On the Measurement of the Coefficient of Friction of Walking Surfaces

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ABSTRACT

Tribometers, or slip meters, are devices used to measure the Coefficient of Friction (COF) between a walking surfaces and a standard material (Neolite). These measurements are being used to determine whether or not the tested surface is slip resistance that presents minimum risk for users. All tribometers have a "foot" (pad), made of standard material, which make the contact with the examined surface. Commercial tribometers are different from each other in many ways: different size and shape feet, different contact pressure between the foot and the surface and groove or non-grooved feet. The purpose of this study is to determine whether or not these differences affecting the reading of the Coefficient of Friction.

I. INTRODUCTION

The need for accurate and repeatable measurement of walking surfaces' COF is rooted in the large expenses associated with Slip and Fall accidents. These accidents are the leading cause of workers' compensation and claims and medical costs associated with them is approximately $70 billion annually [1]. A report by The Bureau of Labor Statistics [2] states "Together, falls, slips, or trips accounted for 35 percent of the injuries and illnesses to heavy and tractor-trailer truck drivers in 2014." In [3] it is reported "'falls on the same level is the second highest category of compensable loss and cost $6.7 billion, according to the 2006 Liberty Mutual Workplace Safety Index. There are numerous reports on the subject but one that demonstrate the severity of this problem is given in a report of a study performed by the National Floor Safety Institute (NFSI) that found that more than 3 million food service employees and over 1 million guests are injured annually as a result of restaurant Slips and Falls accidents. These injuries are increasing at a rate of about 10% annually [4]

The importance of COF measurements is reflected by the numerous of standards, safety codes, technical reports, brochures and technical papers published in the last 50 years. Topics such as: measurement methods and devices, performance of different tribometers, measurement of COF of different materials, shoe's sole design, the effect of contamination on COF, floor treatment, Slip and Fall biomechanics and others were covered in many publications. Some references will be given in the following as related to the discussed topic.

The slipperiness of a surface depends on many factors including: material, presence of moisture or contaminants, slope and cross slope, surface texture, wear, surface finish and the all affecting the Coefficient of Friction (COF) between the sliding surfaces. Therefore, the measurement of COF, which is the dominant factor effecting slipperiness, is commonly used to qualify a walking surface as a safe one.

The COF is defined by the ratio of the shear force that acts tangent to the contact surfaces and the normal force between the two bodies. Thus, in order to find out the value of the COF both forces have to be measured while the bodies are impending motion for the Static COF or in motion for Dynamic COF. In cases of Slip and Fall accidents the static COF is of interest since it represents the maximum available friction. Once slip occurs, the value of the COF assumes its dynamic value which is lower than the static one. Thus, the static COF represents a threshold between slipping and non-slipping conditions.

In order to determine the value of the COF, both the shear and the normal forces have to be measured. A simple test, called "pull test", by which the coefficient of friction force (COF), on any surface, can measured, shown in Figure 1. A foot, made of the material being tested is attached to block of weight W. The block is placed on a horizontal surface being tested, and a pulling force, F, is applied to the block. The pulling force increased to the point that block starts to move (impending motion). At that point the friction force assumes its maximum value and the Static COF is given by the ratio the maximum pulling force and the normal, which in this simple case equals to the weight W. Once the weight is in motion the value of the pulling force drops and this value can be used to determine the dynamic coefficient of friction (DCOF). Thus, the static COF is given by:

$$\mu_s = \frac{F_{max}}{N} \quad (1)$$

This, relationship, was established by C. A. Coulomb in 1781 who extensively study dry friction occurring between the contacting surfaces in the absence of a lubricating fluid. This principle is used, directly or indirectly by all tribometers.

When it comes down to the actual contact between the surfaces, commercial tribometers differ one from the other by the size and shape of the foot being use as well as the normal force applied during the test. A partial list of commercial tribometers is given in Table 1 [5, 6].

Table 1: Details on some commercial tribometers.

