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Canada

Agriculture Canada

SEPTEMBER 1973

Report Rapport

Engineering and Statistical Research Institute - Institut de Recherche Technique et Statistique

7221

Evaluation Of A System For Measuring Small Deformations In The Physical Testing Of Foods

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CONTENTS

Contribution No. 398 from Engineering Research Service, Research Branch, Agriculture Canada, Ottawa, Ontario, K1A 0C6.

EVALUATION OF A SYSTEM FOR MEASURING SMALL DEFORMATIONS IN THE PHYSICAL TESTING OF FOODS

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SUMMARY

An instrumental technique is described for recording deformation to measure food firmness. The time required for the applied force to change between two levels is accurately recorded in digital form. Constant deformation rates are used so deformation is directly proportional to time. Thus the force per unit deformation can be calculated. The new technique is demonstrated with foods to indicate instrument performance. The results demonstrate the inaccuracies that occur when using strip-chart recorders to measure deformations. Response of the new system is adequate to record firmness of products up to 3400 g mm^{-1} at deformation rates up to 100 cm min^{-1} with less than 3% error.

The readings must be interpreted on the basis that firmness is defined as the force required to produce a given deformation, whereas the instrument records the deformation produced by a given force.

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1. INTRODUCTION

The deformation test is useful in measuring food firmness. Szczesniak and Bourne (1969) found that it was chosen by consumers to judge foods such as marshmallows, tomatoes, bread and lettuce which ranged from 14 to 3333 g mm^{-1} in deformability. Szczesniak (1963) defined hardness as "the force necessary to attain a given deformation", this is used here as a definition of firmness.

Mechanical instruments have been developed for this measurement (Diener et.al. 1970; Bourne, 1973). Friction in such mechanisms and the use of dial indicators which impose unaccounted forces on the specimen, can introduce significant errors when measuring small non-destructive deformations under small forces (Voisey and Robertson, 1969). Texture instruments do not usually record both force and deformation directly because of the cost and the operating inconvenience. The following methods are used: a) record force against time and derive deformation (e.g. in an Instron); b) record deformation against time and derive force for Hookean materials, e.g. eggshells (Voisey and Hunt, 1973); c) measure the deformation caused by a selected force (e.g. Schoorl and Boersma, 1962; Voisey and Foster, 1970); d)measure the force resulting from a selected deformation (e.g. Voisey and Walker, 1969). These methods can use either continuous analog recording or electronic and mechanical readouts (Voisey, 1971).

A common problem is that samples of constant dimensions are difficult to arrange unless tedious preparative procedures are used (e.g. in whole fruits and vegetables). If this is not done, the instrument zero deformation setting must be adjusted--without applying force to the food--for each sample. This is time consuming and may not determine the point of zero sample deformation precisely. The most practical method is to deform the sample at a constant rate and record force continuously. It is then assumed that the point where the force starts to increase from zero coincides with zero deformation.

Bourne (1967 a,b) made deformation measurements and found that "a small deforming force gave better resolution between similar samples than does a large deforming force". The small forces produced small deformations, and to increase resolution of measurement, the recorder strip-chart was run at high speed to expand the time (deformation) axis. Errors due to irregularities in the contact surfaces of compression samples were eliminated by recording the deformation between a reference force (e.g. 0.05 kg) and the selected maximum force (e.g. 1.05 kg). This technique is simple and effective, but when large numbers of samples must be tested, costly amounts of chart are used, and time consuming measurements must be taken from each record. The recorder pen response may restrict the allowable deformation rate to less than that required as consumers apply forces at rapid rates to some products (Voisey and Crête, 1973).

The requirements to measure firmness are thus to determine the sample deformation produced by a change in applied force. When proper test conditions are used, where the deformation rate is constant, the requirements are actually to record the time taken for the force applied to change between the levels selected.

A system to automatically record food deformation between two force levels by a timing system is described. The readings are displayed in digital form eliminating the strip-chart and high deformation rates can be used without introducing large measurement errors.

2. DESCRIPTION OF DEFORMATION APPARATUS

A. The Apparatus

The technique was evaluated with a small variable speed compression machine (E.R.S.), similar to that described by Voisey et.al. (1967), recently made to test onions (Figure 1). The force transducer (F, Fig. 2) on the crosshead, was connected to a strain gage signal conditioning system (Series 800, Daytronic Inc., Dayton, Ohio) ideally suited for texture measurements. It can operate force and displacement transducers and display analog, peak, integral and differential readings in digital form or recorded continuously on a strip-chart.

The zero and sensitivity of the transducer (F, Fig. 2) are adjusted by controls on the input module (S), amplified, and the output displayed to four significant digits at the readout (K). The output is also connected to a limit control module (L) which operates at high and low limits, set by calibrated dials. When each limit is reached relays operate to control external equipment. The high limit relay was used to stop the compression machine motor (M), i.e. deformation was automatically stopped at a preselected maximum force, an important feature in non-destructive testing. The specified relay response time is 0.02 sec. which is adequate to control crosshead movement and ensures that the force applied passes through and exceeds the selected maximum by a small amount. In addition, logic outputs are provided to give low "logic 0" (0 to 0.8 volts) and high "logic 1" (2.4 to 5.5 volts) signals to control solid state devices.

A 100 k Hz crystal oscillator (O, Fig. 2) is connected to a pulse counter (C). The low logic output triggers the counter at the low limit and the high output stops the counter. The counter thus accumulates the number of cycles between the two limits. Since the oscillator is stable (± 1 H_3), this gives a precise indication of the time elapsed. One cycle represents 1×10^{-5} sec., and the six digit counter has a measurement range of 1×10^{-5} to 10 sec. The range and resolution can be changed by using a different oscillator frequency.

The frequency response of the strain gage input module is flat to 400 Hz (estimated rise time 6×10^{-4} sec.) which is probably less than the signal rise time generated in most texture tests. The maximum response time of the logic output controlling the counter is 1×10^{-5} sec. which introduces a timing error of 1 cycle. If it is assumed that the logic switching lags the limits set and is equal at both, the errors cancel. The operational repeatability of the limits selected is 0.1% according to the manufacturer.

Interfacing between the limit module and counter, and elimination of motor switching transients is accomplished by inexpensive electronic components which are not detailed here.

B. Operation

The force transducer is calibrated with weights using the input module adjustments so that the digital indicator reads in rational units (e.g. 0 to 5000 g). The sensitivity control on the limit module is then adjusted so that its control dials have the same range. The low limit is set to the force selected as the reference above zero (W_1), and the high limit to the selected maximum force (W_2). These settings are checked by weights.

