how the addition of moisture to the finger affected the static CoF. Compared to dry contact with the rocks there was relatively little change on sandstone, a negative effect on granite, mixed behaviour on dark limestone and a positive effect on light limestone with the addition of moisture. For the granite increasing load improved the

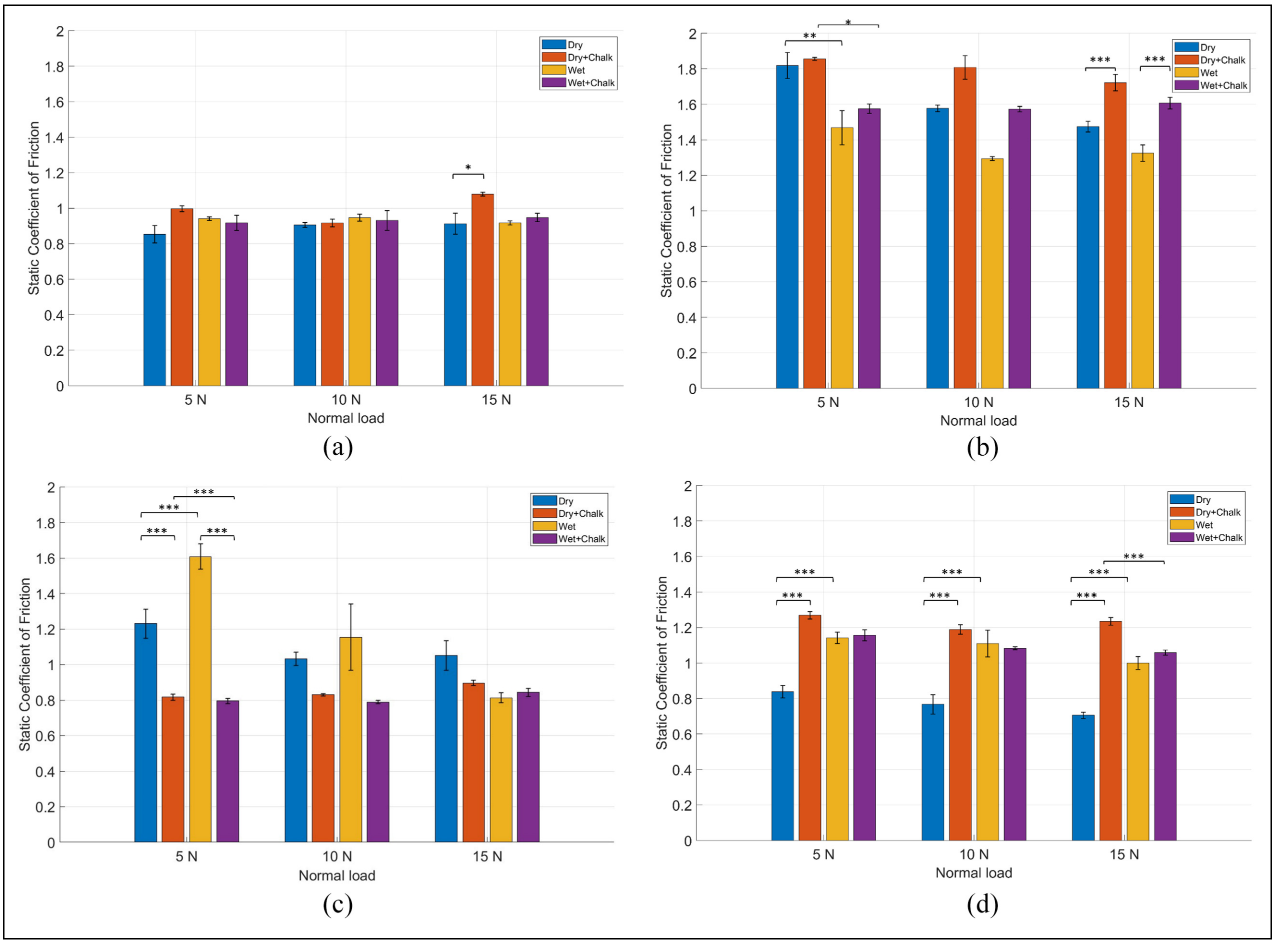

Figure 5. Static coefficient of friction versus normal load in different finger conditions (see legend) for the four different rock samples: (a) sandstone, (b) granite, (c) light limestone and (d) dark limestone. The bar height is the mean and error bars show ±standard error.
Statistic bar key: *$p \leqslant 0.05$. **$p \leqslant 0.01$. ***$p \leqslant 0.001$.

situation – the negative effect of water was reduced, whereas for the carboniferous limestone increasing load worsened the situation – the positive effect of additional moisture was removed and then had the opposite effect. This variation in results shows how the finger pad-rock interaction is a complex system even without the addition of a friction modifier.

Figure 7 shows the results of some additional testing conducted to illustrate the effect of moisture on friction. This testing was on another participant than those shown in the previous figures as the original participant was no longer available, although the results are dependent on the individuals' friction properties the trend in the moisture levels is the focus of this section of testing. This stand-alone testing was performed at a single load of 10 N on the dark limestone sample. The participant pressed their finger into a damp paper towel for varying durations of time, instead of just the 3 s duration which mimicked a sweaty finger in the previous testing, water is used to mimic the moisture of a sweaty finger in a controllable manner to enable consistency. The finger pad absorbs some of the water,[8] the aim of varying the time pressed in the towel was to allow for the absorption and vary the amount of moisture on the surface of the skin.

Considering the dark limestone, at a reduced load the addition of moisture gave a greater improvement in CoF than dry contact. At a lower load, the additional deformability exhibited by the skin is likely to be more beneficial, whereas at a higher load skin is likely to have already filled most asperity gaps. Therefore, additional deformability of the skin is unlikely to further improve the CoF and additional moisture will likely just lubricate the contact.

Based on the results seen here and understanding of friction mechanisms, the 'moisture curve' would likely shift left and right and be stretched vertically and horizontally with changes in load, surface roughness, and surface energy and would require a much more extensive testing programme beyond the scope of this work to fully characterise. Changes in participant would also likely have a significant effect on the moisture curve due to different skin properties and levels of hydration.[23–26] For more robust results, all these variables would require further testing to determine which has the most significant effect.

