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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 sample of walking surface, like a tile, 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.**

***Keywords*— Friction Measurement; Omponent; Tribometer, Slip-Meter, Coefficient Of Friction, Slip And Fall**

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 claims and medical costs, which amounts to 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 reported 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 also reflected by the numerous of standards, safety codes, technical reports, brochures and technical papers published in the last 25 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 others. 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 in contact. Thus, in order to find out the value of the COF both forces have to be measured while the bodies are in 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.

A simple test, called "pull test", by which the coefficient of friction force (COF), on any surface, can measured, is shown in Fig. 1. A foot, made of a standard material usually Neolite, is attached to the bottom of a block of weight *W*. The block is placed on the horizontal surface being tested, and a pulling force, *F*, is applied to the block. At any time the magnitude of the pulling force is equal to the friction force acting between the block and the surface. The pulling force is increasing to the point that block starts to move (impending motion). At that instant the friction force assumes its maximum value and the Static COF is given by the ratio the maximum pulling force and the normal force, which in this simple case it is equal to the weight *W*. Once the weight is in motion the value of the pulling force drops and its value can be used to determine the dynamic coefficient of friction (DCOF). The, the static COF is given by:

$$\mu_s = \frac{F_{max}}{N} \tag{1}$$

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

Equation (1) does not specifies any parameters needed to be satisfied while performing the test. These includes: minimum contact pressure, contact area, contact surface shape and foot surface pattern (e.g. grooves. As a result, commercial tribometers differ one from the other in respect to these parameters as shown in the partial list given in Table 1 [5, 6].

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Published test results, performed by tribometers' manufacturers, and results from a limited set of experiments will be used in the following to examine the effect of the above parameters on the measurements of the COF. Although ASTM C-1028-96 standard was withdrawn, it was used in performing the additional 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 were taken using TCNA standard tile that was tested in an official ASTM interlaboratory Study.

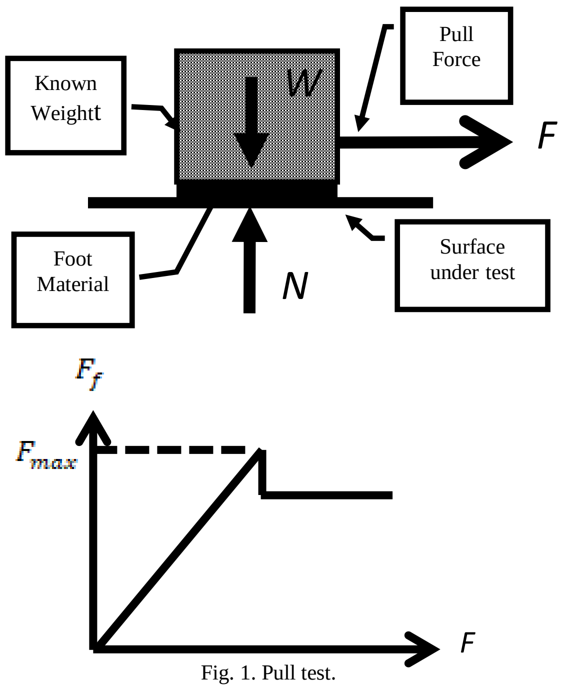

Fig. 1. Pull test.

TABLE I. COMMERCIAL TRIBOMETERS

Device		Foot Shape	Foot area [mm^2]	Load [N]	Pressure [kPa]
50# Hand pull ASTM C-1028		76mm Square	5776	222.4	38.5
BOT-3000		9mm dia. circle	63.617	N/A	-
English XL		33mm dia. 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