A compression speed (X cm min^{-1}) is selected and checked precisely with a stopwatch and scale. The crosshead travel limit-switches are adjusted so that it is raised to clear the largest sample and lowered to compress the smallest sample more than the required amount. The counter is reset to zero by a pushbutton and sample compression started. When the reference force is reached, the counter commences to accumulate the number of cycles at a rate of 100 k Hz until the high limit is reached when the total number of cycles (Y) is displayed. The deformation (D mm) is determined as follows:

$$\text{Crosshead speed} = \frac{X}{6}\ \text{mm sec}^{-1}$$

$$\text{Time elapsed} = 10^{-5}\ Y\ \text{sec.}$$

$$D = \frac{10^{-5}}{6}\ YX\ \text{mm and Firmness} = \frac{W_2 - W_1}{D}\ \text{g mm}^{-1}$$

3. SYSTEM PERFORMANCE

A. System components

Operation of the system and recording the data is rapid and convenient. The test cycle time depends on the selected deformation rate. Typically 160 samples hr^{-1} can be tested.

The deflection of the 500 kg force transducer under test forces up to 5 kg was checked (within 0.002 mm) with a dial gauge and could not be detected. This was expected since the manufacturer specified a transducer stiffness of 234 x 10^3 kg cm^{-1} (i.e. 5 kg = 0.00021 mm). Corrections for transducer deflection to the deformation measurements derived from the crosshead speed were, therefore, not required. The relationship between force applied to the transducer and the digital reading was established by applying incremental forces using a low-friction pulley, cord and weights to apply force vertically upwards at the transducer centerline. The relationship was exactly linear, and hysteresis was not evident. The low and high limit controls were set to operate at 400 and 3200 g.

The analog output of the strain gage input module (S, Fig. 2) was connected to a strip-chart recorder to indicate force against time. Several potentiometric and galvanometric recorders were used, so that a range of chart speeds and different pen response rates was available c.f. the Instron recorder (Table 1). The minimum pen response time, over full-scale, to a signal increasing linearly with time was measured by connecting a signal generator producing a triangular wave to each recorder. The frequency was increased until the pen attenuated the signal by 1%. The minimum allowable time for the pen to move from zero to full-scale under conditions closely approximating a texture test were thus determined. The results (Table 1) indicate that the manufacturers specified recorder performance can be misleading. For example, a 0.2

sec response recorder started to attenuate a linearly increasing signal at about 3 sec full-scale response. This is explained by the fact that the manufacturer determines the minimum response time using a full-scale step-input signal. Under these conditions the servo system driving the pen is operating at maximum speed as the error signal to the pen servo is large until the pen nears full scale. This is not the case when a steadily increasing signal is applied.

B. Using springs to simulate foods.

Four helical coil springs, each having a different stiffness, were ground flat and parallel at the ends. One end of each spring was fitted into a shallow recess in an aluminum block so that they could stand on the base of the testing machine to simulate a food sample.

Each spring was compressed 20 times at 2, 5, 10 and 20 cm min^{-1} in the E.R.S. and an Instron testing machine. The deformation between 400 and 3200 g, recorded on the counter and strip-chart, was noted and the spring stiffness calculated. The differences between the average spring stiffness, according to the counter and chart, were then calculated relative to the chart readings.

The results (Table II) indicated that the differences between chart and counter readings varied, but were generally less than 3%. The variation among the 20 readings on each spring was consistently at a low level and was about the same for both the E.R.S. and Instron machines. This probably indicates that control of crosshead speed was the same in both machines. In the majority of cases the chart gave a higher value of spring stiffness than the counter, indicating that the pen lagged the force signal.

Based on the mean spring stiffness for the four compression speeds used, there were differences in stiffness from the E.R.S. and the Instron readings of a magnitude which appeared to be influenced by spring stiffness, both for the chart and counter readings. There were large differences in values of spring stiffness introduced by compression rate in both the Instron and E.R.S. machines using the chart readings, whereas these differences were smaller for the counter readings indicating the effect of recorder response.

Several sources of error in the readings were investigated and are of interest since they demonstrate errors that can arise in any texture measurement.

Chart speed - Deformation measured from the time axis of the chart depends on the chart speed accuracy. The galvanometric recorders were used because the high pen response recorded force accurately. The charts in these instruments are typically moved by a friction drive. Errors of 0.3 to 3.3% were recorded in the speed of the galvanometer charts (Table 1). Errors are known to occur in other more expensive recording systems (Chan and Warren, 1972). Errors in chart speed were not detected with the potentiometric type recorders which had a positive chart drive using sprockets, perforated paper and synchronous drive motors.

Resolution of measurement - The narrow charts (40 and 100 mm) of the galvanometric recorders and the long chart length used in each test produced a record where the recorded line crossed the 400 and 3200 g (full-scale) levels at an acute angle. Determination of the exact crossing point required a degree of judgment. Errors from this source were found to range up to 2%. To measure the deformation from the wide chart of the potentiometric recorder, it was necessary to project the point where the line crossed 3200 g to the 400 g level. Errors from judging this were found to be up to ± 1% depending on the length of chart used for each test.

Setting of the limit controls - The limit controls settings were checked by weights proving that the limit operated, or did not operate at that particular force, not the actual force required to reach the limit. Subsequent investigation showed that errors from this source could range up to ± 0.3%. The adjustment procedure was modified. After calibration, the zero control was slowly offset so that the digital meter force reading passed through the low and high levels. The actual readings when the limits were reached were observed and the controls adjusted accordingly.

The chart speed errors, taking the data off the charts and pen response probably account for a portion of the differences observed between the counter and chart readings in this test. Theoretically, the possible counter errors are extremely small and the evidence indicates the recorders as the source of error. This was verified by measuring the deflection of each spring compressed in the Instron between 400 and 3200 g with a dial gauge within 0.013 mm under static conditions. Spring stiffness based on these readings was used as a standard for comparison. Each spring was compressed 10 times at 0.5

cm min^{-1} and the deformation noted from the counter reading. This was then repeated at increments of crosshead speed up to 100 cm min^{-1}. Dial gauge readings were taken on each spring before testing at each speed.

The results (Table III) indicate that compared to dial gage reading the errors of measurement according to the counter ranged from ≠ 0.8 to -2.9%. The errors were not related to compression speed but tended to become smaller with decreasing spring stiffness. The counter generally overestimated the spring stiffness indicating that it tended to lag the input signal except for the weakest spring where a slight tendency to underestimate stiffness was apparent as the deformation rate increased. It should be noted that in this test the apparent errors include errors inherent in the comparison technique such as: a) errors in crosshead speed--small errors were detected within the accuracy of measurement possible with a stop watch and scale at speeds less than 20 cm/min. These were not sufficient to account for the errors in counter readings (Table III); b) any back lash in the crosshead drive mechanism; and c) the apparent changes in spring stiffness as measured by the dial gauge which were sufficient to account for the errors between the counter and dial gauge readings.

The results point out that verification of the accuracy of deformation measurements such as used to test foods requires a high degree of precision which was not achieved in this test. The test shows however that the measurement errors of the counter are small over a wide range of test speeds. It is of interest that the resolution of measurement at the highest deformation rate with the stiffest spring (simulating a firm onion) was within 5 digits or 0.02% of reading.

C. Tests with Food Products.

To evaluate the system, several food products were tested. The deformation was determined from the counter and in some cases with a recorder as well. Flat ground stainless steel compression surfaces were used for all the tests.