Device	Foot Shape	Foot contact area[mm^2]	Load [N]	Pressure [kPa]
50# Hand pull ASTM C-1028	76mm Square	5776	222.4	38.5
BOT-3000	9mm diameter circle	63.617	N/A	-
English XL	33mm diameter circle	855.2	N/A	-
Brungraber Mark II	76 mm Square	5776	44.482	7.701
Brungraber Mark IIB	76 cm Square (grooved)	4645	44.482	9.576
Sigler pendulum	38mcm square	1444	N/A	-
HPS	N/A	380	2.7	71
PAST	N/A	5800	9	9
PFT	N/A	280	112	400
AFPV	N/A	1600	360	225
Tortus	N/A	60	02	30
PSC 2000	N/A	250	24	100
GMG 100	N/A	1170	93	80
Shuster	N/A	2600	40	15
BPST	N/A	220	22	100
VIT	N/A	790	37	47
PSM	N/A	500	200	400

Eq. 1 and the details in Table 1, raises few questions:

1) Is there a need for a minimum contact force, or pressure, in order to insure a "good" contact between the surfaces so that the mrasurements will yield reliable value for the COF?
2) Is there a minimum contact area between the surfaces which will insure a correct reading of the COF?
3) Is the shape of the contact area affecting the value of the COF?
4) Is a pattern engraved on the foot, such as the grooves in shoe's sole, affecting the measured value of the COF?

A limited set of experiments were conducted in attempt to answer the above questions. Although ASTM C-108 standard was withdrawn, it was used in performing these experiments since the reason for the withdrawal is not due to technical deficiencies but "**This standard is being withdrawn without replacement due to its limited use by industry".** All measurement was taken using TCNA standard tile that was tested in an official ASTM interlaboratory Study.

II. THE EFFECT OF GROOVED FOOT ON THE VALUE OF THE COF

All research related to the effect of patterns engraved into the foot material, such grooves, are related to tracking capabilities of shoe's sole. In [7, 8] tests were performed with pads that had grooves in 0º, 45º and 90º to the direction of the test.

It was concluded that "For groove directions, the difference between 0º and 45º was not statistically significant. The COF values of these two conditions were, however, significantly higher than that of the 90º condition". In [9, 10] the effect of grooves perpendicular to test direction, on the COF where the surface is contaminated. It was concluded that "Tread groove depth is a significant factor affecting the COF at the footwear–floor interface on wet and water–detergent-contaminated floors tested in this study. It was found that the averaged COF gain per tread groove depth increase in millimeters, on either a wet or water–detergent covered floor, ranged from 0.018 to 0.108, depending on the tread groove width, floor, and contaminant".

From COF measurements point of view the concern is that the use of patterned foot will bias the results. Currently there is one commercial tribometer which uses grooved foot [6]. In [11] two tribometers, Brungraber Mark II and Mark III, were compared. Four different pads were used: 3 flat pad (3" by 3") made of PVC, Neolite and Nitrile, and one grooved pad (15 evenly spaced grooves, 1 mm width and 3 mm deep, perpendicular to the test direction) made of Neolite. "A comparison between the flat and grooved Neolite footwear pads shows that the grooved pad had significantly ($p<0.05$) higher COF readings on the wet surface conditions than those of the flat one on all floors". Also, "On glycerol-contaminated condition, grooved Neolite footwear pad had also significantly ($p<0.05$) higher COF reading than that of the flat Neolite pad. But this difference occurred mainly on the quarry tile."

A series of pull tests according to ASTM C-1028 using TCNA standard tile in dry conditions were performed to further determine the effect of grooved pad on the COF. Three tests were performed using Neolite pads: 1) 3" by 3" square pad with no grooves; 2) 3" by 3" square pad with 6 1/16" wide and 1/16" deep grooves parallel to the pull direction and; 3) 3" by 3" square pad with 6 1/16" wide and 1/16" deep grooves perpendicular to the pull direction. Each test consisted of 40 pulls 10 in each direction along the axes of the tile. The results of these tests are given in Table 2.

Table 2: Tests' results.

	No Grooves	Parallel Grooves	Perpendicular Grooves
Mean	0.382	0.522	0.570
Variance	0.001826	0.002568	0.003208

The results shown in Table 1 clearly show that the grooved pads affecting the COF reading resulting substantially higher value than in the flat pad case. Also, t-Test verified that there statistically difference between the effects of the parallel and the perpendicular grooves on the COF (t_{stat}=4.05, $t_{critical}$=1.99 and P=0.00012).

