MEEN 404 - 905

Experiment 1

Exploring the Effect of Climbing Chalk on the Coefficient of Friction between Human Skin and Rock

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1876

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December 6, 2018

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Abstract

Rock climbing is a popular sport that attracts numerous individuals across skill levels. Chalk (magnesium carbonate) is used by almost all climbers in order to increase hand grip on the rock by increasing the coefficient of friction between the hands and the rock. Current research into the effects of using chalk has been limited to categorical experiments where clean hands are compared to chalked, and fails to determine the optimal amount of chalk that should be used by a climber to maximize the coefficient of friction between their hands and the rock. Therefore, this experiment explores this very question, by measuring the coefficient of friction between a rock and a skin substitute as a function of increasing area density of chalk ρ_A on skin. By using a coefficient of friction testing apparatus, the coefficient of static friction μ between a gelatin skin substitute and a rock climbing hold were measured while increasing the amount of chalk per unit area. It was found that μ was negatively related to ρ_A by the following: $\mu = 1.1719 - 0.0005[\frac{cm^2}{mg}] * \rho_A[\frac{mg}{cm^2}]$ with an R^2 value of 0.7574. These data suggest increasing the area density of chalk on skin by $20[\frac{mg}{cm^2}]$ would decrease the coefficient of friction μ by 0.01, which contradicts user experience. Due to the drying effects of magnesium carbonate, it is hypothesized that the experienced increase of the coefficient of static friction comes from the reduced moisture content on the skin, which is beyond the scope of the experiment. It is recommended that additional tests be coordinated to explore the effects of both area density of chalk and moisture content of skin on the coefficient of static friction between skin and climbing rock.

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Glossary Table

$'Chalk'$	Magnesium Carbonate as used in rock climbing
cm	Centimeter
∂	Partial Derivative
Δ	Error
$FMEA$	Failure Modes and Effects Analysis
F_N	Normal Force
F_f	Force of Friction
g	Gram or acceleration due to gravity
$Gelatin$	A virtually colorless and tasteless water-soluble protein
$Glycerin$	Also know as glycerol: a colorless, viscous liquid used as an emollient
μ	Coefficient of Static Friction
mg	Milligram
μg	Microgram
ρ_A	Area Density of chalk
$'Simulated\ Skin'$	Material made from glucose and glycerin to simulate skin
w	Weight of the rock and the added mass
w_a	Weight of the suspended weight

1 Introduction & Objective

Rock climbing is a popular sport that attracts numerous individuals across skill levels. A commonality between almost all rock climbers is the use of 'chalk.' Historically, this drying substance was made from actual chalk, but in the modern sport of rock climbing, it is magnesium carbonate or similar [1]. Using too much chalk can 'chalk up holds,' making gripping the rock harder, rather than easier [2]. Current research has explored the effects of using chalk on the grip ability of climbers [3]. However this research has only explored the effects of using chalk and not using chalk, and fails to determine the optimal amount of chalk that should be used by a climber to maximize the coefficient of friction between their hands and the rock. Therefore, this experiment explores this very question, by measuring the coefficient of friction between a rock and a skin substitute as a function of increasing amounts of chalk per unit area of skin. The objective of this is to determine the optimal mass of chalk per unit area of skin that should be applied in order to maximize the coefficient of friction between a person's hand and rock climbing holds. This could allow climbers to better perform in competition, or summit routes previously impossible.

2 Theory

Magnesium Carbonate is a drying agent that is used by climbers to increase grip on the rock because it is insoluble in water and prevents sweating [4]. This reduced level of moisture is said to increase the coefficient of friction between a climbers hands and the rock surface being climbed.

It has been shown that glycerine gelatin is an accurate simulation of human skin [5]. Therefore, a mixture of equal parts by volume of water, glycerine, and gelatin combine to create a surface that represents the surface conditions of human skin.