Eggshell Strength - Specific gravity of eggs provides an estimate of the percentage of shell (Olsson, 1936) and is used to estimate egg shell strength on the proven assumption that a greater amount of shell gives higher strength. Shell stiffness (deformation/unit force) is also related to shell strength (force at fracture) (Brooks and Hale, 1955; Schoorl and Boersma, 1962).

Fresh eggs from an experimental flock were selected by floatation in salt solutions to collect 30 with an S.G. of 1.070 to 1.074 and 30 with an S.G. of 1.086 to 1.090. The eggs were compressed at the equator at 2 cm $\min^{-1}$ and the limit controls set to operate at 100 and 1100 g. Deformation was not stopped at the upper limit but allowed to continue until the shell fractured. The maximum (i.e. fracture) force was recorded on the digital force indicator (K, Fig. 2) using a peak detection module (Model 859A, Daytronic Inc.). A non-destructive measurement of shell stiffness (Schoorl and Boersma, 1962) and destructive measurement of fracture force were obtained in each test.

The results (Table IV) show that the deformation system was capable of discriminating differences in stiffness of a product firmer than those tested by Szczesniak and Bourne (1969). A higher S.G. gave a greater stiffness and correspondingly higher fracture force which agrees with extensive data published elsewhere (Voisey and Hunt, 1973).

Onion Firmness - Ang et. al. (1960) measured onion firmness by compressing bulbs between flat plates until they ruptured, using forces up to 57 kg. The ratio of force and deformation at rupture was used as a firmness index.

Forty lots, each comprising 10 onions, 5 ±0.6 cm diameter, stored for 4 months, and representing different varieties or chemical treatments to enhance storage life, were tested. Deformation between 400 and 3200 g was recorded on the counter and galvanometer recorder (A, Table 1) at a compression speed of 15 cm min^{-1}. Previous tests showed that these conditions simulated consumer squeeze tests (Voisey and Crête, 1973).

The results (Table V) showed that the average differences between counter and chart readings within lots were small (-1.3 to 3.3%), but greater errors were noted for some lots. The variation in onion firmness for the pooled data was similar for both counter and recorder, and the readings within lots and within the test were highly correlated ($P > 0.05$). The recorder was assumed to be the main source of errors.

Preliminary tests with onions found soft, medium and firm by sensory tests showed that the force range selected had an effect on the discrimination between firmness as observed by Bourne (1967b).

Lower forces at higher deformation speeds tended to give larger ratios of measurements between onions of different firmness (Table V). The increased resolution in the ranges tested was, however, small.

Apple Firmness - Ten apples of three varieties were removed from storage after 5 months and tested within 24 hr. Two lots of apples were purchased locally from a retailer and tested at the same time. The fruit were compressed at the waist at 15 cm min^{-1} and the deformation for a force change of 100 to 1000 g noted from the counter and a 0.2 sec. response recorder (D, Table 1). In this case, the signal rise time exceeded the recorder pen response. It was recognized that the test did not measure yield force, the index of apple firmness measured by the Magness-Taylor pressure tester (Bourne, 1969), but it provided a means of evaluating the instrument.

The results (Table VI) showed that there were large errors introduced in chart readings by recorder response at the high deformation rate used. Firmness derived from the chart was significantly lower, and the magnitude of the errors was affected by apple firmness. Tests on two varieties compressed at 5 cm min^{-1} indicated that the reverse situation occurred at the lower speed. Variation of counter readings within varieties was generally lower than for the chart readings.

Both the recorder and chart showed differences in firmness for Red and Golden Delicious and Courtland apples just after removal from storage and purchased Red Delicious were less firm than those collected directly from storage. Using the readings for New York Red Delicious as a basis for comparison, the ratio of firmness for each variety was relative according to both counter and recorder. The recorder must, therefore, attenuate the force signal consistently. The firmness ratios for the counter readings were, however, larger than for the chart indicating a better resolution of measurement. The firmness readings were greatly affected by deformation rate. Apples appeared firmer at 5 cm min^{-1} than at 15 cm min^{-1}, indicating the effect of relaxation behaviour on this type of test.

<u>Bread Staling Tests</u> - The firmness of bread has been measured by hyrostatic pressure (Willhoft, 1971), and a deformation test has been used (Katz, 1933; Bourne, 1967b).

Twenty sliced loaves in plastic bags were purchased and compressed at a point one quarter of the loaf length from one end. The loaves were compressed at 15 cm min^{-1}, and the deformation for a force change of 200 to 1000 g recorded on the counter. A maximum force of 1000 g was used since Bourne (1967b) found that consumers applied about 500 g to one side of the loaf to evaluate firmness. The loaves were stored on a laboratory bench and tested each day for 16 days. On the final day the deformation at the opposite end of the loaf was also recorded.

The results (Fig. 3) showed that the bread rapidly became firmer in the first 3 days, and this continued at a slower rate for about 6 more days. The firmness appeared to be stabilized by about the ninth day. On the sixteenth day the average firmness at the end tested was 130 g mm^{-1} compared to 133 g mm^{-1} at the other end tested for the first time. Variation among loaves throughout the experiment was high producing coefficients of variation ranging from 17 to 26%.

Marshmallow Deterioration in Air - The viscosity and elasticity of marshmallows was measured by Tiemstra (1964) and changes in firmness with time were measured by Bourne (1973).

Twenty marshmallows were kept in air and tested daily for 14 days. The deformation for a force change of 100 to 1000 g and 200 to 1000 g at a compression speed of 15 cm min^{-1} was recorded on the counter. The results (Fig. 4) show that firmness increased during the first 7 days. There was then a sharp reduction between the seventh and ninth days, and firmness then again increased. Bourne (1973) found that marshmallow firmness increased non linearly over a period of 10 days. It was presumed that the observed reduction was caused by the formation of a hard brittle layer on the outside of the marshmallow which changed its behavior until it was broken. There were only small differences between readings obtained using force ranges of 100 to 1000 and 200 to 1000 g (Fig. 4). Variation among readings increased with time throughout the test (Table VII) indicating that the marshmallows became less uniform with time exposed to air.

Other Foods - Fresh and processed foods were purchased locally and 20 samples of each tested. A deformation rate of 15 cm min^{-1} and a force range of 100 to 1000 g were used. Deformation was recorded on the counter and a 0.2 sec response potentiometric type recorder (E, Table 1). Potatoes, onions, apples, tomatoes, oranges, weiners and marshmallows were compressed between flat plates. Potato cores 1 cm diameter and 2 cm long were similarly tested. Carrots were tested in bending using the bending attachment of the Ottawa Texture Measuring System (Voisey et. al. 1972). The carrots were supported over a span of 10 cm and deflected at mid span. The diameter of each carrot at each end of the span was measured and the average of these readings assumed to be the mean diameter. The effect of repeated tests on the apparent firmness of the products was evaluated by testing 10 samples each 5 times in rapid succession.