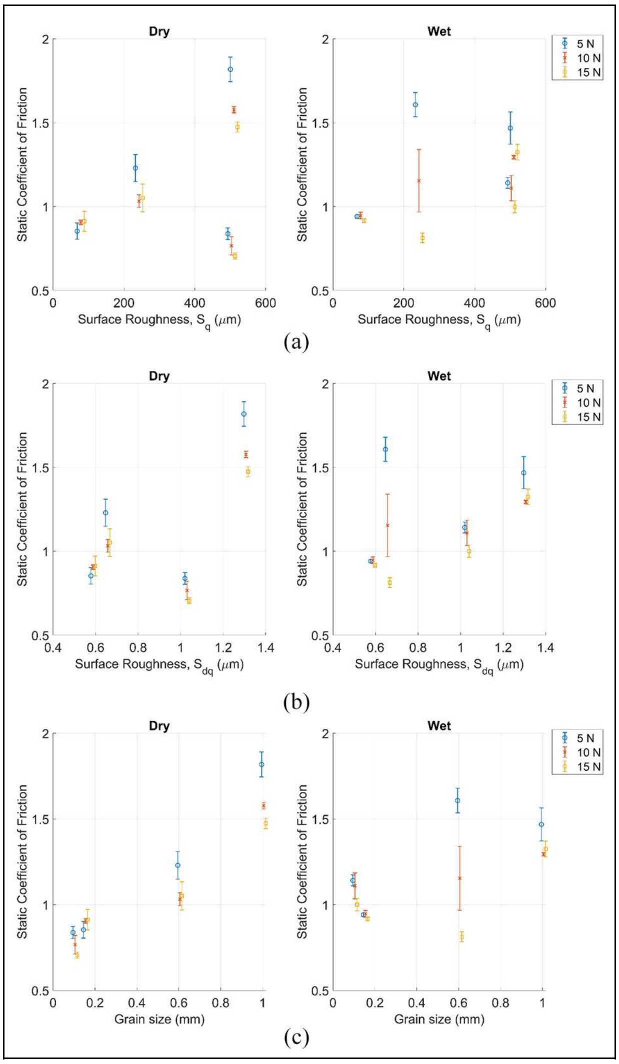

Figure 6. Summary of results with a focus on the effect rock sample surface parameters on the static coefficient of friction in both wet and dry conditions without chalk, across the three loads tested. Parameters shown are: (a) RMS roughness, S_q, (b) RMS gradient, S_{dq} and (c) approximate grain size. Roughness values for 5 and 15 N are slightly offset from their actual values to prevent overlapping data and provide clarity in results. The centre point is the mean and error bars show ±standard error.

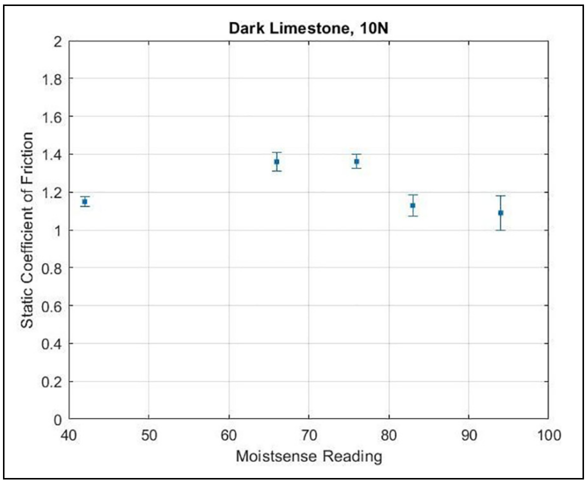

Figure 7. The effect of varying levels of moisture on finger pad-rock friction. Tested on the dark limestone sample at 10 N normal load, without the use of chalk. Average MoistSense reading recorded after placing finger on paper towel for 0, 1, 3, 6 and 9 s. The centre point is the mean and error bars show ±standard error. Participant 2.

Table 4. The difference in mean static coefficient of friction with the addition of moisture, without the use of chalk, compared with dry contact.

Rock	Difference in mean static CoF with the addition of moisture		
	5 N	10 N	15 N
Sandstone	+0.09	+0.04	+0.00
Granite	−0.35	−0.28	−0.15
Dark limestone	+0.38	+0.12	−0.24
Light limestone	+0.30	+0.34	+0.29

Green indicates a positive change, red a negative change and white no change.

The curve that may be associated with the sandstone, could be such that the dry and wet moisture levels were either side of the peak, resulting in similar values, like the dry and 6 s points in Figure 7. This assumption is speculative, and the behaviour may be significantly different due to the different surface chemistry, which is not characterised in this study, or topology.

Chalk as a friction modifier

Table 5 shows the effect that chalk had on static coefficient of friction across all test conditions. It shows a varied performance with both positive and negative changes in CoF across different test conditions. Chalk had the most positive effect on light limestone in dry conditions and the most negative effect on dark limestone in wet conditions. These mixed results are not surprising considering the complex behaviour observed with changes in moisture.

Load. There was a general trend in the data of increasing effectiveness of chalk with increased load which can be seen in Table 5. This trend may be due to the chalk being more compressed into asperity gaps or displaced out of the surface at higher loads, providing third body action and thus being less able to act as a solid lubricant, as suggested by Amca et al.[5] A solid layer of easily sheared chalk between the finger and rock would likely reduce the coefficient of friction. If there is less chalk separating the finger and rock, it will diminish its ability to act as a solid lubricant. Chalk filling voids to reduce friction could equally be cancelled out by larger and deeper voids between asperities at higher roughness values meaning that the chalk does not fully fill

Table 5. The difference in mean static coefficient of friction with the use of chalk for each of the test conditions, compared with no chalk.