In another set of tests the COF of 8 different tiles was measured in the same way using a flat and a grooved (parallel to the pull direction) Neolite pads. Each test consisted on 10 pulls along a single direction of the tile. The results are shown in Table 3.

Table 3: Tests' results for 8 different tiles.

Tile	Pad	Mean	Variance
Porclain (Polished)	Flat	0.548	0.000208
	Grooved	0.818	0.004483
Porcelain (Rough)	Flat	0.654	0.000361
	Grooved	0.813	0.000978
Ceramics - I	Flat	0.447	0.000362
	Grooved	0.628	0.000272
Vinyl	Flat	0.725	0.000245
	Grooved	0.994	0.002110
Granite	Flat	0.615	0.001703
	Grooved	0.914	0.007382
Ceramics (Textured)	Flat	0.461	0.000072
	Grooved	0.893	0.000426
Ceramics - II	Flat	0.405	0.000072
	Grooved	0.607	0.000109
TCNA tile	Flat	0.382	0.001826
	Grooved	0.522	0.002568

The same results are shown in Figure 2 which indicates that the COF's values obtained using the grooved pad are higher, in all cases, compared with the corresponding results obtained with the flat pad.

III. THE EFFECT OF FOOT CONTACT AREA ON THE VALUE OF THE COF

A series of pull tests in which two square Neolite pads of $3in^2$ and $9in^2$ were performed on TCNA standard tile according to ASTM C-1028. 10 pulls were performed in dry conditions along the same direction with each pad. The contact pressure on the pads was approximately 28[kPa] with deviation of 0.909[kPa] (0.1[psi]. The tests' and the statistical analysis results are given in Table 4. As shown, the results of the t-Test indicate that within 95% confidence level there is no difference between the COFs. Meaning that the contact area does not affect the value of the COF.

Table 4: Tests' results for different contact areas.

	Contact area [in^2]	
	9	3
Contact Pressure [kPa]	28.828	27.918
Mean	0.386	0.387
Variance	0.000106	0.000186
F	0.568	
$F_{Critical}$	0.314	
T	0.123	
$T_{Critical}$	2.100	

In a different experiment two circular Neolite pads were used. This time the contact pressure varied and the coefficient of friction was determined in two ways: 1) The mean of the COF for each pressure (see Table 5); and 2) By linear regression as shown in Figure 3.

Table 5: Tests' results with circular pads

D=1.833[in]			D=1.401[in]		
Normal [lb]	Pull [lb]	COF	Normal [lb]	Pull [lb]	COF
2.538	2.100	0.462	3.400	1.700	0.500
5.006	3.400	0.485	5.869	2.600	0.443
6.506	4.200	0.493	7.369	3.500	0.475
8.975	4.700	0.428	9.838	4.700	0.478
11.981	5.600	0.467	12.838	5.300	0.413
Mean		0.467			0.461
Variance		0.00064			0.001159

Table 6: Tests' results with circular pads

Diameter [in]	1.833	1.405
Contact area[sqin]	2.638	1.55
COF	0.467	0.462
Variance	0.00064	0.001159
F	0.552	
$F_{Critical}$	0.156	
T	0.286	
$T_{Critical}$	2.364	
COF (linear regression)	0.4622	0.4452

IV. THE EFFECT OF LOAD (CONTACT PRESSURE) ON THE VALUE OF THE COF

As shown in Table 1, the difference in contact pressure vary by two order of magnitude, from 7.7 kPa to 400kPa. The simple Coulomb friction law, expressed in Eq. 1, does not specify the necessary contact pressure to insure a reliable estimation of the COF.

A set of experiments, using a 3 inch square Neolite pad and the same TCNA tile, with different pressures was performed. Each experiment consisted on 20 pulls, 10 in one direction and 10 in the opposite direction. The results are summarized in Table 7.

Table 7: COF for different pressures.

