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Relative humidity and wetting affect friction between apple and flat surfaces

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A b s t r a c t. The objective of this study was to determine the influence of relative humidity and dipping in water on the static and dynamic coefficients of friction of apple on four surface types. Knowledge of the coefficient of friction of fruits and vegetables is useful in the design of handling equipment and improving the production systems that will reduce apple damage. Two different cultivars (Gala and McLemore) were tested using a linear sliding friction test device connected to an Instron universal testing machine, data acquisition system, and a personal computer. The tests were carried out with ten replications per treatment combination under constant sliding speed and sample temperature. Samples were placed in air at 35, 55, 70, 95% RH and dipped in water. Relative humidity (RH) and dipping in water (WD) treatments had significant effect on both static and dynamic coefficients of friction. Changes in static coefficient of friction (SCF) with increasing RH were different for Gala and McLemore apples. Coefficient of friction tended to increase or decrease depending on sample moisture content, type of sliding surface and cultivar.

K e y w o r d s: coefficient of friction, humidity, water dipping, apple

INTRODUCTION

Improved handling and storage methods are needed to provide high quality apples (McClure, 1995). The coefficient of friction is an important physical property in engineering design of equipment for harvesting and handling to minimize abrasion of fruits (Puchalski and Brusewitz, 1996). Fruit surface quality is affected by surrounding environmental factors such as, temperature, humidity, and airflow (Grierson and Wardowski, 1978). Apples became more susceptible to bruises when stored at low temperature and high humidity (Zhang *et al.*, 1992; Dobrzañski and Rybczyñski, 2000). Halderson and Henning (1993) found differences in tuber skin strength kept in two different soil moisture conditions. Schaper and Yaeger (1992) found significant differences in static and dynamic coefficient of friction between washed and unwashed potatoes, which was related to the type of surface.

A modified direct shear apparatus used for determining the coefficient of friction of granular materials on smooth and corrugated surfaces should be useful because it most closely simulates the actual conditions at the frictional interface in grain bin when grain slides down the wall (Molenda *et al*., 1996, 2000; Horabik and Molenda, 2000). The coefficients of static and dynamic friction of sunflower seed and kernels increased linearly with moisture content (MC) in the range of 4-20% MC (Gupta and Das, 1998), for lentil seeds at 7-33% MC (Carman, 1996), and for soybeans at 8-17% MC, red kidney beans at 10-15% MC and peanuts at 3-15% MC (Chung and Verma, 1989). The static coefficient of friction increased linearly over the range of 4-27% MC for pumpkin seeds (Joshi *et al.*, 1993), over the range of 6-15% MC for pigeon peas (Shepherd, 1986), over the range of 7-22% MC for cumin seed (Singh and Goswami, 1996). Moisture content affected the static coefficient more than the type of surface while the type of surface affected the dynamic coefficient more than sample moisture content (Chung and Verma, 1989). Two varieties of raisons had different changes in friction forces at moistures below 18% while at moistures above 30% friction was relatively constant (Kostaropoulos, 1997). For low grain moisture (12% wheat, 6% canola, and 11% lentils) the dynamic coefficient of friction increased over the range of 25 to 85% relative humudity (RH) while at higher grain moisture (19% wheat, 16% canola, 21% lentil) the friction coefficient increased for humidities from 25 to 70% and then decreased at 85% (Zhang and Kushwaha, 1993).

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The objective of this work was to determine the influence of relative humidity and surface wetting by dipping in water on the static and dynamic coefficient of friction of apple on masonite, paper, plastic and rubber surfaces.

MATERIALS AND METHODS

Two apple cultivars with characteristics as shown in Table 1 were used to represent different surface characteristics. Fruits were harvested from Oklahoma orchard at optimum maturity for cold storage based on flesh firmness and color. McLemore apples were harvested on 24 July and Galas were harvested on 15 August. Apples were selected during hand picking according to mass and dimensions to insure uniformity. All samples were placed in storage at 6°C and 95% RH. Gala apples were stored for 6 to 10 days and McLemore apples were stored for 10-14 days before friction tests were conducted.

Apples were taken out from storage 12 h before measurement and they were separated into five, 35, 55, 70, and 95% and dipped in water groups of 10 apples each. One group was dipped in water for 10 h, removed, wiped dry, and covered with plastic until testing. A second group was left in the room which was at 24°C, 70% RH. The other three groups were placed in environmental chambers at either 35, 55, or 95% RH until testing.