The results (Table VIII) show that the firmness of the foods ranged from 62 g mm^{-1} for marshmallows to 2103 g mm^{-1} for apples. The differences between recorder and chart readings ranged from 1 to 14% indicating that in most cases the recorder response was exceeded. The variation among 20 samples was almost identical for the counter and chart readings for the foods tested. This again indicates that the recorder attenuates the signal by a consistent amount under a given set of conditions.

Repeated tests on foods showed that there was a large apparent increase in firmness after the first test (Table IX). There was a general tendency for the firmness to increase gradually in the subsequent 3 tests. The differences introduced were sufficient to change the average firmness according to the 50 readings from 106 to 124% of the average of 10 readings in the first test. The change is probably caused by damage to the food even at the small forces used in this test. Thus, in testing changes of firmness with time two tests should be made at the beginning and the first reading discarded to reduce this effect. The first points of the curves shown for bread and marshmallows (Figs. 3 and 4) may, therefore, be in error. However, there is the possibility that the food may return to its original condition if sufficient time is allowed between tests.

It is well known that sample dimensions affect the firmness readings obtained (e.g. Ang et. al., 1960). In this experiment each commercial product was generally within a narrow size range. However, in any firmness test the effect should be investigated. This is demonstrated by the relationship between bending stiffness and mean diameter of carrots (Fig. 5).

4. DISCUSSION

If small deformations under small forces are used to measure food firmness, a high degree of resolution and accuracy of measurement is required to reliably detect differences. One method is to use a high chart speed and a wide chart to expand the force and deformation scales. Errors can be introduced in taking data from the charts and by recorder pen response and chart speed. However it appears that relative differences can be measured when pen response is exceeded providing the signal attenuation is consistent but the resolution of measurement may be reduced.

The new apparatus provides a rapid method for measuring deformation between two force levels to estimate food firmness at higher deformation rates than possible with a strip-chart recorder. It can discriminate the difference between and within products. The elimination of charts cuts operating costs and reduces the labour and the errors inherent in reading the charts. The results indicate some of the sources of errors in any texture tests. Providing the recorder response is not exceeded, counter and recorder readings differ by a small amount which probably originates at the recorder.

The new method can be used to indicate deformation in any existing food deforming mechanism such as compression or puncture testers. The deformation rate must be constant for accurate results, but this is already a standard requirement in any texture test. The instrumentation also provides a means of checking deformation rates under operating conditions that is more accurate than using a stop watch and scale.

The minimum cost of the system described to record only deformation (excluding the force transducer and compression machine) is $1250. The method can also be arranged to measure the force change between two selected deformations by using a displacement instead of a force transducer.

A point that must be considered is the load cell capacity. To obtain maximum resolution a minimum capacity is desirable so that the indicator can be driven to full scale and minimize errors for the small forces that may be required. This may make the force transducer deflections significant, and a compromise must be chosen. For example, a 2.5 kg capacity load cell deflects 0.1 mm kg^{-1} introducing a tedious correction to the readings.

Before applying the new method or any technique for measuring food firmness, the test conditions selected should take into account: a) the difference between samples is greater at small deformations under small forces (Bourne, 1967a, b); b) the difference between samples is numerically larger at high deformation rates because of the non linear relationship between the force resisting deformation and time; c) high deformation rates reduce the effects of sample relaxation; d) a yield point must not occur during the test, or properties other than compressibility will affect the result; c) the dimensions of the sample may affect the result (Brinton and Bourne, 1972); f) the apparent firmness of a product changes during repeated tests; and g) in compressing products having curved contact surfaces, the force resisting deformation is changing with the area of contact as well as with the compression of the material. That is, the initial deformation may be a surface phenomena due to the infinite stresses theoretically generated at a point contact which accounts for the markedly non linear relationship between force and deformation at the start of the test. A question remaining is: "should instrumental test conditions be arranged so that the forces and deformation rate are in the range used by humans, or in the range that gives the maximum differentiation between samples, and train judges to operate in the optimum range for instrumental methods" (Private communication, M.C. Bourne, 1973). Also, does the consumer evaluate firmness by a deformation test of the product surface, the whole product or a yield type test such as is used for apples and sweet corn.

5. CONCLUSION

The new instrument provides an effective means of recording food deformation under a wider range of conditions than presently possible using strip-chart recorders. Capital and operating costs are reduced. The method may serve to evaluate the relationships between instrumental and sensory evaluations of firmness efficiently. Test conditions must be optimized to give the best correlation between sensory and objective tests.

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Acknowledgement

The authors wish to acknowledge the valuable advice and assistance given by M.C. Bourne, New York Agricultural Experiment Station, Geneva, New York, and D.C. MacDonald who constructed and tested the equipment.

TABLE 1

Recorders used in experiment

Recorder	Type	Maximum chart speed mm/sec	Specified pen response	Measured minimum pen response time sec	Chart width mm	Chart drive mechanism	
						Type	Speed error %
A	Galvanometric	200	130 Hz	0.005	40	Friction	0.3 - 2.0
B	Galvanometric	50	30 Hz	0.1	100	Friction	1.7 - 3.3
C	Potentiometric	8	0.8 sec F.S.	--	250	Positive	0
D	Potentiometric	203	0.20 sec F.S.	3.33	250	Positive	0
E	Potentiometric		1.00 sec F.S.	16.66	250	Positive	0
Instron	Potentiometric	33	0.25 sec F.S.	--	250	Positive	0

TABLE II
Stiffness of four springs calculated from chart and counter readings

Test machine:		E.R.S.						Instron					
		Stiffness[a]			Coefficient of variation		Recorder used[c] and chart speed	Stiffness[a]			Coefficient of variation		Recorder used[c] and chart speed
Spring number	Crosshead speed	Chart	Counter	Difference[b]	Chart	Counter		Chart	Counter	Difference[b]	Chart	Counter	
	cm min^{-1}	g mm^{-1}	g mm^{-1}	%	%	%	mm sec^{-1}	g mm^{-1}	g mm^{-1}	%	%	%	mm sec^{-1}
1	20	3401	3492	2.67	0,78	0.61	A200	3221	3141	-2.48	0.78	0.75	A200
	10	3391	3476	2.50	0.62	0.72	A200	3052	3124	2.36	0.95	0.71	A200
	5	3352	3424	2.14	1.17	1.03	A50	3199	3241	1.31	0.90	0.72	A50
	2	3478	3410	-1.96	0.85	0.90	A20	3359	3256	-3.16	0.51	1.01	B50
2	20	1971	1986	0.76	0.88	0.84	A200	2059	2040	-0.92	2.03	1.01	A200
	10	1961	1983	1.12	1.21	1.21	A200	2035	2086	2.51	0.68	0.46	A200
	5	1891	1936	2.37	0.96	0.56	A50	1950	2003	2.72	0.69	0.64	A50
	2	2086	1990	-4.60	0.64	0.81	A20	2141	2059	-3.83	1.70	0.73	B10
	2	2075	1940	6.00	1.76	0.85	C8	2191	2075	5.00	1.32	0.48	C8
3	20	757	772	1.98	0.61	0.74	A200	860	769	-10.58	2.73	0.63	A200
	10	756	766	1.32	1.09	0.54	A50	760	768	1.05	0.76	0.78	A20
	5	757	761	0.52	0.66	0.62	A50	748	771	3.07	0.32	0.52	A50
	2	807	769	-4.71	0.82	0.59	A5	750	767	2.27	0.57	0.44	B10
	2	794	767	3.0	0.95	0.64	C8	799	784	2.0	0.94	0.47	C8
4	20	261	265	1.53	0.61	0.72	A50	295	271	- 8.14	0.67	0.63	A50
	10	275	274	-0.36	0.59	0.56	A50	275	272	- 1.09	0.72	0.41	A20
	5	268	268	0.00	0.72	0.51	A5	265	272	2.26	0.35	0.47	B10
	2	299	276	-7.69	0.72	0.53	A5	265	271	2.26	0.66	0.47	B2.5