The coefficient of static friction is defined as the ratio of the maximal frictional force exerted by two surfaces tangentially on each other to the normal force exerted by the same two surfaces on each other. This relationship is summarized by Equation (1). The forces F_N and F_f can be found from an extension of Newton's First Law, show as Equation (2). The downward normal force from the weights and the rock on the simulated skin is calculated as their mass times gravity $w = m * g$. Additionally, the frictional force that is required to hold the rock and weights in place is equal to the tension in the string which equals the weight of the suspended weights. The downward force on these weights is equal to $w_a = m_a * g$. By increasing the applied weight of the suspended mass, eventually the tension in the string will overcome the static frictional force. This force can be assumed to be the maximum static frictional force, and can be used in Equation (1) to calculate the coefficient of static friction.

$$\mu = \frac{F_f}{F_N} \tag{1}$$

$$F = m * a \tag{2}$$

$$\rho_A = \frac{m}{A} = \frac{4m}{\pi D^2} \tag{3}$$

Because it has been shown that the use of chalk increases grip and therefore increases the coefficient of friction, it is expected that the coefficient of static friction between the rock and the simulated skin will increase as chalk is added to the surface [3]. However, it has also been determined that too much chalk decreases climbing performance by decreasing grip and therefore the coefficient of friction [2]. At some point, there must be a transition between these two effects. Therefore, it is expected that there will be a rise in the coefficient of friction to a point, and then a decrease as excess chalk is added.

3 Experimental Apparatus

In order to perform this experiment, an experimental apparatus capable of applying a force tangential to the surface of the simulated skin was needed. Additionally, it was necessary to be able to measure that force as it is applied to the rock. Therefore, the apparatus outlined in Figure 1 was devised.

This apparatus is similar to a standard coefficient of friction testing apparatus. However, a weight that was increased induced the horizontal force to oppose friction. Additionally, the rig as designed has additional benefits of being significantly less expensive and more readily available.

Additional instrumentation needed for this experiment are a 4kg scale and a high-precision scale. The absolute uncertainties ($0.1g$ for the ScoutPro, $0.0001g$ for the GEM20, and $0.00127cm$ for the SPI Dial Calipers) were found from the user manuals of the two scales and the calipers [6][7][8]. The percent uncertainties were calculated by dividing the average measured value from the raw data in Table 3 in Appendix C by the absolute uncertainties of each device.

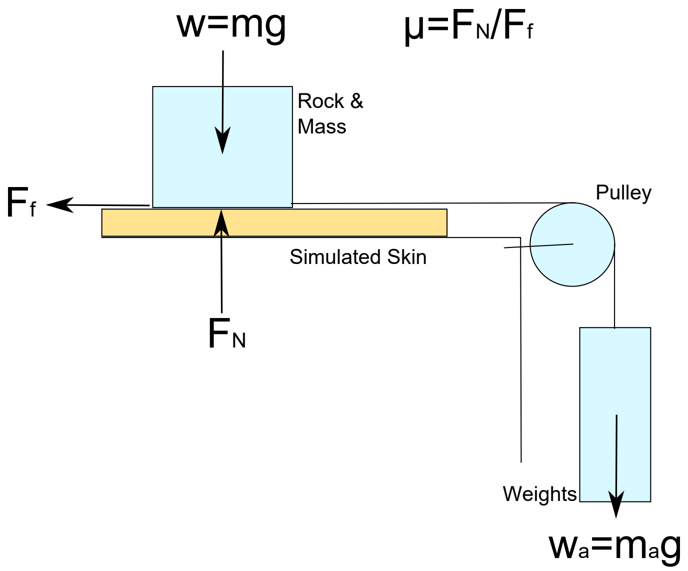

Figure 1: Schematic of Experimental Apparatus

Table 1: Instrumentation Uncertainty

Instrument	Uncertainty	Units	Percent Uncertainty
Scout Pro 4000g Balance	0.1	g	0.00810%
GEM20 Jewelry Scale	1	mg	1.85%
Brown and Sharpe 12” Caliper	0.00127	cm	0.00549

From Equation (1), the partial derivatives can be calculated for F_f and F_N. From Equation (3), the partial derivatives can be calculated for D and m. These values can be substituted into Equation (4) to calculate the uncertainty in the dependent variable μ and the independent variable ρ_A the area density of chalk. The uncertainty in the coefficient of friction is $0.117 * 10^{-3}$ which equates to an average relative uncertainty of 0.0115% The uncertainty of the mass density of chalk ρ_A is $2.38[\frac{mg}{cm^2}]$ which equates to a relative uncertainty of 0.727%

$$\Delta u = \sqrt{\left(\frac{\partial x}{\partial u}\Delta x\right)^2 + \left(\frac{\partial y}{\partial u}\Delta y\right)^2} \tag{4}$$

