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By

Matthew A. Kilgas

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Title of Thesis: THE EFFECT OF MAGNESIUM CARBONATE (CHALK) ON GEOMETRIC ENTROPY, FORCE AND EMG DURING ROCK CLIMBING

This thesis by Matt Kilgas is recommended for approval by the student's Thesis Committee and Associate Dean and Director, School of Health and Human Performance and by the Assistant Provost of Graduate Education and Research.

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ABSTRACT

THE EFFECT OF MAGNESIUM CARBONATE (CHALK) ON GEOMETRIC ENTROPY, FORCE AND EMG DURING ROCK CLIMBING

By

Matthew A. Kilgas

Rock climbers often attribute the cause of a fall to the inability to maintain contact between the hands and the surface of the rock. Rock climbers turn to magnesium carbonate (chalk) to combat this problem even though little scientific evidence supports its use. Rock climbers believe that chalk dries the hands of sweat and improves the coefficient of friction between the hands and the surface of the rock (COF_H). The purpose of this study was to assess whether or not chalk affects geometric entropy (GE) or muscular activity during rock climbing. Participants were asked to complete a predesigned movement sequence with and without the use of chalk. The body position of the climber was recorded using a video camera. Following the movement sequence participants hung from a standard climbing hold until they slipped from the climbing structure. COF and the ratio of the vertical forces on the hand and feet (FR) were determined by a force platform mounted behind the climbing structure. Electromyography (EMG_{avg}) was recorded throughout the trial. Although there was no difference in the COF, FR, or EMG_{avg}, participants were able to hang longer after the use of chalk.

Keywords: Friction, hang time, chalk, body position, bouldering

ACKNOWLEDGMENTS

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SYMBOLS AND ABBREVIATIONS

Chalk-Magnesium Carbonate

COF_H-The coefficient of friction between the hands and the surface of the rock

COP-Center of pressure

COF-Coefficient of friction

COM-Center of mass

GE-Geometric Entropy

LOM-Line of Motion

C-Convex hull

YDS-Yosemite Decimal System

CF-Chalk First

CS-Chalk Second

EMG-Electromyography

FR-the ratio of the vertical forces imparted by the hands and feet

GE_{FV}-The geometric entropy when filmed perpendicular to the climbing surface

GE_{SV}-The geometric entropy when filmed parallel to the climbing surface

LOM_{FV}-Line of motion when filmed perpendicular to the climbing surface

LOM_{SV}- Line of motion when filmed parallel to the climbing surface

EMG_{avg}- The average EMG after a root mean squared integration was performed

HT-Hang time

CT-Climbing time

Sig-Significance Level

Introduction

Rock climbing has developed from a simple training method for alpine mountaineering, and has grown into its very own sport with international competition. This growth in popularity can be attributed to the growth of indoor climbing structures and the installation of many permanent anchors on outdoor climbing areas. The availability of permanent anchors increases the safety of the climbers, and has given them a dedicated training location allowing them to develop their skills. Many climbers are pushing their limits and climbing on extremely difficult terrain. Climbing routes that were once thought as impossible can now be completed by recreational climbers. The growing popularity of rock climbing has led to a growing demand by researchers to understand the physiological demands required by rock climbing. [1–10] Researchers are attempting to understand anthropometric measures and training adaptions that allow climbers to complete ascent on difficult terrain.

Goddard and Neumann have described a model for rock climbing performance that includes background conditions such as availability of climbing resources and equipment, experience, psychological effects such as fear and arousal, climbing specific techniques, and physical abilities. [11] A model used to explain rock climbing performance can be very difficult to formulate because of the wide variety of climbing terrain, style, and type. There are two different climbing sub-disciplines: route climbing, which is characterized by longer vertical climbing, in which aerobic metabolism and muscular endurance are favored; and bouldering which involves shorter, and often more difficult climbing moves, favoring powerful and explosive moves over endurance. [12] Even individual routes and problems can include different features requiring different climbing techniques. Regardless of route type, body type, or climbing experience, many

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climbers often attribute the cause of a fall or the failure to complete a route as the inability to maintain contact between the hands and the rock. [13]

In an attempt to increase and maintain contact with the rock, climbers often use magnesium carbonate (chalk) on the hands. This substance is meant to increase the static coefficient of friction between the hands and the rock (COF), and presumably dry the hands of sweat. [14–16] Chalk is carried by climbers in a "chalk bag" attached at the waist. As climbers progress through the route they dip their fingers into the chalk. While many climbers turn to chalk to improve their climbing performance there is very little evidence supporting its use, and some studies have even shown a decrement in performance. [15–17] This decrement maybe due to two different factors. The first includes the drying effect of chalk, which decreases skin compliance and in turn reduces the coefficient of friction. [17, 18] Secondly, chalk from the hands accumulates on the hold to form a granular layer which may cause slipping. [16,17]