Rock	Difference in mean static CoF with the use of chalk					
	Dry			Wet		
	5 N	10 N	15 N	5 N	10 N	15 N
Sandstone	+0.14	+0.01	+0.17	−0.02	−0.02	+0.03
Granite	+0.04	+0.23	+0.25	+0.11	+0.28	+0.28
Dark limestone	−0.41	−0.20	−0.16	−0.81	−0.37	+0.03
Light limestone	+0.43	+0.42	+0.53	+0.01	−0.03	+0.06

Green indicates a positive change, red a negative change and white no change.

the gaps and so does not affect the finger deformation or actual contact area, similar to Figure 9(d).

Considering Figure 5(c), in the example of dark limestone where there is significant load dependency of CoF in the wet condition, it is interesting that the addition of chalk removed this load dependency. The chalk likely reduced the moisture content of the finger, limiting the additional adhesion from increased deformability, but also limiting the ability of water to lubricate the contact.

Roughness. Figure 8 shows how the same rock parameters as Figure 6 affected the CoF in both dry and wet conditions but with the addition of chalk. There was again a general trend of increasing CoF across most parameters, with exceptions. The addition of chalk increased the strength of the relationships previously seen without chalk resulting in grain size showing the strongest relationship (Figure 8(c), correlation coefficient of $r_{rm} = 0.96$ and 0.97 and p-value < 0.01 and 0.01 for dry and wet conditions with chalk, respectively). RMS surface roughness S_q showed the weakest correlation (Figure 8(a), correlation coefficient of $r_{rm} = 0.71$ and 0.72 and p-value < 0.01 and 0.01 for dry and wet conditions with chalk, respectively), followed by RMS gradient S_{dq} (Figure 8(b) correlation coefficient of $r_{rm} = 0.93$ and 0.93 and p-value $= 0.22$ and 0.02 for dry and wet conditions with chalk, respectively). These changes are likely a result of changes in adhesive forces due to the introduction of a third body, as well as changes in the deformation and topology of skin as a result of moisture changes. Further investigations on the effect of surface parameters would be beneficial and could be controlled through the manufacture of artificial climbing holds with specifically designed surfaces rather than variable natural rocks.

Moisture. In general, chalk had a more positive effect in dry conditions than wet conditions which was an unexpected result considering that the intended use of chalk for climbers is to reduce moisture during contact. Chalk increasing friction in dry conditions has thus far been unexplained and so a proposed mechanism is suggested using Figure 9. In some conditions, chalk may fill asperity gaps and allow additional adhesion between the finger and chalk, which in turn adheres to the rock