The results of the failure modes and effects analysis (FMEA) summarized in Table 2 indicated that extreme care must be taken in the measurement, application, and distribution of the chalk on the surface of the rock and the skin. As a result, the experiment procedure was adjusted to not require the cleaning of the surfaces between tests by having chalk only increase in mass per unit area. Additionally, procedures to weigh a towel before and after being used to spread the chalk were added. This would help mitigate the issue. In regards to improper loading, procedures were added to check the loading condition of the rock and suspended mass before beginning the test to ensure the string is tangent to the surface, aligned with the center of mass, and the suspended mass is not in contact with any sidewalls. To mitigate the possibility of measurement error, the scales should be zeroed before use and be allowed to stabilize. Finally, multiple skins from the same batch will be made in case there is a tear in one of them.

4 Experimental Procedures

1. The simulated skin was prepared.
    - $\frac{1}{2}$ cup each of water, glycerin, and glucose were mixed and heated to above $60°$C, mixed thoroughly, and poured into a 9 in round mold.
    - The mold was allowed to return to room temperature and completely set.
2. The apparatus was prepared.
    - The simulated skin was removed from the mold and placed on the platform.
    - The rock and masses were weighed.
3. The coefficient of friction was tested.
    - The weighted rock was placed in the center of the skin and the masses were suspended, and the wire was checked for proper alignment.
    - Mass was added to the suspended masses until the rock began to slide without stopping.
    - The amount of suspended mass was recorded.
    - These procedures were repeated twice more.
4. The coefficient of friction with chalk was tested.
    - The mass of the piece of paper towel used for spreading chalk was weighed.
    - Using the high-precision scale, $0.025g$ of chalk was weighed and the towel piece was used to spread out the chalk. The paper towel was weighed again.
    - Step 3 was performed again.

- Chalk was continually added in $0.025g$ increments until a total of $0.2g$ was reached. The mass of chalk added was increased by $0.25g$ each test until the total mass reached $0.4g$.

5. All data was verified as recorded.

5 Results

The results from the experiment are summarized in Figure 2. This figure is a plot of the coefficient of static friction between skin and the climbing hold as a function of the mass per unit area of the chalk. μ is the dependent variable of choice of the experiment. Chalk in terms of mg/cm^2 was chosen as the best representation of the independent variable because it removes the relationship of the dependent variable to the area of the surface. The blue circles represent every data point taken during the experiment. Due to the very low error values in both ρ_A and μ (2.38$[\frac{cm^2}{mg}]$ and 0.0001168 respectively), the plotted error bars are too small to be visible (see Appendix A for calculations). The dotted line is a least squares regression line calculated from the entire set of data and has an equation $\mu = 1.1719 - 0.0005[\frac{cm^2}{mg}] * \rho_A[\frac{mg}{cm^2}]$ and an R^2 value of 0.7574.