Li et al. showed a decrease in the static COF while using chalk, [16] a finding that contradicts the belief held by many rock climbers. This study however was not rock climbing specific. It involved the use of a specially designed table that applied a 3.5 kg load to pull a rock surface away from the subjects under different conditions of rock type - water/no water, chalk/no chalk. The participants were asked to slowly reduce their fingertip force until the rock surface began to slip. [16] Fuss recreated this study by monitoring movements in the center of pressure (COP) of the fingertips on a force plate. Fuss found that when the chalk is just placed on the hand and finger, the static COF was enhanced, while chalk on both the hand and hold reduced the coefficient of friction. In an attempt to recreate this investigation in a more sport-specific manner, Amca et al. used a hang board, a device specifically made for rock climbing training. [14]

The subjects were asked to hang on certain features while the angle of the hang board was manipulated. The researchers also suggested that chalk actually improved the static COF. [14]

The use of chalk to improve the COF is not without controversy. In studies that assessed the Coefficient of Friction in rock climbing, the static COF or the point where slippage or motion occurs was measured. At this point the climber would be falling from the rock face; thus this may be an impractical measurement for rock climbing.

Fuss and Neigl used a biomechanical model to assess the COF_H in rock climbing. [15] They defined the COF as the ratio of the tangential force to the normal force independent of the point of slippage COF_H. Using this model they described how body position and the movement of the center of mass (COM) could manipulate the COF between the hands and the rock without reaching the point of slippage. [15] For example if the climber moves the COM closer to the wall the COF will decrease; this allows the rock climber to maintain contact on a smoother hold. [15] The complexity of the movement of the center of mass of a rock climber can be quantitatively measured using a calculation of geometric entropy (GE).

Geometric Entropy is calculated by a line drawn depicting the movement of the climber's center of mass (LOM). Software was used to find the Convex Hull (c) or the perimeter of the path taken by the climber. Geometric Entropy is calculated as $GE = \ln \frac{2*LOM}{C}$ in accordance with Sibella (2007) and Cordier (1994). [19,20] From this it can be determined that the lower the value of GE the more fluent the climbers movement. [19] This fluent movement has been shown to correlate with energy expenditure. [21]

The purpose of this study was to assess whether or not chalk affects GE, or muscle activity during rock climbing. A secondary purpose was to assess any differences in the forces involved in a static hang until failure with or without chalk.

Methods

Nineteen recreational rock climbers (13 males, 6 females) were recruited from the local climbing community. Participants had a mean height of 173.5 ± 7.0 cm, and a mean weight of 67.5 ± 3.4 kg. All subjects had experience rock climbing for more than one year, and had the ability to climb at least 5.10 (range = 5.10 to 5.12) on the Yosemite Decimal System (YDS) rating scale. The YDS is the most common system employed in the United States. The numeral 5 represents free climbing followed by a decimal point, the number after the decimal represents the difficultly of the hardest sequence of the climb from .0 (easiest) to .15 (most difficult). Participants on average spent 6.56 ± .34 hours per week climbing. These experience and climbing ability levels ensured that all participants are familiar with climbing specific technique. In addition all subjects habitually used chalk during their recreational climbing pursuits.

Anthropomorphic Measurements

Testing began with basic anthropomorphic measures of height, weight and arm span. Height was measured using a stadiometer. The participant stood with their back to the vertical wall mounted ruler, then a sliding horizontal headpiece rested on the subject's head. A researcher noted the height of the headpiece. Weight was assessed by having the subject step onto an electronic digital scale (Tanita BWB-800A; Arlington Heights, USA). Participants wore all the clothing and shoes they wore during the climbing session. A researcher noted the weight to the

subject to the nearest tenth of a kilogram. Arm span was assessed using a wall mounted

horizontal ruler, which subjects stood with their backs to the wall with their arms abducted to a

point perpendicular to the longitudinal axis. A researcher noted the distance from the longest

finger to the longest finger on the opposite hand.

Climbing Test Protocol

The climbing was performed on a vertical indoor climbing structure fitted with modular

climbing holds. Once the participants completed anthropomorphic testing, they were

randomized into chalking first (CF), or chalking second (CS). Subjects were required to

thoroughly wash their hands with soap and water for 15 seconds, at least 5 minutes before each

trial. Participants were required to perform a static hang from specific holds until they could no

longer maintain contact and slipped from the climbing structure. (see figure 1.) They were

allowed to maintain contact on the wall at four points, both hands and feet. Participants were not

instructed or given advice on hanging technique. Following the static hang until failure,

participants took a 10 second rest, then immediately began climbing a predesigned boulder route

set by an experienced route setter. The boulder route consisted of 14 hand holds and 11 foot

holds arranged in a semi-circle around the indoor climbing structure (see figure 1.)   The route

ended with another hang until failure from the same points listed above. The subject did not

come off the climbing structure from the end of the boulder problem to the beginning of the

second static hang. All participants completed the above procedure twice, once with chalk and

once without chalk. During the chalking trial participants were allowed to chalk prior to the first

and second hang and before the boulder route. Participants did not reapply chalk while climbing

the boulder route. All climbing holds were cleaned via brushing with a firm nylon brush before

each trial.

Forearm muscle activity.