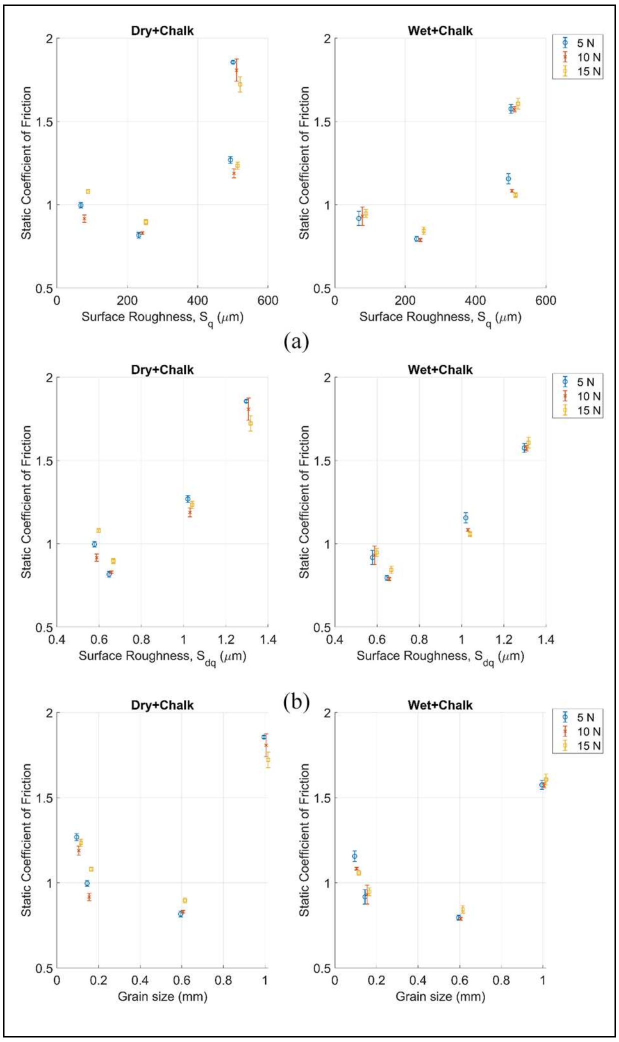

Figure 8. Summary of results with a focus on the effect of rock sample surface parameters on the static coefficient of friction in both wet and dry conditions with the addition of chalk, across the three loads tested. Parameters shown are (a) RMS roughness, S_q, (b) RMS gradient, S_{dq} and (c) approximate grain size. Roughness values for 5 and 15 N are slightly offset from their actual values to prevent overlapping data and provide clarity in results. The centre point is the mean and error bars show ±standard error.