[a] Mean of 20 readings

[b] Difference = $\frac{\text{Chart - Counter}}{\text{Chart}}$ x 100%

[c] See Table 1

TABLE III

Errors observed between means of 10 counter and dial gauge readings of spring stiffness measured over a force range of 400 to 3200 g

Spring number	Compression speed			Counter reading	Spring deflection		
	Selected	Measured[a]	Error[b]		Counter	Dial gauge	Error[c]
	cm min^{-1}	cm min^{-1}	%		mm	mm	%
1	0.5	0.5029	-0.59	925758	0.771	0.762	-1.16
	2.5	2.4979	+0.08	201303	0.838	0.813	-2.90
	5.0	4.9875	+0.25	94136	0.784	0.762	-2.80
	5.0	--	--	100098	0.834	0.813	-2.51
	10.0	9.9834	+0.17	49401	0.823	0.813	-1.21
	20.0	20.0	0	23279	0.775	0.762	-1.67
	25.0	25.0	0	20249	0.843	0.831	-1.42
	50.0	50.0	0	10143	0.845	0.831	-1.65
	100.0	100.0	0	5134	0.855	0.831	-2.80
	Mean[d]						2.01
2	0.5			1677950	1.398	1.390	-0.57
	2.5			336401	1.400	1.370	-2.14
	5.0			168180	1.401	1.384	-1.25
	5.0			167206	1.393	1.370	-1.65
	10.0			83625	1.393	1.370	-1.65
	20.0			41923	1.397	1.372	-1.78
	25.0			33567	1.398	1.384	-1.00
	50.0			16762	1.396	1.384	-0.85
	100.0			8489	1.414	1.384	-2.12
	Mean[d]						1.45
3	0.5			4538795	3.780	3.760	-0.52
	2.5			906987	3.779	3.734	-1.20
	5.0			452420	3.770	3.770	0
	5.0			452644	3.770	3.730	-1.06
	10.0			228008	3.800	3.759	-1.08
	20.0			112802	3.760	3.785	+0.66
	25.0			91506	3.812	3.797	-0.39
	50.0			45768	3.814	3.797	-0.44
	100.0			22934	3.822	3.797	-0.65
	Mean[d]						0.67
4	0.5			12805256	10.670	10.640	-0.28
	2.5			2557794	10.650	10.560	-0.85
	5.0			1284172	10.701	10.719	+0.16
	5.0			1298831	10.820	10.560	-2.40
	10.0			641398	10.680	10.640	-0.38
	20.0			318800	10.620	10.640	+0.18
	25.0			256864	10.702	10.719	+0.15
	50.0			128544	10.710	10.719	+0.80
	100.0			64175	10.695	10.719	+0.22
	Mean[d]						0.60

[a] Mean of 10 determinations.

[b] $$\frac{\text{Selected - Measured}}{\text{Selected}} \times 100\%$$

[c] $$\frac{\text{Dial gauge - Counter}}{\text{Dial gauge}} \times 100\%$$

[d] Neglecting sign.

TABLE IV

Summary of data for eggs

Specific gravity	1.070 - 1.074	1.086 - 1.090
Stiffness[a] (g mm^{-1})	12936	19932
C.V. (%)	13.8	9.1
Fracture force (g)	2870	3847
C.V. (%)	11.9	13.9

[a] Mean of 30 eggs

TABLE V

Summary of data for onions

Firmness - Chart[a]	(g mm^{-1})	3140
Firmness - Counter[a]	(g mm^{-1})	3078
Average difference[b]	(%)	-1.3 to 3.3
Maximum difference[b]	(%)	-6.3 to 8.7
Minimum difference[b]	(%)	-0.1 to 0.4
C.V. - Chart	(%)	7.7
C.V. - Counter	(%)	7.3
r for 10 samples in each variety		0.87 to 1.00
r for 400 samples pooled		0.93 to 0.99

[a] Mean for 10 bulbs of 40 varieties or 400 bulbs

[b] $\frac{\text{Chart - Counter}}{\text{Chart}}$ x 100% keeping positive and negative errors separate for 10 bulbs

Ratio of Firmness

Force g	10 to 100		50 to 500	400 to 3200	
Compression speed cm min^{-1}	5	15	15	5	15
Ratio					
Soft-firm			1.79		1.49
Medium-firm			1.36		1.20
Medium-firm	1.48	1.33	--	1.27	1.33
Soft-medium			1.31		1.29

TABLE VI

Firmness of apples measured for a force change of 100 to 1000 g. Means of 10 readings. Chart Speed 20.32 cm sec^{-1} (8 in sec^{-1}) Pen response 0.2 sec full scale.

Variety		Fruit diameter at compressed axis		Variation of firmness readings		Firmness			Length of chart
				Chart	Counter	Chart	Counter	Difference[a]	
	Compression speed	Mean	C.V.	C.V.	C.V.	Mean	Mean		Mean
	cm/min	cm	%	%	%	g mm^{-1}	g mm^{-1}	%	in
N.Y. Red Delicious	15	6.8	3.1	14.0	9.0	1930	2775	-44	1.038
N.Y. Golden Delicious	15	6.6	2.9	14.3	11.8	1005	1184	-18	2.432
N.Y. Courtland	15	7.1	3.3	8.2	5.4	1823	2487	-36	1.158
MacIntosh[b]	15	7.9	5.7	10.8	9.0	1368	2045	-49	1.408
MacIntosh[b]	5	7.9	5.7	8.6	12.5	2215	1972	+11	3.90
Red Delicious[b]	15	7.9	3.3	22.7	14.0	1703	2108	-24	1.366
Red Delicious[b]	5	7.9	3.3	21.3	16.5	2157	1917	+11	4.01

[a] $\frac{\text{Chart - Counter}}{\text{Chart}} \times 100\%$

[b] Purchased locally at retail stores

TABLE VII

Variation of firmness readings among 20 marshmallos during 14 days.