Forearm muscle activity was assessed using surface Electromyography (EMG). electrodes were placed approximately 1/3 of the distance from the medial epicondyle of the humerus to the styloid process of the radius. Disposable self-adhesive Ag/AgCl dual electrodes (Noraxon, Scottsdale, AZ, USA) were placed on the muscle in line with the fiber direction. Impedance between the electrodes was verified to be less than 5000Ω. All electrodes were on the right arm of the subject. EMG data were recorded at 1000 Hz using BTS FREEMG wireless system (BTS Bioengineering, Milanese Milano, Italy). The raw EMG signal was filtered (10hz-450hz) and rectified. Then a root mean squared integration performed. The mean EMG signal (EMG$_{avg}$) was recorded.

Geometric Entropy.

Participants performed the boulder route and static hangs in front of two video-cameras recording at 30 Hz. Camera one was set at a height of 1.5 meters, aligned approximately with the center mark of the wall, and was positioned 10 meters back to ensure the whole wall was filmed. This camera was filming perpendicular to the surface of the bouldering wall. Camera 2 was placed facing perpendicular to camera 1, at the same height and distance from the center of the wall. This camera filmed parallel to the surface of the wall. The two cameras, positioned in this fashion, recorded the movement of the climber in the frontal and sagittal planes. Climbers wore a nylon belt around their natural waist fitted with reflective markers placed along the midline of sagittal and frontal planes to approximate center of mass (COM) of the individual, in the plane of each video camera. Video analysis was performed on MaxTRAQ Standard Version 2 (Innovision Systems Inc. Columbiaville, MI, USA). The video analysis was used to determine a line of

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motion (LOM), or a line drawn by the movement of the climber COM. Software was used to find the Convex Hull (c) or the perimeter of the path taken by the climber. Geometric Entropy was then calculated as GE=ln$\frac{2*LOM}{C}$ in accordance with Sibella (2007) and Cordier (1994) [19,20].

Static Hanging

Hanging was performed on a specifically designed hang board. The surface was the same for the right and left hand. Three pairs of footholds were mounted on the lower force plate at different heights to accommodate different sized individuals, however the foot height was maintained for each of the hangs (See figure 1). Two force plates (OR6-7-2000 AMTI, Watertown, MA) were used to assess the outward horizontal and downward vertical forces on the hands and feet, the COF was calculated by the horizontal force divided by the normal force. The highest COF calculated during the hang was recorded. The ratio of the vertical forces on the hands and the vertical forces on the feet (FR) was also calculated using the forces measured by the force plates. The mean (FR) measured during the hang was recorded.

Statistical Analysis

All data were entered to SPSS Version 21 (SSPS Inc., Chicago IL, USA) for statistical analysis. The difference between the chalk and no chalk, on Climbing time (CT), Front View Geometric Entropy (GE$_{FV}$), Side view (GE$_{SV}$), Front View Line of Motion (LOM$_{FV}$), Side View Line of Motion (LOM$_{SV}$), EMGavg, Hang time (HT), COF, FR was assessed by a paired samples T-test. An alpha of .05 was considered statistically significant (p≤.05).

<center>**Results**</center>

As shown in Table 1, there were no significant differences between groups in height, weight, arm span, training hours, or rock climbing experience. All data are described as mean ± standard deviation.

There was no significant difference in GE between the chalk and no chalk condition. The GE of the climber when filmed perpendicular to the climbing surface (GE_{FV}) was 1.1791 ± 0.7023 with chalk and $1.1675 \pm .6626$ without chalk (p=0.359). The entropy of the climber, when filmed parallel to the climbing surface (GE_{SV}), was 1.2139 ± 0.12824 with chalk and 1.2488 ± 0.14838 without chalk (p=0.44). The LOM from the front view and side view were not significantly different with or without chalk. The LOM for the front view (LOM_{FV}) with chalk was $2.36 \times 10^5 \pm 1.44 \times 10^5$, and $2.34 \times 10^5 \pm 1.44 \times 10^5$ without chalk (p=0.924). The LOM for the side view (LOM_{SV}) with and without chalk, respectively, was $2.21 \times 10^5 \pm 1.36 \times 10^5$ and $1.87 \times 10^5 \pm 1.50 \times 10^5$ (p=0.372).

There was no significant difference in the mean EMG (EMGavg) recorded throughout the climbing and hang. The EMGavg with chalk and without chalk, respectively, was 0.329 ± 0.4483 mV, 0.328 ± 0.4755 mV (p=.968). There was also no significant difference in the maximal COF recorded during the hang, with and without chalk, respectively, 0.3714 ± 0.119, and 0.3852 ± 0.14854 (p=0.748). Finally, no significant difference was found in the ratio of vertical forces on the hands to the feet (FR) with and without chalk, respectively, 0.4482 ± 0.2318 and 0.4738 ± 0.2597 (p=.571).

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There was a significant difference in hang time (HT). The hang time with chalk and without chalk, respectively, was 62.9 ± 36.7 s, and 49.3 ± 25.2 s (p=0.046). See table 2.