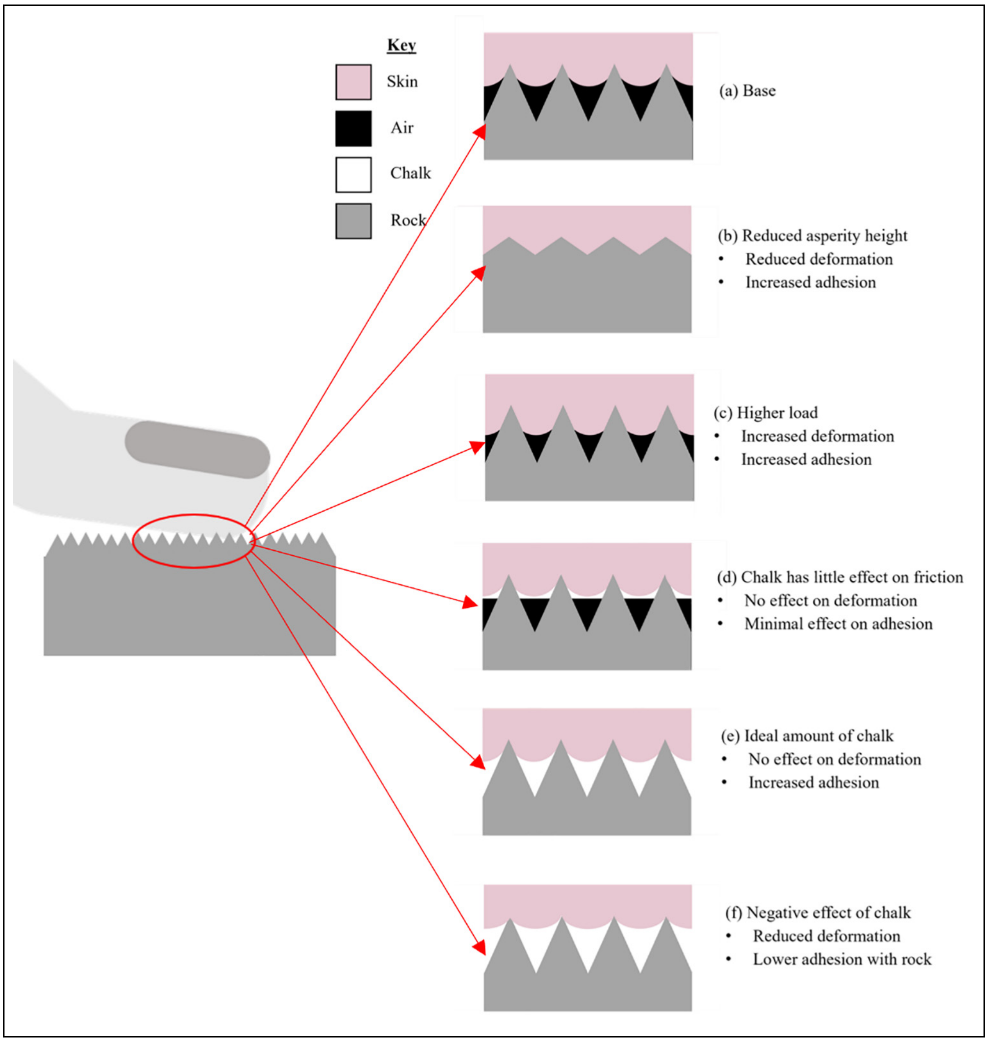

Figure 9. Visualisation of the base case (a) and the effect of changing asperity height (b) normal load (c) and the amount of chalk in the contact (d)-(f) on deformation and adhesion friction mechanisms in the finger pad-rock interface.

surface, without significantly reducing the deformation of the finger into asperities, as shown by Figure 9(e). With less than this amount of chalk the contact would be relatively unaffected (Figure 9(d)) and with further addition of chalk adhesion and deformation would be reduced (Figure 9(f)) and would eventually form a solid lubricant layer of easily sheared chalk, as suggested by Li et al.[4] In this study the effect of chalk improving CoF was seen immediately after application of chalk and this effect may change over time through repeated finger contacts, or absorption of moisture by the chalk from the environment. This instant effect of fresh chalk application would support the often-seen climber behaviour of brushing holds between climbs in the belief of improving the CoF, which has not been scientifically tested but is accepted in the climbing community as making an appreciable difference in some scenarios. This method to brush rocks would also avoid the build-up of chalk and limit its effects as a solid lubricant, so the mechanism is untested but is out of scope for this work.

Consistency. Another behaviour shown by Figure 5, but more clearly shown in Table 6 is that the use of chalk resulted in more consistent behaviour across most finger conditions and rock types, thus overall standard error was reduced in both wet and dry conditions, although again, this was not always the case.