Forces used g	100 to 1000		200 to 1000	
Day	SD ± g mm^{-1}	CV %	SD ± g mm^{-1}	CV %
0	4	6	-	-
1	33	22	-	-
4	-	-	57	21
5	112	24	132	27
6	201	29	229	33
7	317	32	396	39
8	246	30	293	32
9	180	26	234	30
10	235	26	295	31
13	267	25	333	30
14	381	31	447	34

TABLE VIII

Firmness of foods measured by counter and recorder (means of 20 samples)

Product	Firmness			Coefficient of variation	
	Counter $g\ mm^{-1}$	Chart $g\ mm^{-1}$	Difference[a] %	Counter %	Chart %
Whole potatoes	1408	1604	-14	23	21
Potato cores	726	776	- 7	12	11
Onions	1791	1690	6	28	30
Apples	2103	2082	1	14	18
Tomatoes A	294	299	- 2	22	25
Tomatoes B	254	267	- 5	27	28
Carrots[b]	1295	1462	-13	32	33
Oranges	852	862	- 1	25	24
Wieners	633	613	- 3	16	15
Marshmallos	62	67	- 8	6	5

[a] $\text{Difference} = \dfrac{\text{Chart - Counter}}{\text{Chart}} \times 100\%$

[b] Tested in bending all other results for compression.

TABLE IX

Effect of successive tests on apparent firmness of foods. Means of 20 samples expressed as a percentage of the reading on the first test.

Product	Test number					
	2	3	4	5	Mean[a]	C.V. (%)
Whole potatoes	117	120	122	121	116	8
Potato cores	125	129	132	134	124	11
Onions	105	106	108	109	105	3
Apples	123	124	129	129	120	12
Tomatoes A	118	118	119	118	115	7
Carrots	106	107	108	108	106	3
Oranges	115	119	120	121	115	8
Marshmallos	113	116	116	116	112	7

[a] for 50 readings

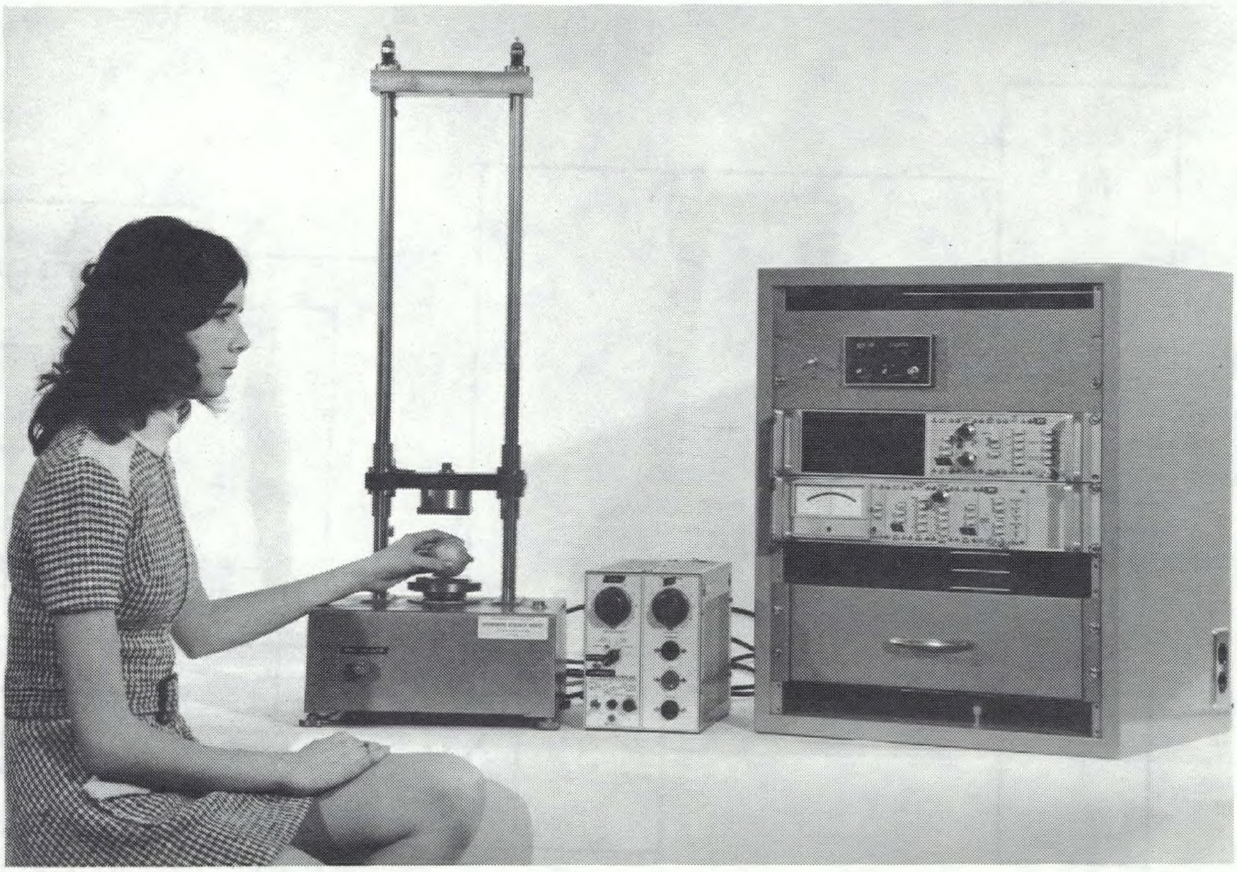

Figure 1. The apparatus - from left to right - compression machine, crosshead speed control and recording system. The recording system has the counter at the top and the strain gage conditioning and indicating equipment below.