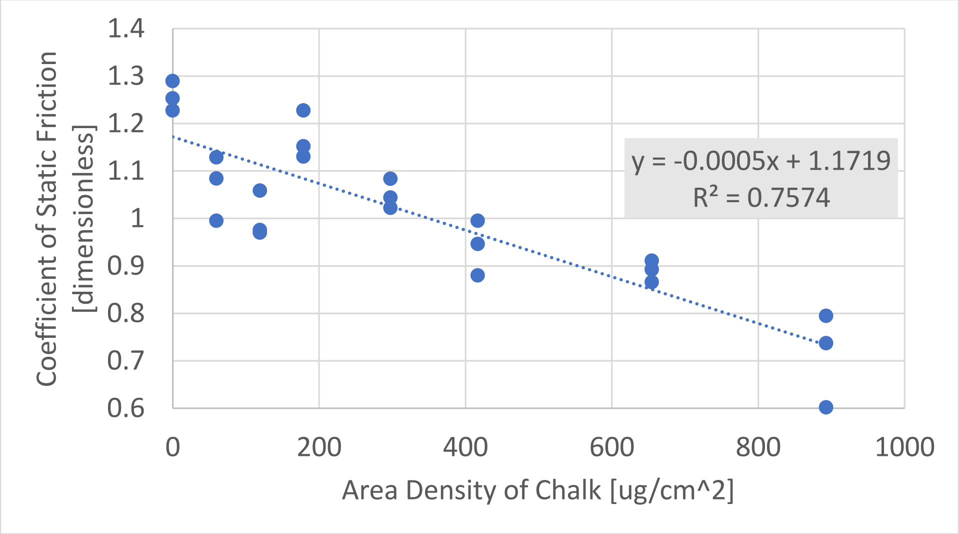

Figure 2: Experimental Data with Trend Line

6 Discussion of Results

These data outlined in Figure 2 show the surprising result that the coefficient appears to only decrease linearly with respect to the thickness of chalk applied. According to the data collected, 75.4% of the change in the coefficient of static friction between skin and rock can be attributed to changes in the area density of chalk applied. This contradicts the predicted results from previous experiments and user experience [2][3]. This data seems to imply that no amount of chalk would be beneficial to the user during any kind of climbing experience, as the point of most grip, would be with no chalk applied. This would directly contradict the experience of climbers [1]. However, this is not the case. Magnesium carbonate is often used as a drying agent: specific to climbing for reducing the effects of sweat on the hands [4]. Therefore, this data suggests that the application of magnesium carbonate chalk to the hands of climbers is only beneficial if it serves to reduce the surface moisture of the skin, as is suggested by Fuss and Niegl [9]. Any amount of excess chalk will only reduce the gripping ability of the climber by decreasing the coefficient of friction between their hands and the rock being held. Without further testing, this experiment cannot fulfill the original objective of determining the optimal amount of chalk to be used by climbers to maximize their coefficient of friction.

7 Summary

- Climbers use chalk to increase grip, but do not have an amount shown to be optimal.
- The objective of this experiment was to determine the optimal g of chalk per cm^2 to maximize μ.
- Experience suggests an increase in μ with increasing chalk use, and an eventual decrease with overuse.
- The data showed a linearly negative trend between the chalk mass per area and μ, contradicting the negative quadratic trend that was expected.
- The calculated line of best fit for this data was $\mu = 1.1719 - 0.0005[\frac{cm^2}{mg}] * \rho_A[\frac{mg}{cm^2}]$ with an R^2 value of 0.7574.
- The data suggests that increasing chalk negatively affects μ when skin moisture is negated.
- Therefore, it is hypothesized that chalk only serves as a drying agent to reduce the negative effects of sweat, rather than to increase μ between skin and rock, as shown by Fuss and Niegl [9].

8 Conclusions

- Without further testing including the effects of skin sweat on the coefficient of friction between climbing rock and human skin, an optimal amount of chalk for climbers to use cannot be currently given.
- The data collected shows the coefficient of static friction between dry skin and rock decreases linearly as a function of mass per unit area of chalk with a least squares regression of $\mu = 1.1719 - 0.0005[\frac{cm^2}{mg}] * \rho_A[\frac{mg}{cm^2}]$

9 Recommendations

It is recommended that additional testing be performed in order to explore the relationship between the amount of applied of chalk, surface moisture of skin, and the coefficient of static friction between skin and rock. Such an experiment would allow for the determination of a optimal amount of chalk to be used given the surface conditions of a climber's hands.

References

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[8] MSC. *0” to 12” Range, 0.001” Graduation, 0.1” per Revolution, Dial Caliper*, 2018.

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A Uncertainty Analysis

$$\frac{\partial \mu}{\partial F_f} = \frac{1}{F_N}$$

$$\frac{\partial \mu}{\partial F_N} = \frac{-F_f}{{F_N}^2}$$

$$\frac{\partial D}{\partial \rho_A} = \frac{4}{\pi D^2}$$

$$\frac{\partial m}{\partial \rho_A} = \frac{-8m}{\pi D^3}$$

$$\Delta\mu = \sqrt{\left(\frac{\pm 0.1}{1221.7}\right)^2 + \left(\frac{-1235.2 * \pm 0.1}{1221.7^2}\right)^2} = 0.0001168$$

$$\Delta\rho_A = \sqrt{\left(\frac{4 * \pm 0.001}{\pi * 23.12^2}\right)^2 + \left(\frac{-8 * 0.054 * \pm 0.00127}{\pi 23.12^3}\right)^2} = 2.38\frac{mg}{cm^2}$$