The improvements in consistency seen in results with chalk are a key observation. While a high CoF is obviously desirable, consistency in CoF is also desirable for climbers. In general climbers attempt to complete a route or problem in as few attempts as possible which often involves drawing from experience and learning from mistakes on previous attempts. High variability in CoF could cause unexpected falls and new failure points which would hinder progress. If chalk gives a

Table 6. The difference in standard error of static coefficient of friction with the use of chalk for each of the test conditions.

Rock	Difference in standard error of static CoF with the use of chalk					
	Dry			Wet		
	5 N	10 N	15 N	5 N	10 N	15 N
Sandstone	−0.03	+0.01	−0.05	+0.03	+0.04	+0.01
Granite	−0.06	+0.05	+0.02	−0.07	+0.00	−0.01
Dark limestone	−0.06	−0.03	−0.07	−0.06	−0.18	−0.01
Light limestone	−0.01	−0.03	+0.00	+0.00	−0.07	−0.02

Green indicates a reduction, red an increase and white no change.

more repeatable CoF this may allow climbers to more easily gauge the normal load required for holds on repeat attempts of a climb and therefore be more efficient with their energy expenditure.

Other considerations. There are some factors in this study that we have been unable to investigate in much detail and should be considered as areas of future work. One important consideration is that chalk is a type of limestone and therefore may have the potential to form some different friction mechanism(s) when used on limestone rock which is especially important when considering that limestone is soluble in water. Does climbing on limestone naturally provide some of the mechanisms we have seen with chalk? There were larger differences in behaviour between the two limestones tested in this study than between the limestones and other rock samples.