II. THE EFFECT OF GROOVED FOOT

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 a feet that had grooves in 0^0, 45^0 and 90^0 to the pulling direction of the test. It was concluded that "For groove directions, the difference between 0^0 and 45^0 was not statistically significant. The COF values of these two conditions were, however, significantly higher than that of the 90^0 condition". In [9, 10] the effect of depth of groves, perpendicular to pulling direction depth, on the COF where the surface is contaminated was investigated. 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 grooved foot will bias the results in comparison to the one obtained with a flat foot. Currently there is one commercial tribometer which uses grooved foot [6]. In [11] two tribometers, Brungraber Mark II and Mark III, were compared where four different feet were used: 3 non-grooved feet (3" by 3") made of PVC, Neolite and Nitrile, and one grooved foot (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 feet on the COF. Three tests were performed using Neolite feet: 1) 3" by 3" square feet with no grooves; 2) 3" by 3" square feet with 6 1/16" wide and 1/16" deep grooves parallel to the pull direction and; 3) 3" by 3" square feet with 6 1/16" wide and 1/16" deep grooves perpendicular to the pull direction. Each test consisted of 40 pulls in set of 10 in four directions perpendicular to each other. The results of these tests are given in Table 2 which clearly indicating that the grooves on the feet affecting the COF reading resulting substantially higher value than in the non-grooved foot case. Also, t-Test verified that there is statistically difference between the effects of the parallel and the perpendicular grooves on the COF ($t_{stat}=4.05$, $t_{critical}=1.99$ and $P=0.00012$).

TABLE II. TESTS' RESULTS FOR GROOVED AND NON-GROOVED FEET

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

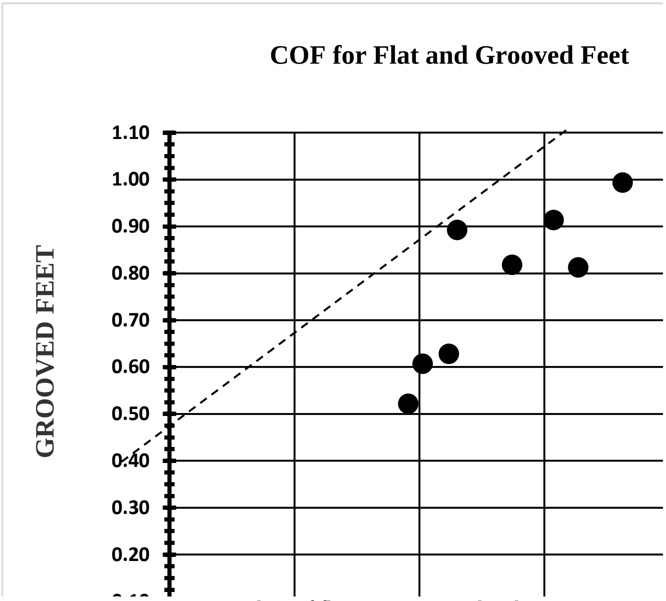

Fig. 2. COFs values of flat versus grooved pads.

In another set of tests the COF of 8 different tiles was measured in the same way using a non-grooved and a grooved (parallel to the pull direction) Neolite feet. Each test consisted on 10 pulls along a single direction of the tile. The results are shown in Fig. 2. which indicates that the COF's values obtained using the grooved feet are higher, in all cases, than the ones obtained with the flat feet.

III. THE EFFECT OF FOOT CONTACT AREA

A series of pull tests in which two square Neolite feet 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 feet. The contact pressure on the pads was the same 28[kPa] with deviation of 0.909[kPa] (0.1[psi]. The tests' and the statistical analysis results are given in Table 3. 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.

In a different experiment two circular Neolite feet of two different areas 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 4); and 2) By linear regression as shown in Fig. 3. The results of bot experiments are given in Table 6.

IV. THE EFFECT OF CONTACT PRESSURE

The simple Coulomb friction law, expressed in (1) does not specify the necessary contact pressure to insure a reliable measurement of the COF. Thus, a set of experiments, using a 3 inch square Neolite pad and the same TCNA tile, with two different contact pressures, vary from 7.7 kPa to 400kPa were performed. Each experiment consisted on 20 pulls, 10 in one direction and 10 in the opposite direction. The results are summarized in Table 6.