Immediately following friction tests firmness readings (with an Effegi penetrometer) were taken on each apple using 11.1 mm probe pressed against a peeled side. Moisture content of each apple was determined by drying finely cut pieces of apple to constant weight at 70°C. Friction coefficients for four sliding surfaces (masonite, paper, plastic, and rubber) were determined using a device proposed by Puchalski and Brusewitz (1996). A simplified diagram of this device is shown in Fig. 1. The device was made up of four major components: (1) the frame (1 m high, 0.44 m wide, and 0.70 m long), (2) stationary sample holder, (3) moveable horizontal plate (to which is mounted the test surfaces) connected to the crosshead of an Instron machine and (4) data acquisition system (not shown) including a personal computer.

The sample holder had two independently adjustable jaws that held the sample in place as the horizontal plate (and abrasive test surface) moves. The ‘sandbag’ (part of the sample holder) applied the required normal force generated through the ‘pivot arm’ by the counter weight. The movable

T a b l e 1. Characteristic of tested material

Cultivar	Treatment	Firmness (N)		Moisture content (%)		Weight (g)		Dimension (mm)			
								Min		Max	
		M	SD	M	SD	M	SD	M	SD	M	SD
Gala	35% air RH	73.6	9.6	81.6	0.5	148.0	9.0	69.0	5.7	71.0	2.2
	55% air RH	72.4	8.0	82.9	0.8						
	70% air RH	67.6	7.9	82.9	0.8						
	95% air RH	73.6	9.6	83.0	0.9						
	Water-dipping	72.4	8.0	83.4	0.6						
McLemore	35% air RH	31.0	1.6	84.4	0.9	153.4	13.2	73.1	2.3	74.9	2.4
	55% air RH	32.6	2.0	84.9	1.4						
	70% air RH	35.6	2.6	84.9	0.9						
	95% air RH	31.1	1.6	85.2	0.8						
	Water-dipping	32.6	2.0	86.1	1.1						

M - mean value, SD - standard deviation.

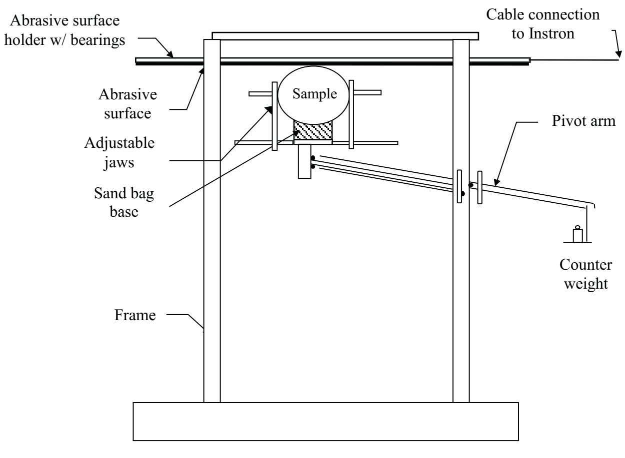

Fig. 1. Friction test device.

horizontal plate, 0.1 m wide and 0.6 m long, was mounted on precision rails and linear bearings to minimise friction. The horizontal plate was connected to the crosshead of an Instron machine by a 1.0 mm diameter steel cable. All tests were conducted with a constant normal force of 17 N and sliding speed of 4.17 mm s^{-1} over a travelling distance of 0.3 m.

RESULTS AND DISCUSSION

Table 1 gives the characteristics of all apples tested. Gala apples were more firm than McLemore. The moisture content of the two varieties were approximately the same. McLemore apples were somewhat larger than the Gala.

An analysis of variance of the friction data showed that all treatments of relative humidity and dipping in water were significant (P=0.05) for all dependent variables (Table 2). All interactions (treatment × surface, treatment × ripe, surface × ripe, treatment × surface × ripe) were significant for all dependent variables, except for treatment × ripe of McLemore.

Static coefficient of friction

The effect of RH and water-dipping on static coefficient of friction of both cultivars is given in Fig. 2. Variability in the data depends on both cultivar and surface material. The static coefficient of friction of the Gala variety decreased with increasing in RH from 35 to 70%, except for rubber at 35% RH. The average decreases in static coefficient of friction were 18.8, 15.0, 8.4 and 5.3% for masonite, paper, plastic and rubber surfaces, respectively. This is due to the decreased adhesion between the apple and the test surfaces as the RH increases. After passing the 70% RH, the static coefficient of friction for the Gala increased with increasing in RH by 29.4, 6.1, 1.4 and 1.5% on masonite, paper, plastic and rubber, respectively.

Since the McLemore apples were more ripe than Gala (note the data in Table 1) an inverse relationship was noted between coefficient of friction and apple treatment, i.e., RH and dipping in water, except on masonite and rubber surfaces (Fig. 2). Changes in static coefficient of friction for McLemore apples on masonite were very small and not significant.