Pressure [kPa]	P_1 7.292	P_2 16.413	P_3 27.918	P_4 46.678	P_5 59.864
COF	0.337	0.349	0.383	0.373	0.382
Variance	0.000298	0.000209	0.000225	0.000522	0.000862

A single factor ANOVA test that covers the data obtained in all 5 experiments indicated that the mean value of the COF of these experiments are not the same (F=19.928 and $F_{Critical}$=2.467). Meaning that the contact pressure between the surfaces does effect the value of the COF. The results are also shown in Figure 4.

A single factor ANOVA test that covers the data for the three highest contact pressures (encircled in Figure 4, indicated that their mean values of the COF are the same, meaning that the data for these three cases belong to the same population (F=1.092 and $F_{Critical}$=3.158). It is obvious from Figure 4 that the COF value corresponds to the lowest contact pressure does not belong to the population. A single factor ANOVA test that covers the data for the three highest contact pressures and the lowest one eventually proved it (F=19.148 and $F_{Critical}$=2.724). No convincing explanation were determined for the COF value found for the contact pressure P_2. In any case, a single factor ANOVA test for the data of the lowest two pressures indicates that they are not of the same population (F=5.135 and $F_{Critical}$=4.098), as well with the three higher pressures (F=11.014 and $F_{Critical}$=2.724).

V. THE EFFECT FOOT SHAPE ON THE READING OF THE COF

The commercial tribometers, shown in table 1, use either square or circular pads. A set of pull tests, using the same TCNA tile, were performed using a square and a circular pads both have the same area of one square inch and made of Neolite. For each pad 20 pull tests were performed 10 in one direction (North) and the other in the opposite direction (South). The results are given in Table 8.

F-test indicate that the variances are the same (F=1.1440 and $F_{Critical(one\ tail)}$=2.1554). As expected, a corresponding t-Test indicated that the means are not the same (belong to different population with 95% confidence interval t_{Stat}=7.678 and $t_{Critical\ (two\ tails)}$=2.024). In simple words the mean value of the COF for the square pad is different from the one for the circular pad. Thus, it can be concluded that the shape of the pad does affect the reading of the COF. The same data was analyzed where the pull direction was considered (Circular North v. Square North etc.) statistics analysis results are summarized in Table 9. Again, the results indicate that the foot's shape affecting the COF reading.

Table 8: Tests' results.

Direction	Foot's Shape	
	Square	Circle
North	0.259	0.345
	0.287	0.354
	0.278	0.335
	0.297	0.345
	0.306	0.345
	0.306	0.354
	0.268	0.354
	0.287	0.354
	0.268	0.335
	0.297	0.354
South	0.268	0.297
	0.268	0.278
	0.287	0.306
	0.278	0.325
	0.268	0.316
	0.249	0.345
	0.259	0.345
	0.287	0.335
	0.326	0.364
	0.326	0.373
Mean	0.283	0.338
Variance	0.000457	0.000551

Table 9: Statistical analysis results.

Direction	North		South	
Shape	Square	Circle	Square	Circle
Mean	0.285	0.281	0.348	0.328
Variance	0.000281	0.000676	0.0000621	0.000897
F	4.526		1.326	
$F_{Critical}$	3.178		3.178	
T_{stat}	10.612		3.735	
$T_{Critical}$	2.160		2.101	

VI. CONCLUSIONS

From the results presented above the following conclusions can be drawn:

1) Grooves on the tribometer's foot do affect the COF reading by almost 50%.
2) It appears that the contact area between the tribometer's foot and the tested surface does not affection the reading of the COF.
3) A minimum contact pressure between the tribometer's foot and the tested are is required. Given the limited results, the value of the minimum pressure cannot be definitely determined. However, contact pressure of 25kPa - 30kPa appears to be adequate.
4) The shape of the foot is effecting the reading of the COF but the results obtained by the limited number of test show a difference of 19.4% (when pull direction is egnored).

One has to bear in mind that the above conclusions were derived from a very limited number of experiments. Additional experiments, preferred in lab environment, are needed for better understanding the effect of the above parameters.

All this issues can be solved if a reference surface can be produced with very high repeatability resulting the same COF. Thus, it will be expected that all tribometers will measure the same value of COF, eliminated the confusion discussed above.