Discussion

The purpose of this study was to assess if the use of chalk on the hands affected body position, GE and muscle activity during rock climbing. A second objective was to determine if chalk on the hands affected force during a static hang to failure. Although there were no significant differences in GE, muscle activity, or the forces involved in a static hang, participants could maintain a longer static hang until failure while using chalk.

Rock climbers often attribute the cause of a fall to the inability to maintain contact between the hands and the rock. [13] The climber should be able to maintain contact provided the COF_H is less than the static COF between the hands and rock. Fuss found a static COF on an artificial climbing hold to be 0.958 ± 0.145, and 0.722 ± 0.087 with and without chalk respectively. [22] If the values determined by Fuss et al. are roughly equivalent to the static COF between the holds and the climbing holds used in the present study, then chalk should not have an effect because the COF calculated (0.37-.038) was much lower than the static COF without chalk. Therefore climbers without chalk would not have to change body position or muscular activity to lower the COF_H to prevent slipping from the hold. This may explain why EMG_{avg}, and GE did not change with the use of chalk.

Fuss and Neigl (2009) demonstrated that more experienced rock climbers produce a higher $COF_{H.}$ [23] They do this by redistributing their body weight so that more weight is on their feet and less on their hands. This reduces the normal force of the fingertips and increases the

COF_H. It is advantageous for a rock climber to do this because it reduces the muscular force generated by the finger flexors, and thus attenuates fatigue. If chalk does increase the static COF_H then more experienced rock climbers may benefit from chalk by allowing them to produce a higher COF_H without exceeding the static COF. It is possible that the climbing population in the present study never produced a COF_H high enough to exceed the static COF without chalk, and therefore climbers did not have to change body position or muscular activity to maintain contact with the hold.

It has been proposed that lower GE represents more economical movement. [19] The lower the value of GE, the less "disordered" would be the movement of the participants' COM; and therefore the more efficient the climbing. [19] Watts et al. has shown that changes in GE are related to changes in energy expenditure. [21] Because no significant difference was observed for GE, in either plane, with the use of chalk, it can be inferred that the climber will progress through the route in a similar manner with chalk as they would without chalk. Therefore, the efficiency of movement may not be improved with the use of chalk. Electromyography also did not show any significant differences with the use of chalk. Moreover, CT was not significantly different with the use of chalk. By reducing the contact time with the hold and climbing faster, rock climbers can save muscular energy which may attenuate fatigue. [23] This result combined with the no changes observed in GE, or EMG_{avg} provides some evidence that perhaps the energy expenditure of this climb was not affected by the use of chalk.

Rock climbing generally involves repeated static hangs as the climber rests or searches for the optimal way to progress through the route. To maintain contact during static hangs rock climbers must maintain a COF_H at or below the static COF. To do this requires isometric contractions of the finger flexors, [24] which creates the downward normal force onto the climbing

hold. As the muscle fatigues there is a reduction in the external moments applied to the finger joints. This in turn reduces the normal force of the fingers and moves the COP closer to the joints and away from the wall, this increases the COF_H.[23] Because there was no change in EMG_{avg}, COF_H, or the FR during the static hang it is possible that the cause of the fall may not be attributed to muscle fatigue.

Rock climbers believe that chalk dries the hands of sweat. Contrary to the common opinion among climbers, the addition of moisture actually increases the COF on most surfaces. [18,25–36] However if there is sufficient moisture as to create a lubricating layer between the hand and the surface then the COF is reduced. This indicates that there is an optimal level of moisture to create the highest COF. [28,29,33,34,37] Carrie et al. measured the dielectric constant of skin before and after the application of chalk. These authors found that chalk had no effect on the moisture level of the finger [17]. These authors however did not investigate the use of chalk in the presence of natural perspiration, or the moisture level over time. It is possible that the use of chalk affects the rate of perspiration. In the case of rock climbing, as the climber progresses through the route the addition of moisture through sweat will accumulate. As the climber maintains a static hang the surface of the rock occludes the skin surface. This occlusion prevents the evaporation of moisture from the skin surface and leads to an increase in the moisture level at the interface. [38] To the authors' knowledge the effect of chalk on sweat rate has not been investigated. However moisturizers and skin lubricants such as petrolatum, heavy mineral oil and glycerin, can create lasting increases in the COF of human skin by subsequently reducing the sweat rate. [31] Nacht, Close, Yeung and Gans showed these materials resulted in an initial decrease in the COF of human skin, but as the materials absorbed into the surface of the skin the hydrating effect overcame the diminishing lubricating effect, and a gradual increase in the COF, over baseline,

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was observed. [31] The results of Nacht et al. demonstrated that a change to the sweat rate can affect the static COF of skin and its contacting surface. It is possible that chalk reduces the sweat rate of the fingertips, which in turn attenuates the addition of moisture into the interface of the fingers and climbing hold, and prolongs the hang until failure by increasing the time it takes to build-up a lubricating layer of moisture.