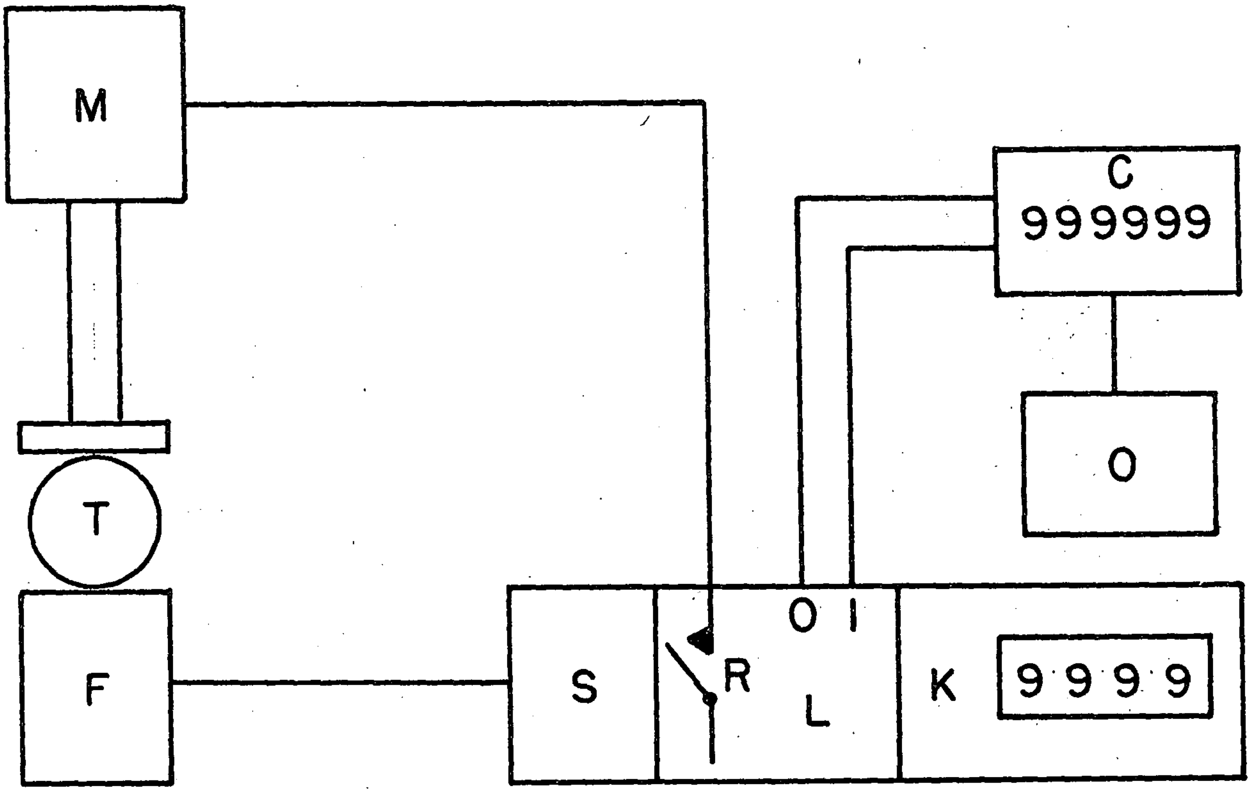

Figure 2. Schematic diagram of apparatus. C. Pulse counter (Model 2306A, Electronic Research Co., Shawnee Mission, Kansas); F. Force Transducer (Model FLIU-3SG, Strainsert Co., Bryn Mawr, Pennsylvania); K. Digital Indicator (Model 890, Daytronic Corp., Dayton, Ohio); L. Limit Module (Model 853, Daytronic Corp.); M. Variable speed motor driving compression machine; O. 100 k Hz oscillator (Model CO231, Vectron Laboratories Inc., Norwalk, Connecticut); R. Relay in limit control; S. Strain gage input module (Model 878A, Daytronic Corp.); T. Test sample.

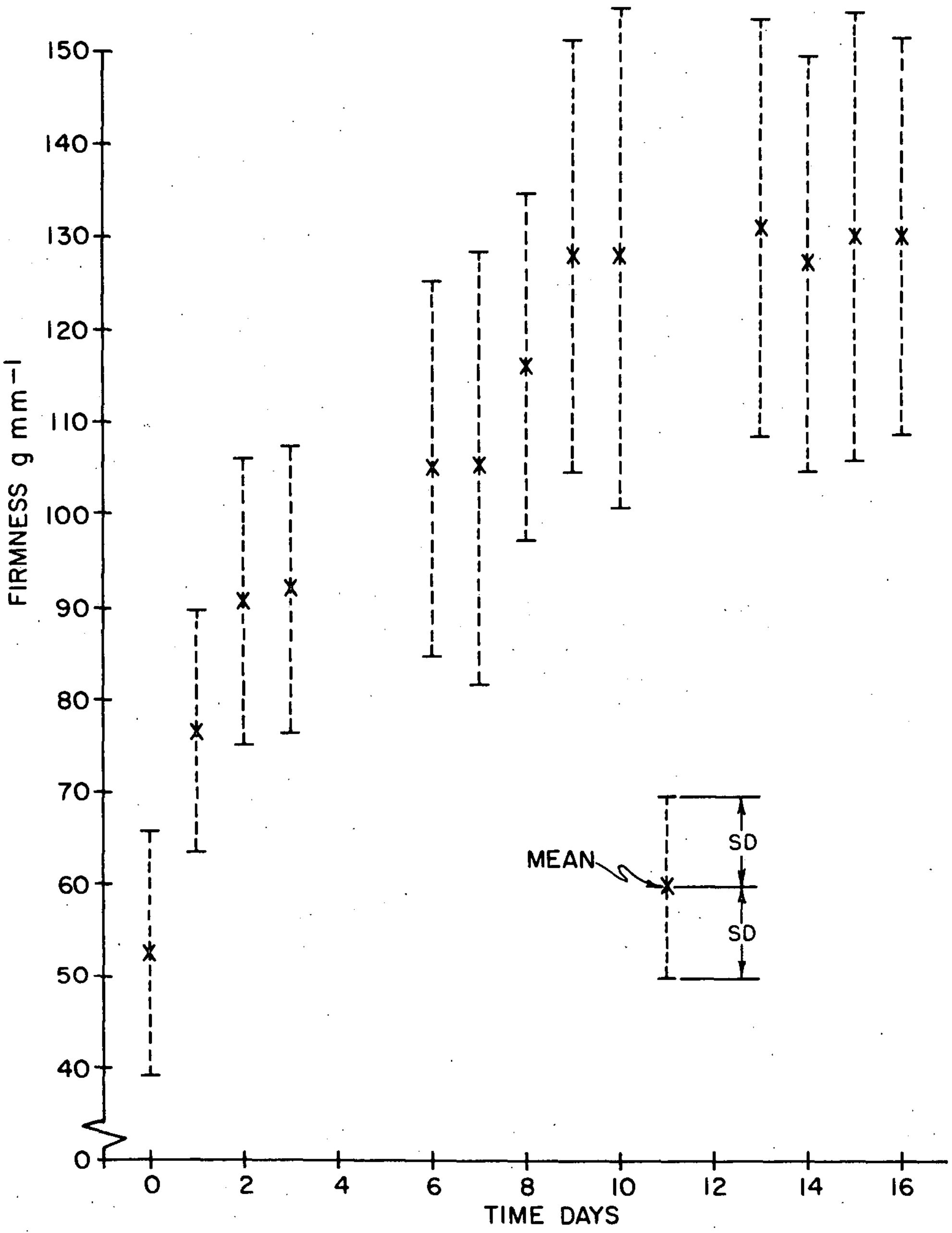

Figure 3. Firmness of bread during staling. Each point is the mean of 20 loaves. Vertical lines represent standard deviations.