VII. REFERENCES

[1] National Floor Safety Institute, https://nfsi.org/

[2] BLS News Letter USDL 15-2205, November 19, 2015

[3] Liberty Mutual Research Institute for Safety, Vol. 10, No. 3,

[4] Slips and Falls Study: Objective Auditing Techniques to Control Slips and Falls in Restaurants, CNA June 2007. Autumn 2007.

[5] Wen-Ruey Chang, et. al., "The role of friction in the measurement of slipperiness, Part 2: Survey of friction measurement devices", Ergonomics, Vol. 44, Issue 13, 2001.

[6] Mark IIIB Slip meter Certification tests http://w w.slip-test.com/Slip-Test_MarkIIIB_F2508_Certification.pdf

[7] Kai Way Li, Chin Jung Chen, "Effects of tread groove orientation and width of the footwear pads on measured friction coefficients", Safety Science, Vol 43, 2005.

[8] Li Kai Way, CHEN Chin Jung, LIN Ching-Hua, HSU Yao Wen, "Relationship Between Measured Friction Coefficients and Two Tread Groove Design Parameters for Footwear Pads*", TINGHUA SCIENCE AND TECHNOLOGY ISSN 1007-0214 11/15 pp712-719 Volume 11, Number 6, December 2006.

[9] Kai Way Lia, Horng Huei Wub, Yu-Chang Linb, "The effect of shoe sole tread groove depth on the friction coefficient with different tread groove widths, floors and contaminants", Applied Ergonomics 37 (2006) 743–748

[10] Kai Way Li, Chin Jung Chen, "The effect of shoe soling tread groove width on the coefficient of friction with different sole materials, floors, and contaminants", Applied Ergonomics 35 (2004) 499–507

[11] Kai Way Li*, Jing Hui Horng, "A Comparison of Friction Measurement Results Using Two Slipmeters", Proc. 2009 IEEE IEEM, pp. 2159-2163

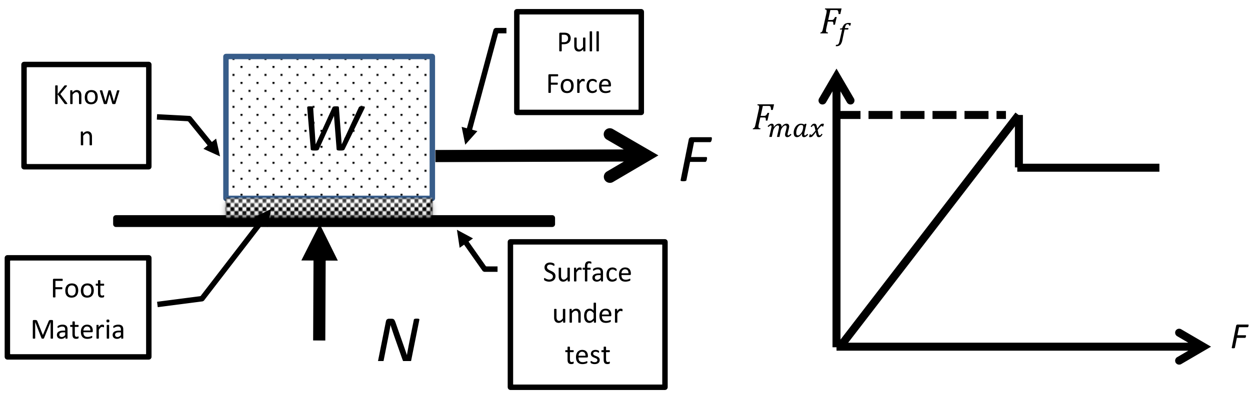


Figure 1: Pull test.