T a b l e 2. Analysis of variance probabilities for significant levels of static and dynamic coefficients of friction

Independent variable	Statistic coefficient of friction		Dynamic coefficient of friction	
	Gala	McLemore	Gala	McLemore
Treatment	0.0028	0.000	0.000	0.000
Surface	0.0000	0.000	0.000	0.000
Cultivar ripe	-	0.000	-	0.000
Treatment × surface	0.0053	0.000	0.002	0.000
Treatment × ripe	-	0.000	-	0.150
Surface × ripe	-	0.000	-	0.000
Treatment × surface × ripe	-	0.000	-	0.012

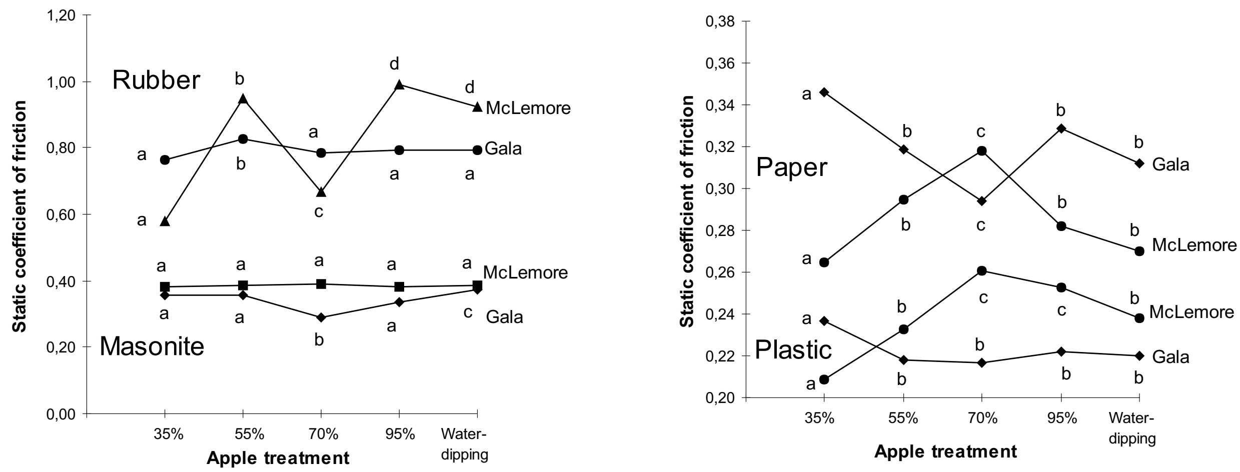

Fig. 2. Effect of apple treatment (RH and dipping in water) on static coefficient of friction of Gala and McLemore against different 4 friction surfaces. Different letters represent a significant difference in means, within a curve, by Duncan's multiple range test at the 5% level.

At 70% RH the static coefficient of friction of McLemore showed largest value on paper and plastic surfaces. From 35 to 70% RH, the SCF increased linearly 22% followed a decreasing tendency in SCF.

It should be noted at this point that McLemore and Gala apples have different surface characteristics which could influence the magnitude of the SCF at different RHs. Changes in adhesion (affecting the SCF between fruit and sliding surface) appears to depend on level of moisture in the sample surface, characteristics of the fruit surface that relate to the cultivar.

Dynamic coefficient of friction

The effects of RH and water-dipping on the dynamic coefficient of friction (DCF) of both cultivars are presented in Fig. 3. These data follow the same trend as shown in Fig. 2. Up to the 70% RH (for masonite, plastic, and rubber) and 95% (on paper) the DCF decreased with increasing in relative humidity. Above these RH levels the DCF then increased at higher levels of RH.

Increase in adhesion, between fruit and sliding surface, affecting the value of coefficient of friction (Mohsenin, 1986), started after reaching the certain level of moisture content of sample surface exposed to the action of environment. It depended on characteristic of sliding surface. Plastic, with very smooth and wet surface, tended to show an increase in DCF in an increase in RH. Paper with its tendency to absorbed water needed high RH before the DCF tended to increase. The average change of the DCF was 24% on masonite, paper and plastic and 10% on the rubber surface.

Polynomial models

All of the curves were modeled on a third degree polynomial equations that provided a better fit to the raw data than other models for Gala and McLemore apples. All equations are shown in Table 3. All polynomial models were significant at P=0.05. The plastic surface produced the best fit. It was also observed, that generally coefficients of