Discussion

Determining the effectiveness of chalk as a friction modifier in rock climbing is complex and a definitive generalisation cannot be provided as it is highly situational. The applied normal load made the least difference to the static CoF of the variables tested, except for on dark limestone in wet conditions, on which a higher load reduced the CoF, likely an effect of specific skin moisture and a specific surface topology and chemistry. With the use of chalk there was a general trend of increasing effectiveness of chalk with increased load, explained by chalk being more compressed into asperity gaps or displaced out of the surface at higher loads and therefore less able to act as a solid lubricant.

Analysis of the results from testing a range of rocks with varying surface roughness and chemistry has indicated that CoF generally increased with surface roughness parameters, although these were likely masked by differing surface chemistries of the rock samples. The key roughness parameter is the grain size. This parameter indicates that when fingers are in contact with rocks that have larger grain sizes higher CoF is experienced. It is therefore thought that the dominant friction mechanism is ploughing. More ploughing would be expected where more acute angles in the surface roughness are present.

The addition of moisture to the finger pad-rock contact to simulate a sweaty hand both increased and reduced the CoF in different test cases. Increases in CoF were likely from increased moisture improving the deformability of the finger skin and thus increasing friction through increased contact area and ploughing. Reductions in CoF were likely a result of water acting as a lubricant in the contact. There is a complex relationship between the finger moisture, rock topology and other properties of the rock which require further study to be fully understood. This relationship will also likely change from person to person and climb to climb and even throughout a climbing session, in which climbers often perceive a change in their fingertip skin condition – a ‘climbing state’. Further research could investigate the mechanism behind this phenomenon. This might involve studying changes in skin texture, sweat production or other physiological factors that influence friction during climbing.

Interestingly, chalk had an overall more positive effect in dry conditions than the wet conditions in this testing, resulting in a new proposed mechanism for chalk increasing coefficient of friction without affecting the moisture of the skin. At the appropriate amounts for the topology, chalk filling asperity gaps may increase friction by increasing overall contact area and thus adhesion of the contact. The results further show that the CoF was affected by the different surface of the rocks, to develop the testing further artificial holds with consistent surface texture could be used to provide a standardised methodology. Repeating this test with artificial climbing holds could offer scientific evidence regarding the effectiveness of a magnesium ban in climbing gyms that experience ‘white cloud’ issues.

Conclusions

A generalisation of chalk increasing or decreasing friction cannot be made, having conducted testing on a range of different rocks with varying roughness and chemistry, with wet and dry fingertips, it is shown to be situational. Friction testing was conducted on one participant to assess the trends across the different rock surfaces; however, it should be recognised that the results are somewhat dependent on a person's friction properties. In some situations, the presence of chalk improved the CoF and in some it worsened it. The following conclusions can be made from this study. However, chalk is shown to modify friction for a positive climbing experience with a more predictable, repeatable level of friction observed with chalk applied.

1. The test method described here provides a consistent method to test different loads, moisture conditions and rock types. The method allows the participant to control the normal load in a representative way to how they would be in contact with the rock whilst climbing.
2. The roughness of the rock generally correlates with the level of CoF in the contact, with higher CoF experienced on rocks with higher surface roughness parameters. The grain size is seen to be the most dominant of these parameters, with rocks with sharper asperities creating more ploughing and hence higher CoF.
3. Moisture in the contact adds an additional complexity and the effect on CoF is inconsistent, dependent on many factors including rock topology and level of moisture. The resulting variation in CoF can be down to excess water acting as a lubricant or deformation of human skin.
4. Chalk increases CoF more in dry conditions than wet conditions, increasing adhesion through the filling of asperity gaps.
5. Although chalk does not always increase friction, the application of chalk was shown to make the CoF more consistent in most situations and therefore more predictable for climbers.

Further investigations on the effect of surface parameters would be beneficial and the effect of variable natural rock surfaces could be compared with artificial climbing holds.

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