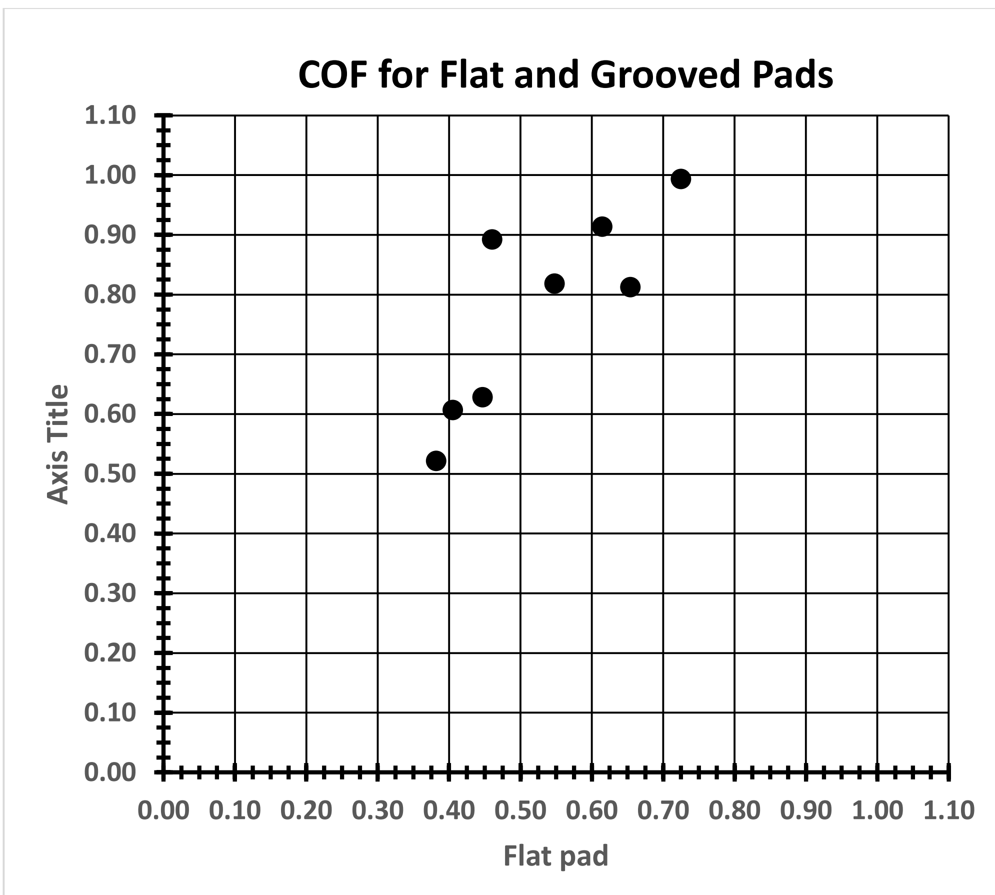
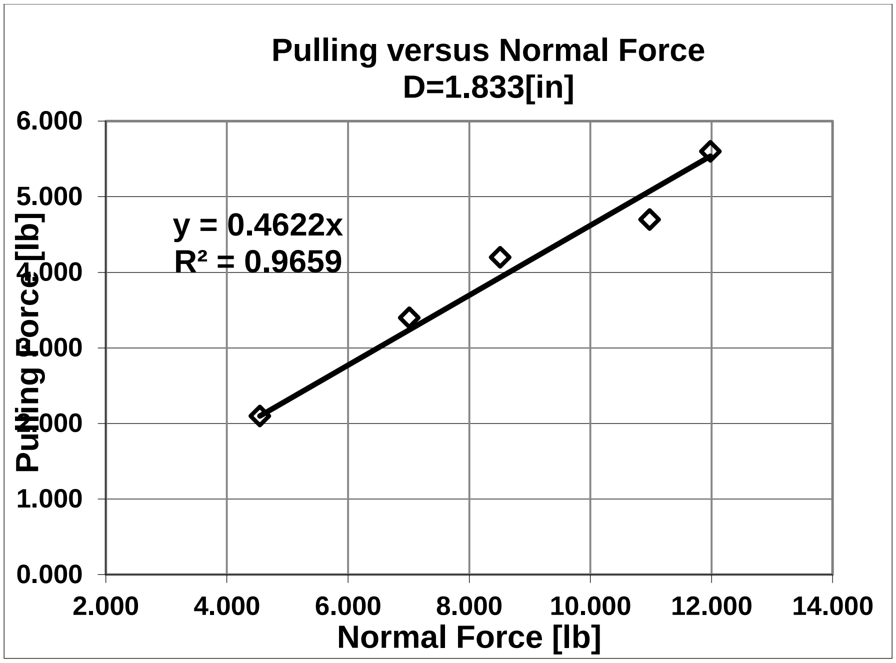


Figure 2: COFs values of flat versus grooved pads.