B FMEA

Table 2: Failure Modes and Effects Analysis

Item	Severity	Occurrence	Detection	RPN
Leftover Chalk Residue	5	4	8	160
Improper Loading	9	7	1	63
Measurement Error	7	4	2	56
Rip in Simulated Skin	4	6	1	24

C Raw Data

Table 3: Raw Data

Mass of Chalk [g]	Applied Chalk $[mg/cm^2]$	Trial 1 [g]	Trial 2 [g]	Trial 3 [g]	Avg. [g]	μ
0.000	0.000	1499.5	1530.8	1575.2	1535.2	1.2566
0.025	59.52	1378.6	1216	1324.4	1306.3	1.0693
0.05	119.0	1191.5	1293.3	1185.1	1223.3	1.0013
0.075	178.6	1407.3	1499.5	1380.6	1429.1	1.1698
0.125	297.6	1323.9	1249.1	1275.2	1282.7	1.0500
0.175	416.7	1216	1155.9	1075.2	1149.0	0.9405
0.275	654.8	1112.7	1057.7	1090.1	1086.8	0.8896
0.375	892.9	735.4	971	900.6	869.0	0.711

Mass of Weights	1221.7 g
Surface Area	420.0 cm^2

D Example Calculations

$$Percent\ Uncertainty = \frac{uncertainty}{average\ measurement} = \frac{0.1g}{1234.5g} = 0.00810\%$$

E Experimental Setup

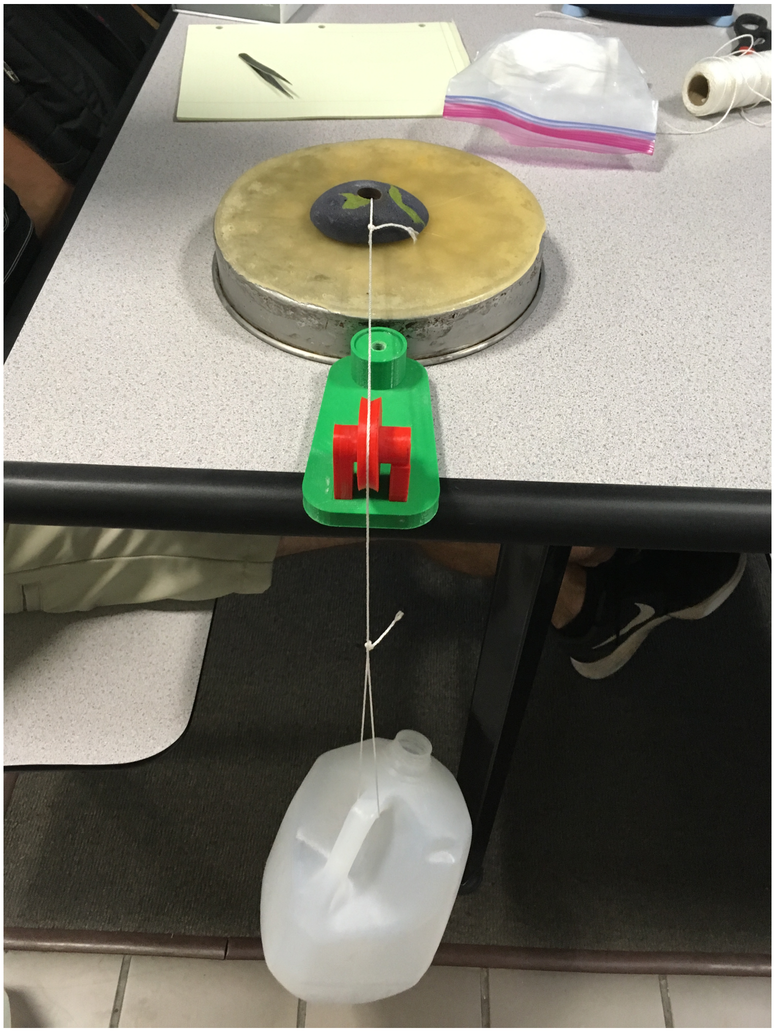

Figure 3: Experimental Setup