Friction against the skin has been shown to be a major determinant in the prehensile forces during lifting and hold tasks. [39–41] Smith, and Cadoret demonstrated that a reduction in friction is accompanied by a compensatory increase in grip force. [39] In the case of the present study it is possible that the addition of moisture to the interface created a lubricating layer, and reduced the static COF. Due to the prolonged hang and muscle fatigue it may have not been possible to increase the prehensile force causing a fall from the static hang. Another possibility exists that due to the addition of moisture, or muscular fatigue, the participants perceived a fall as imminent and let go of the climbing hold before a measurable change in the COF was observed.

The increase in hang time could also be attributed to a possible psychological benefit. The majority of rock climbers use chalk and generally believe chalk increases the COF. [22] It is impossible to blind participants to chalk. Chalk is a white powder that is clearly visible and therefore participants can easily distinguish between testing variables.

The present study used recreational rock climbers whose ability well exceeded the difficulty of route. The boulder problem was set in such a way to minimize falls, because GE [21] and COF_H [23] have been shown to change with repeated attempts. Therefore attempts were kept at minimum to reduce changes caused by practice or learning. It is possible that the ease of completing the route decreased the effect of chalk. Static hangs are common in rock climbing, as

they allow for resting and route finding. Because the route was relatively easy when compared to the experience of the climber, route finding and rests were minimized. On longer and more difficult climbing terrain, chalk may provide benefits to the climber by increasing hang time which allows the climber more time to rest and route find.

In conclusion, chalk had no significant difference in EMG_{avg}, GE, CT, COF_H or FR. However, these results may be different in more experienced climbing populations. Chalk was shown to significantly increase hang time until failure. This is advantageous to the rock climber because it prolongs rests and allots more time to find the optimal way to progress through the route.

Table 1. Mean ± standard deviation (SD), and significance level (sig) of Height, Weight, Arm Span and Training time

	Chalk first	Chalk second	sig
Height (cm)	174.6 ± 7.1	172.7 ± 6.4	0.32
Weight (kg)	68.7 ± 5.7	65.9 ± 6.9	0.53
Arm span (cm)	176.2 ± 8.1	174.4 ± 7.8	0.38
Training time (hours)	6.8 ± 3.40	5.8 ± 3.50	0.98

Table 2. Mean ± standard deviation (SD), and significance level (sig) of each variable assessed. Climbing time (CT), Front View Geometric Entropy (GE_{FV}), Side view (GE_{SV}), Front View Line of Motion (LOM_{FV}), Side View Line of Motion (LOM_{SV}), Average EMG (EMGavg), Hang time (HT), Coefficient of Friction (COF), Ratio of the vertical forces on the hands to the Feet (FR)

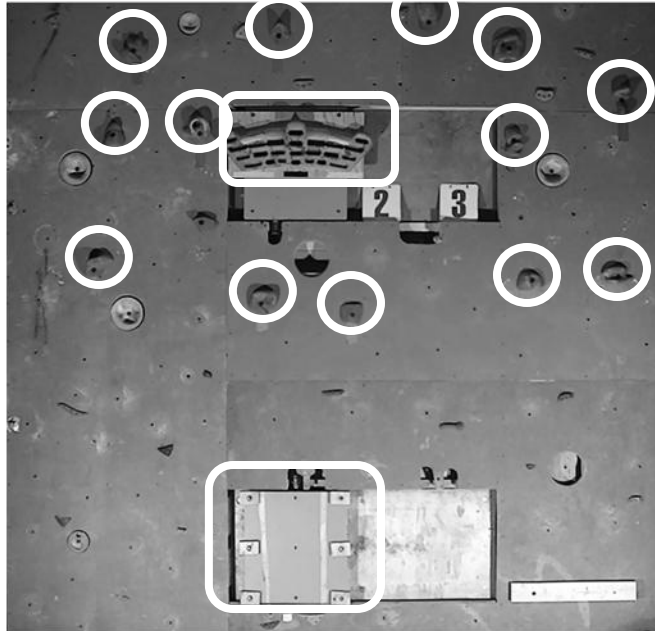|	Chalk	No Chalk	Sig
CT (s)	36.9 ± 7.7	38.6 ± 8.0	0.215
GE_{FV}	1.18 ± 0.70	1.17 ± 0.66	0.359
GE_{SV}	1.21 ± 0.13	1.25 ± 0.148	0.440
LOM_{FV} (cm)	$2.36 \times 10^5 \pm 1.45 \times 10^5$	$2.34 \times 10^5 \pm 1.45 \times 10^5$	0.924
LOM_{SV} (cm)	$2.22 \times 10^5 \pm 1.36 \times 10^5$	$1.87 \times 10^5 \pm 1.50 \times 10^5$	0.372
EMG_{avg} (mV)	0.33 ± 0.45	0.33 ± 0.48	0.968
HT (s)	62.95 ± 36.75	49.30 ± 25.18	0.046
COF	0.37 ± 0.12	0.38 ± 0.15	0.748
FR	0.45 ± 0.23	0.47 ± 0.26	0.57

Figure 1. The indoor climbing structure. The bouldering route is outlined by the circles.

Participants started the route from the lower right holds. They progressed up, then left across the

climbing structure, from there they climbed down and into the center. They then immediately

went to the hang board for the static hang. The static hang was performed on the hang board and

foot holds outlined by the rectangles.