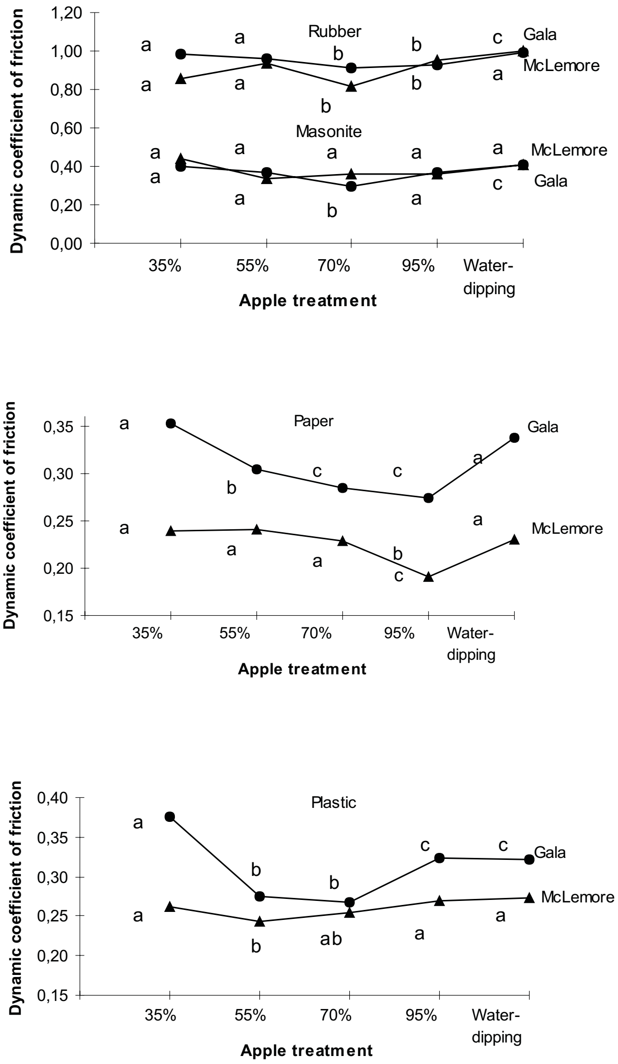

Fig. 3. Effect of apple treatment (RH and dipping in water) on dynamic coefficient of friction of Gala and McLemore against 4 different friction surfaces. Explanations as in Fig. 2.

T a b l e 3. Polynomial models of friction coefficient vs. surrounding RH (x*) of Gala apples

Coefficient of friction	Sliding surface	Regression equation	r^2
Static	Masonite	$4.0917 x^3 - 7.753 x^2 + 4.50 x - 0.46$	0.967
	Paper	$-0.5498 x^3 + 1.474 x^2 - 1.25 x + 0.64$	0.759
	Plastic	$-0.5456 x^3 + 1.262 x^2 - 0.94 x + 0.44$	1.000
	Rubber	$3.3939 x^3 - 7.192 x^2 + 4.83 x - 0.23$	0.798
Dynamic	Masonite	$3.3546 x^3 - 5.912 x^2 + 3.06 x - 0.09$	0.970
	Paper	$2.2205 x^3 - 3.919 x^2 + 1.98 x + 0.04$	0.820
	Plastic	$-2.4533 x^3 + 5.995 x^2 - 4.64 x + 1.42$	0.998
	Rubber	$3.9901 x^3 - 7.505 x^2 + 4.28 x - 0.22$	0.965

* values from 0.35 to 0.95 - apples kept in air RH from 35 to 95% and 1- ones dipping in water.

T a b l e 4. Coefficients* of equation of $ax^3 + bx^2 + cx + d$ of dynamic coefficient of friction vs. surronding RH of unripe U and ripe R McLemore fruits

Sliding surface	Coefficients							
	a		b		c		d	
	U	R	U	R	U	R	U	R
Masonite	-0.1537	-1.7913	0.800	4.447	-0.91	-3.46	0.62	1.22
Paper	1.9224	7.0030	-3.842	-14.149	2.33	8.79	-0.19	-1.37
Plastic	-0.2087	2.4064	0.565	-4.529	-0.45	2.55	0.35	-0.14
Rubber	3.8759	11.0840	-7.695	-20.999	4.91	2.30	-0.14	-1.29

* for all $r^2 > 0.718$.

regression equation of the DCF versus RH have larger absolute values for ripe fruits (firmness of 33 N) than for unripe ones (firmness of 71 N). Hence, these measurements could be used to show differences in ripeness (see Table 4).

CONCLUSIONS

1. The relative humidity (RH) surrounding apples had significant effect on both static and dynamic coefficients of friction.

2. The changes in static coefficient of friction with increasing air RH were different for Gala and McLemore apples. All three parameters considered in this study (cultivar, sample moisture and surface type) had a definite influence on static (SCF) and dynamic (DCF) coefficients of friction.

3. The dynamic coefficient of friction decreased with increasing RH up to the either 70 or 95% depending on sliding surface for both cultivars.

4. RH had a greater effect on the coefficient of friction for paper and plastic than for rubber surface.

5. Wetting by dipping in water had a 33% greater effect than 95% RH on the dynamic coefficient of friction on paper and rubber surfaces.

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