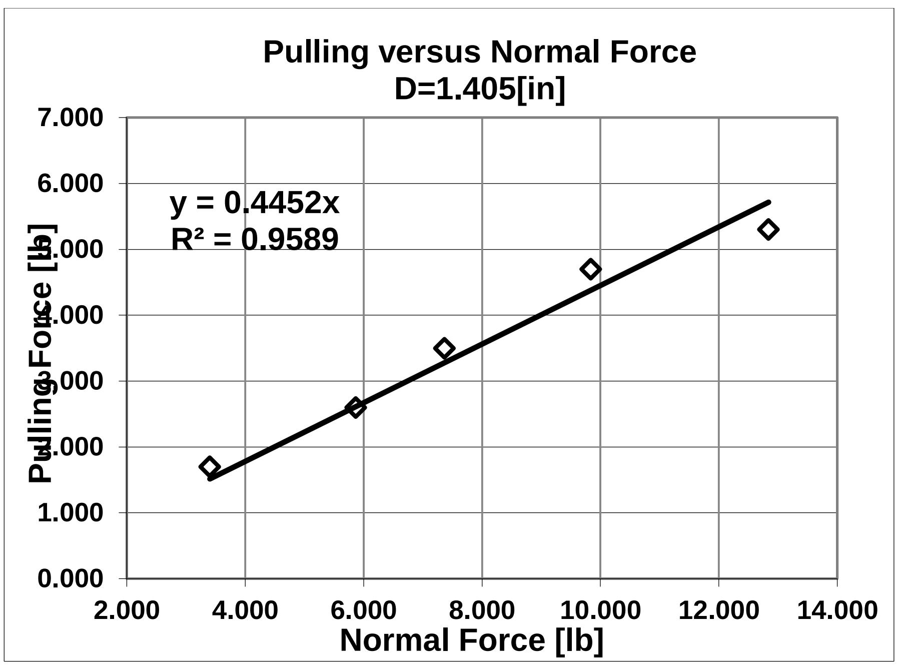


Figure 3: COF by linear regression.

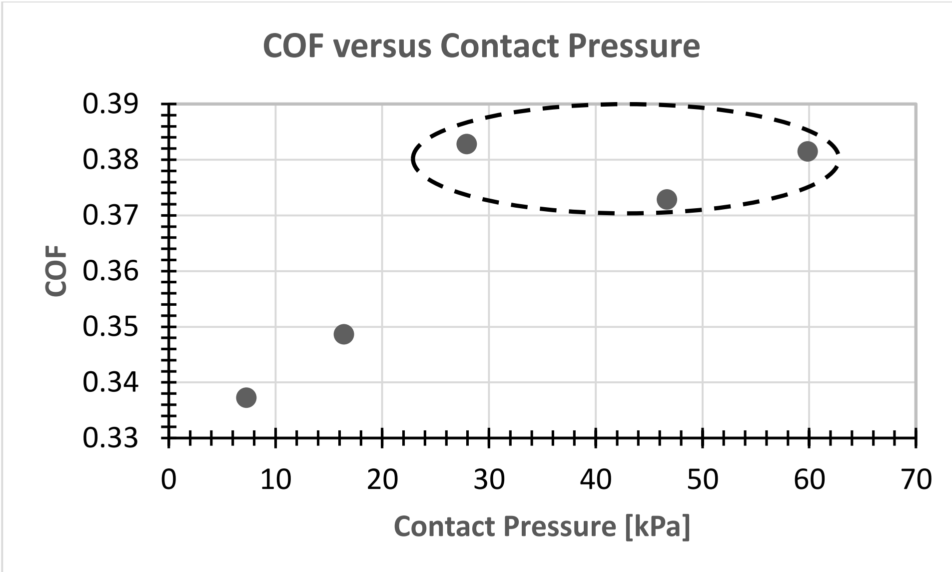


Figure 4: COF values for different contact pressures.