Literature Review

Rock climbers often attribute the cause of a fall as the inability to maintain contact between the hands and the rock. [13] Grip friction is required to prevent slipping off the object, therefore a reduction in friction is a significant problem in rock climbing. [15] Rock climbers employ the use of magnesium carbonate (chalk) to attempt to overcome this problem. Chalk is meant to increase the coefficient of friction between the hands and the rock (COF_H) and presumably dries the hands of sweat. [14–16] Climbers use a chalk bag attached at the waist and dip their hands into the chalk as they progress through the route. Although most climbers use chalk there is little empirical evidence to support its use, and some studies have even shown a reduction in the COF. [15–17]

The COF used in this paper refers to a static COF, and not a kinetic COF unless otherwise stated. The term kinetic COF refers to the COF between moving surfaces, and would only occur when the hands are already sliding on the surface of the rock. Static COF refers to the friction coefficient between non-moving surfaces and is therefore essential to maintain contact between the hands and the rock. [15] As the applied force increases the COF will increase up until a maximum point where motion occurs. The static COF is higher than the kinetic COF, as evidenced by the fact that it is generally easier to maintain the motion of a sliding object than it is to start motion in the first place. The general model for COF is the ratio of the forces tangential to the surface divided by the forces perpendicular to the surface.

Fuss and Niegl created a biomechanical model to analyze the COF in climbing. [15] These authors defined Static COF as the ratio of the horizontal forces (FH) to the normal force (FN) between two static surfaces COF=FH/FN. This situation refers to horizontal grip surfaces. By

defining COF in this manner, the COF changes with the normal force applied and is independent of the point of slippage. The sum of the vertical forces in rock climbing is equal to the body weight of the climber (BW) plus any addition vertical forces (FV) imparted by musculature on hands and feet. (FN = BW + FV) Since there are multiple surfaces in contact with the rock, various hands and feet, the sum of all the vertical forces is equal to bodyweight. FH is the horizontal frictional force. Using the hands as the point of reference and summing the moments around the center of mass, the frictional force on the hands is equal to BW times the horizontal distance between the rock wall and the center of mass (d) and divided by the vertical distance between the hand and the feet (D)

FH = BW*d/D. (Eq. 1)

Therefore the COF at the hands (COFH) can be calculated by

COFH = (BW*d)/(D*FNH) (eq. 2),

Where FNH is the normal force at the hands. [15]

Factors affecting the COF

The COF is affected by many variables. Chalk, moisture on the skin, roughness of the hold and skin, skin contact area, and body position can all affect the COF. [23] In rock climbing the climber will be able to maintain contact with the rock as long as the outward applied force does not exceed the product of the normal force and the COF. Climbers however do not intend on reaching this point. [23]

Chalk

There are limited studies that have attempted to examine the effect of chalk on the Static

COF in climbing. The first study to attempt to measure the Static COF in climbing was by Li,

Margetts and Fowler. [16] In this experiment subjects were seated with elbows bent at 90 degrees

and their fingertips in contact with a rock surface. The rock surface was pulled away from the

subject at a force of 29 N. The subjects were asked to apply sufficient fingertip force in order to

prevent the rock surface from sliding. Subjects then gradually reduced the fingertip force until

slippage occurred. Strain gauges measured the normal force. Three rock surfaces where used

(sandstone, granite and Slate) along with two moisture conditions (wet hand and dry hand) and

two coating conditions (chalk and no chalk). This study found that chalk actually decreased the

static COF. The authors contributed this finding to the build-up of a granular layer of chalk, the

particles then 'roll' creating a slippery surface. Therefore the author concluded that rock climbers

should avoid the use of chalk during climbing, and use alternative methods for drying hands. [16]

This study however reported very high static COF. The static COF measured in this study is 2.5-

3, the equivalent of freely hanging from a surface at an incline greater than 68°, thus unlikely to

actually exist. [14,15,22] Furthermore the 29 N used in this study was very small in comparison to

the forces seen in rock climbing, which can be up to the body weight of the climber. [14] Increasing

the forces will deform the surface of the skin leading to a larger microscopic contact area

between the skin and surface of the rock. [42]

Carrè, Tomlinson, Collins and Lewis [17] conducted a similar experiment to Li et al. Using

a bespoke friction rig, the subject pressed their middle finger onto two surfaces a polished steel

and sandstone surface with a force of 10-15N. The subject then slowly moved the fingers linearly

away from a load cell. The tangential and normal forces were recorded. Carrè et al. found that on

the polished steel surface, a dry finger on a dry surface produced a lower kinetic COF than the

finger without chalk. Carrè did however find that when the moisture was added to the finger or surface, Chalk improved the kinetic COF. [17] This is thought to occur because in dry conditions the chalk creates a separation of finger and the surface, acting like a solid lubricant. The experimental set-up used by Carrè however measured the coefficient of kinetic friction because the finger slid across the surface. As noted above this would only affect a climber if their hands were already sliding across the surface of the rock. Carrè did however find that on the sandstone surface the dry, chalk free finger had a decreased kinetic COF, the author concluded that this was due to the lubricating properties of the sandstone particles. [17]

Yet another study by Fuss et al. used an artificial climbing hold, under conditions of dry hand, wet hand, hand covered with powder chalk, hand covered with liquid chalk, dry hand on a surface covered with liquid chalk, and hand covered with powder chalk on a messy surface. The fingers provided the normal force and a tangential force was applied until slippage occurred. Fuss found that powder chalk is significantly better than the dry hand condition, on a clean hold. However, if the hold is covered with chalk, then powder chalk actually reduces the static COF. [22] This result contradicts the study Li, Margretts, and Fowler, [16] and supports the common opinion among climbers.