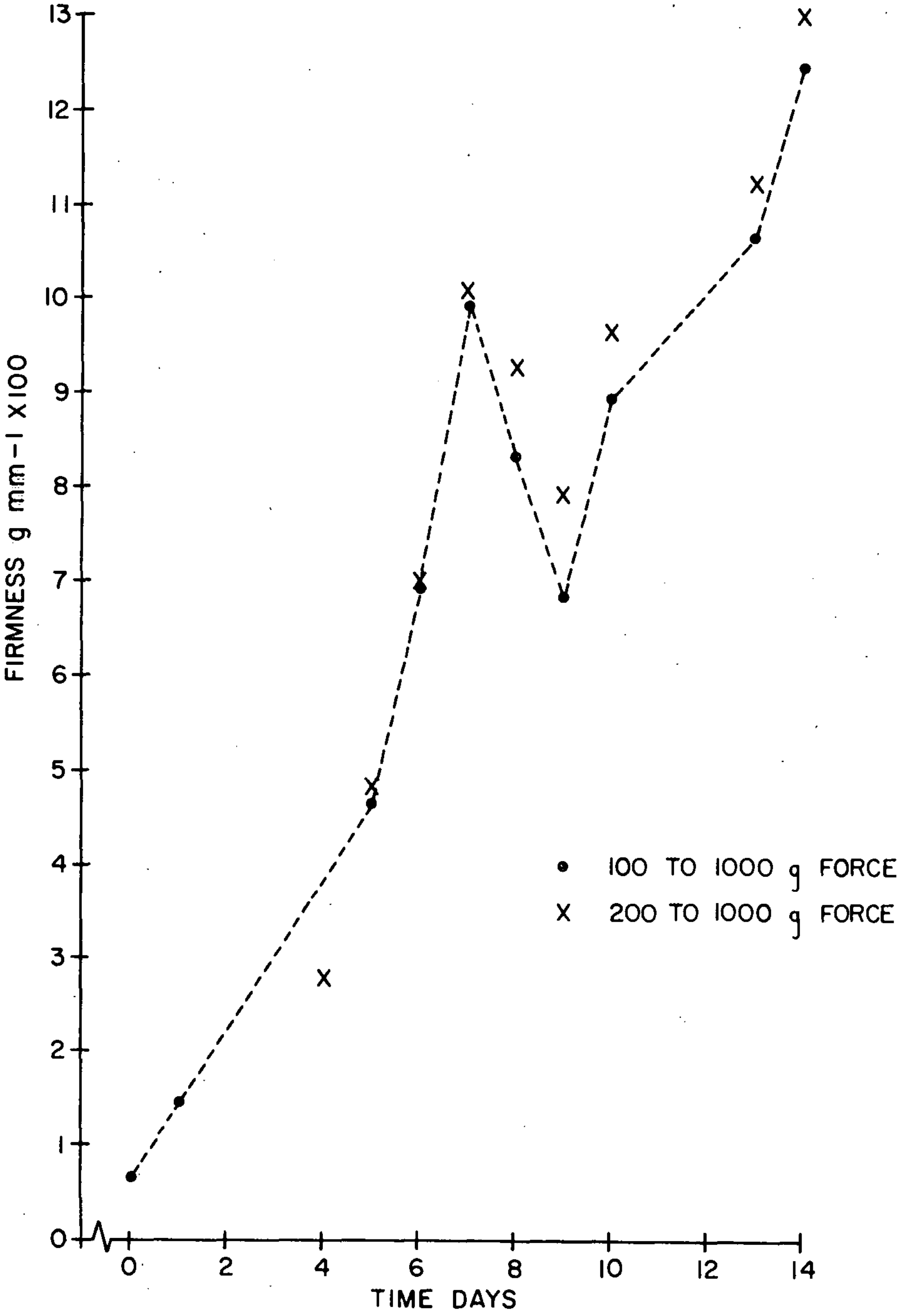

Figure 4. Changes in marshmallo firmness with time. Each point is the mean of 20 marshmallos.

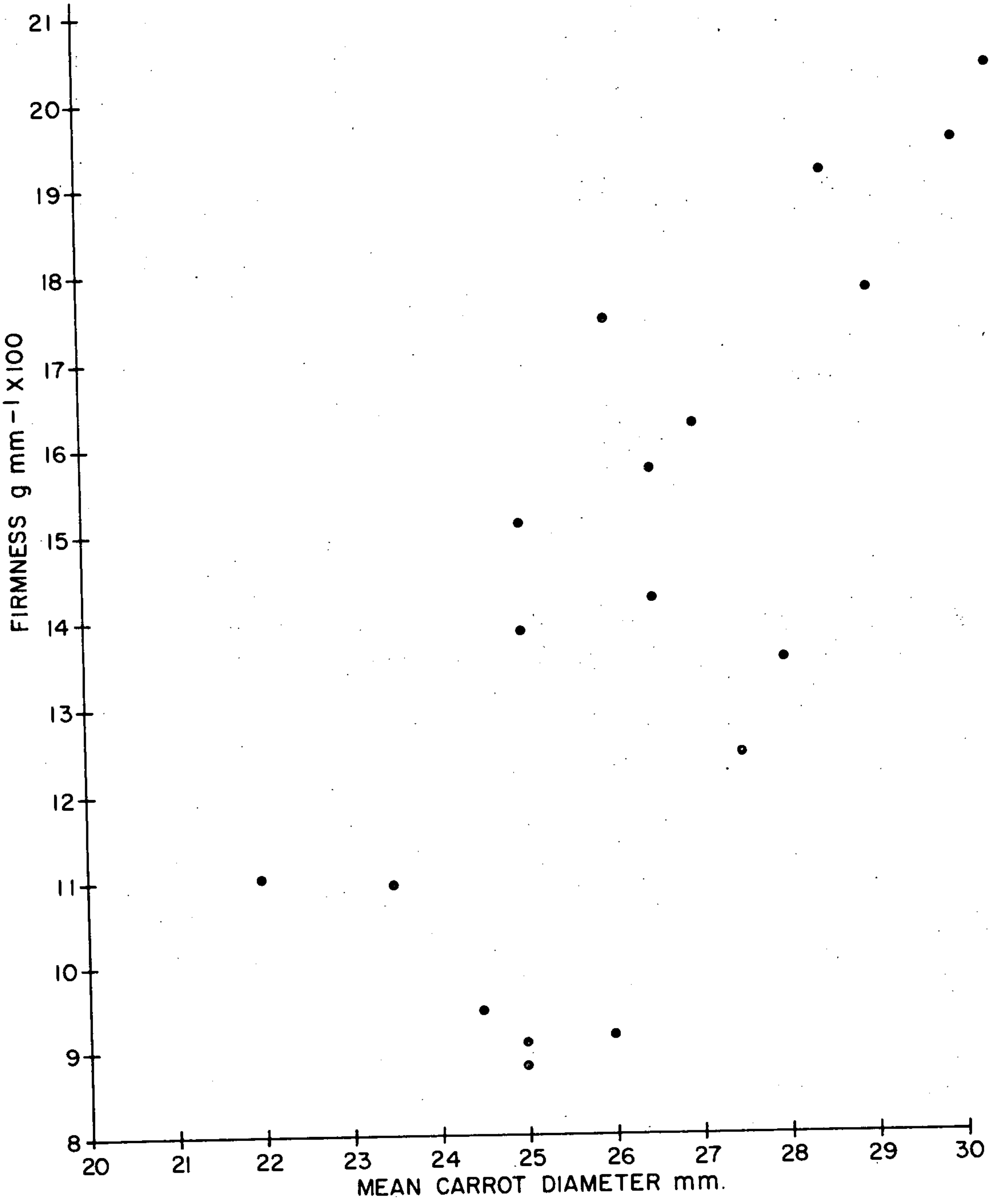

Figure 5. Scatter diagram of carrot stiffness in bending against mean diameter.