TABLE III. 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	

TABLE IV. EFFECT OF FOOT'S AREA BY REGRESSION

D=1.833[in]			D=1.401[in]		
Normal Force [lb]	Pull Force [lb]	COF	Normal Force [lb]	Pull Force [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		Mean	0.462
	Variance	0.00064		Variance	0.001159

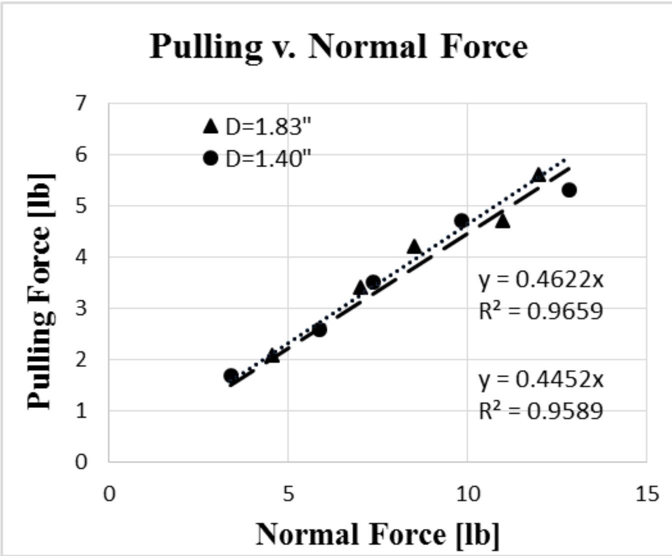

Fig. 3. COF by linear regression.

TABLE V. SUMMARY OF RESULTS FOR FOOT'S AREA EFFECT

	SCOF	
Diameter [in]	1.833	1.405
Contact area[sqin]	2.638	1.55
COF (mean)	0.467	0.462
COF (linear regression)	0.4622	0.4452

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TABLE VI. THE EFFECT OF CONTACT PRESSURE

Pressure [kPa]	P_1	P_2	P_3	P_4	P_5
	7.292	16.413	27.918	46.678	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 Fig. 4.

A single factor ANOVA test that covers the data for the three highest contact pressures (encircled in Fig. 4, indicated that their mean value 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 Fig. 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. 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).In any case, it appears that a minimum contact pressure is required for reliable measurements.

V. THE EFFECT OF FOOT SHAPE

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 Neolite feet of the same area of one square inch. 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 7.

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 foot is different from the one for the circular foot. Thus, it can be concluded that the shape of the foot 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 7. Again, the results indicate that the foot's shape does affect the COF reading.

VI. CONCLUSIONS

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

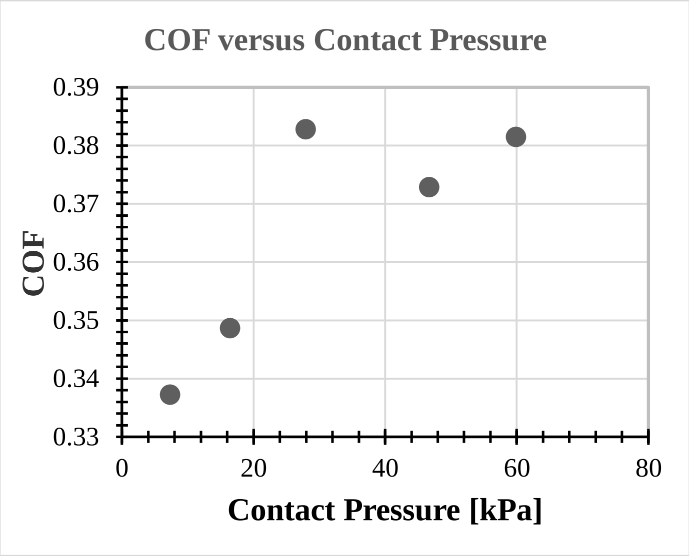

Fig. 4. COF values for different contact pressures.

1) Grooves on the tribometer's foot do increasing the COF reading by almost 50%.
2) It appears that the contact area between the tribometer's foot and the tested surface does not affect the reading of the COF
3) A minimum contact pressure between the tribometer's foot and the tested surface 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 tests show a difference of 19.4% (when pull direction is ignored).

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.

TABLE VII. THE EFFECT OF FOOT'S SHAPE

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	

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