Amca, Vigouroux, Aritan and Berton attempted to measure the static COF using a hang board with limestone and sandstone rocks mounted to it. [14] These rocks were attached so that the rock surface was perpendicular to the board. As the subjects hung from the holds the inclination of the hang board was manipulated until the subjects slipped from the hang board. The static COF was then calculated with the angle of the hang board and the point of slippage. Amca found that chalk improved the static COF by 18.7% and 21.6% for limestone and sandstone respectively. [14] This study better represented the forces seen in actual rock climbing, where the

normal force can be equivalent to body weight. Because the skin is a viscoelastic material the normal applied skin changes the contact area and thus changes the static COF. [43]

Moisture

The effect of moisture on the static and kinetic COF of human skin is well documented, contrary to climber's beliefs, moisture increases the Static COF of skin. [18,25–36] Reducing the moisture of skin decreases the compliance of the skin thereby reducing the static COF. [18] Sivamani et al. also concluded that the drying effect of Isopropyl Alcohol, a common component in 'liquid chalk', decreased static COF. [33] The adhesion component of friction shows that hydration of the skin affects the COF because the addition of liquid creates liquid bridges between the ridges of the skin and the surface. These bridges reduce the static COF by creating shear forces. [35] In addition, increasing the skin hydration decreases the stiffness of the skin due to its plasticity, which increases the contact area of skin. [36,44]

Andre, Lefevre and Thonnard conducted an experiment to examine the effects of varying degrees of skin moisture. [25] They concluded that and low levels of skin moisture the static COF was low, and as the moisture increased so did the static COF until it reached a maximum point where the static COF then decreased as moisture continued to increase. These results along with others indicate that there is an optimal level of moisture to create the highest COF. [28,29,33,34,37] In addition to there being an optimal level of moisture, the effects of moisture lasted for only minutes, until the additional moisture evaporated and skin returned to its normal state. [32]

Moisturizers and skin lubricants such as petrolatum, heavy mineral oil and glycerin, can create lasting increases in the COF on human skin by subsequently reducing the rate of transepidermal moisture loss. [31] Nacht, Close, Yeung and Gans showed these materials resulted

in an initial decrease in the kinetic COF of human skin, but as the materials absorbed into the surface of the skin the hydrating effect overcame the diminishing lubricating effect, and a gradual increase in the kinetic COF, over baseline, was observed. [31] While the hydrating effects of water last only 10-15 minutes, these products increased the kinetic COF for up to and beyond 6 hours. [31]

Li et al, and Fuss found that the addition of water to the skin hold interface had no effect on the static COF. [16,17,22] Although these studies did not monitor changes in amount of moisture throughout the test, as the applied fingertip force increased the hands sweat more thus more moisture would be present as the test went on. [17] In addition Amca et al. showed that ambient temperature and humidity had no effect on the static COF. [14] This study however did use a limited range of temperatures (11.9-28.0° C), and was also conducted outdoors so temperature and humidity could not be properly controlled. [14]

Relative humidity can affect the COF of human skin. [44] The COF increases with a factor of 2 if the ambient conditions change from relatively dry (30% humidity) to a relatively humid climate (90% humidity). [44]. This change can be attributed to several possible mechanisms. As the humidity increases the Young's modulus of skin greatly decreases, because of this the elasticity of skin increases, which leads to a greater microscopic contact area between the rock and the hands. [44] Swelling of the stratum corneum, the outermost layer of the skin, creates a smoothing effect which increases the microscopic contact area of the skin. [43,44] An addition, the ambient temperature and humidity may also increase the friction due to the condensation of water on the surface, by the environment. [44]

Carré et al. attempted to better control the moisture levels in his experiment.[17] Carré et al. measured the dielectric constant of the skin before and after the application of chalk. Carré found that chalk did not affect the moisture level of the finger, and therefore chalk does not 'dry' the hands as rock climbers presume it does. [17] Carré did however find a significant change in the kinetic COF when water was added to the interface of the hands and the polished steel surface. When both the surface and the finger were dry chalk was found to decrease the kinetic COF, when water was added to the system the kinetic COF increased. [17] It was hypothesized that dry chalk acts as a solid lubricant increasing the distance between the fingers and the surface, but when moisture is added the chalk and water combine to produce a viscous solution that when sheared increases the COF through the adhesion theory. [17]

Surface roughness

In general the static COF between a hand and a hard surface decreases with increasing surface roughness, except in cases of very rough surfaces, where the surface roughness increases the COF. [44] This occurs because increasing the surface roughness increases the distance between the surface and its ridges, this allows fewer liquid bridges to form, and decreases the real microscopic contact area of the skin. [35,43] Derler, Huber, Fuez and Hadad investigated the kinetic COF of wet foot skin on the microscopic surface properties. They found that two components of friction: adhesion and deformation were found to increase with the surface roughness [43]. There is a strong dependence of friction on rock type. [45] Amca et al found that sandstone had a higher static COF than Limestone. The authors concluded that this was due to a rougher surface than limestone. [14] Li et al also found that sandstone produced a higher COF than slate or granite. [16] Fuss et al found that sandpaper produced a higher static COF than an artificial rock climbing

hold. [22] More research is needed to investigate the static COF on different rock types and different surfaces encountered during rock climbing.

The surface roughness of skin can also affect the static COF. [18] Manuskiatti, Schwindt, and Maibach showed that skin roughness differed between age groups and anatomical site. [46] Cua, Wilhelm and Mailbach showed that the static COF differs with respect to anatomical site. [47,48] These authors contributed this finding to changes in skin hydration, non-apparent sweating and sebum secretions, [47,48] although Manuskiatti et al. found no correlation to skin roughness and stratum corneum hydration. [46] Although there are no studies showing differences in the skin roughness of the finger-pads between subjects, results on other anatomical sites provide some evidence that skin roughness may affect the static COF between the hands and rock while climbing.

Skin contact area

Between most surfaces the contact area of a material is independent of the COF, however because skin is a viscoelastic heterogeneous material, it does not follow Amonton's law, this means the frictional force is dependent on contact area, and sliding velocity. [35] Increasing the pressure increases the deformation of the skin and creates a larger microscopic contact area of the skin and asperities of the rock surface. [43] Tang, Ge, Zhu, Cao, and Li attributed the COF increasing with a higher contact pressure to the penetration and ploughing of surface asperities into the skin [42]. Derler, Gerhardt, Lenz, Bertaux and Hadad however observed no damage to the skin or any visible modifications of the skin surface after more than 550 friction measurements. [43]This information lead the authors to conclude that the skin deformation plays a much larger role in friction than ploughing or abrasion of the skin. [43] Deformation of the skin however is not

as significant as the adhesion component of friction. [43]

Body position

When looking at the effects of body position on the COF_H, the COF is independent of the point of slippage and therefore is calculated as the ratio of tangential force to the normal force. As long as the climber maintains a COF_H less than the static COF the climber should maintain contact with the rock. Using the equation 2 from above $COF_H = (BW*d)/(D*FNH)$, it can be seen that the distance from the center of mass to the wall surface and the distance between the hand and feet both play a role in the COF in rock climbing. Using this equation Fuss and Niegl [15] drew the following conclusions:

1.   As the COM moves closer to the wall the greater the percentage of body weight may be placed on to the feet without affecting the COF_H.

2.   As the feet move closer to the hands, a larger percentage of body weight must be placed on the hands to maintain the COF_H.

3.   For certain instances it is important that the climber decrease the COF_H as not to slip off smoother holds with a lower static COF, in this case the climber can unload the feet and place a greater percentage of body weight onto the hands, or move the COM closer to wall. [15]

Therefore as the climber shifts the weight from the hands to the feet, the COF_H increases. In many cases it is beneficial for the climber to impart a higher COF, by decreasing the fingertip force, as this force in lessened (FNH) muscle energy can be spared and fatigue may be attenuated. [23]

Fuss and Neigl used an instrumented climbing hold, to measure the force acting on the hold during the 2002 Climbing World Cup in Singapore. They concluded that the better climbers have a higher COF, closer to the point of slippage. [23] Using the same instrumented climbing hold, Fuss and Neigl completed a training and found that the more familiar a climber is with the route the higher the COF. [23] The more trials the climber completed the shorter the contact time, the smaller mean and peak forces, and smaller the impulse. The short contact time in combination with the smaller normal force imparted by the hands, increases the COF and may lead to fatigue attenuation. [23]

In conclusion, fiction is an essential factor in rock climbing. Rock climbers must maintain a COF_H below the static COF in order to maintain conduct with the hold. The available evidence suggests that many factors affect the static COF and the COF_H between the hands and the rock including: chalk, moisture, surface roughness, skin contact area, and body position. Although somewhat controversial, scientific evidence seems to suggest that rock climbers should employ the use of chalk on clean, chalk free surfaces. They should remove excess moisture from their hands, but should not use any agents that excessively dry their hands such as isopropyl alcohol. In general rock type and skin roughness may affect the static COF although more information is needed before further conclusions can be made. Lastly, to attenuate fatigue, rock climbers should move their COM close to the climbing surface, which allows them to reduce the amount of body weight placed on the hands. However on smoother holds, with a lower static COF, the climber must place a greater percentage of body weight onto the hands to reduce the COF_H below the static COF.

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