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CONTRIBUTION TO STUDY ON MECHANICAL PROPERTIES OF TOMATO FRUITS

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In the last thirty years experts have paid an increased attention to mechanical properties of tomato fruits, especially in association with introducing mechanical harvest. The selection and breeding of varieties suitable for mechanical harvesting requires the development of tests on the basis of which it would be possible to assess objectively mechanical properties of individual varieties, especially the resistance of fruits to direct damage under various conditions. Initially, simple pressure tests were used for this purpose. These tests consisted in measuring the force required for pressing a plunger of a constant diameter into the fruit to a certain depth. This method, which had proved good much earlier in testing the fruit ripeness — Magness-Taylor test — did not appear suitable for testing the firmness of tomatoes [1, 2]. More detailed studies on the firmness of the tomato fruit as a whole [3, 4] have shown that the skin of the tomato plays a much more important role than the skin of the other fruits; in the case of a soft tomato fruit the firmness of the skin determines fully even the firmness of the whole fruit. The fruit firmness can be determined consistently by means of a destructive test.

This paper presents the results of a great number of measurements conducted in four different tomato varieties with the aim to find, using statistical methods, relationships between measured values of different parameters.

METHODS OF MEASURING AND OF ANALYSING THE DATA

Four tomato varieties were studied: Olomoucké (ČSSR), Nova (USA), VF — 65 (USA), and UC — 134.1.2 (USA); the last three are usually reported as apt for mechanical harvesting. The common variety Olomoucké was involved in measurement for the purpose of comparison. Before measuring, early in the morning, the tom to fruits in due number were picked from the respective variety in the experimental field of the Department of Horticulture, University of Agriculture, Prague, and transported to the laboratory. For each of the varieties two series of tests were carried out:

A — series — destructive compressing of the fruit between two plates,
B — series — non-destructive pressing of a plunger into the fruit.
The designations of individual parameters are to be found in Table 1.

Table 1

PARAMETERS, WHICH WERE MEASURED

D_m	—	degree of maturity defined by numbers 1—4: 1 — unmature, 2 — harvesting maturity, 3 — consuming maturity, 4 — overmature. Determined on the base of panel test
C	—	colour, defined by numbers 1—6: 1 — green, 2 — green-yellow, 3 — orange, 4 — light red, 5 — red, 6 — dark red.
d	—	diameter of fruit in mm,
V	—	volume of fruit in 10^{-4} m^3,
F_o	—	force necessary for tearing of fruit from the stem in N,
S	—	area of binding between the fruit and the stem in 10^{-6} m^2,
σ	—	maximum stress on the area of binding between the fruit and the stem which apears during tearing, in MPa,
F_c	—	force at which tomato cracks during the compression between two plates — in N,
D_c	—	deformation of fruit between two plates at cracking in mm,
$\frac{F_c}{D_c}$	—	in Nm^{-1},
t_w	—	thickness of soft wall of tomato fruit in mm,
t_s	—	thickness of tomato skin in mm,
D_E	—	degree of elasticity, see eq. (1),
E_f	—	effective modulus, see eq. (2).

In *A* series of tests 50 fruits of each variety were measured at different stages of maturity. The force F_0, needed for taking off the fruit from the stem, was assessed as first. The Instron compression cell with appropriate measuring apparatus was used as dynamometer. The plant stem was strongly attached to the weight (mass 8 kg) on the compression cell and the fruit under study was pulled upward by hand. The force at which the separation of the tomato occurred, was read on the record made by registering apparatus of the Instron deformation apparatus.

Thereafter, average diameter d, volume V, and mass of the fruit, as well as the area of junction between fruit and stem S were determined. Additionally, the degree of maturity Dm and the colour of the fruit C were assessed according to the scales in Table 1.

Each fruit was compressed at the rate 1.67 mm s^{-1} between two plates using the Instron uiversal testing machine. The force F_c and the deformation D_c corresponding to the cracking of the fruit were read on the deformation curve at the point of maximum value of the force during compression. After the deformation test the thickness of the fruit skin t_s and the thickness of the soft tissue under the skin (t_w) were measured. Both measurements were made by mechanical devices.

Test series B was carried out on twelve fruits at various stage of maturity. Besides determining the fruit size, stage of ripening, colour, and thicknesses t_w and t_s, these fruits were exposed to the above mentioned non-destructive test. A steel plunger with a plane face and 6 mm diameter was pressed against the wall of the tomato at the rate 0.0835 mm s^{-1}. The course of the whole test is demonstrated by the graph in the form of the dependence of force on time (Fig. 1). When the deformation curve began to show a tendency to non-linear course, the process of pressing was stopped, and after 60 second relaxation of the fruit tension, the force was removed at the same rate 0.0835 mm s^{-1}. As result of the non-destructive test the degree of elasticity D_E and the effective mo-

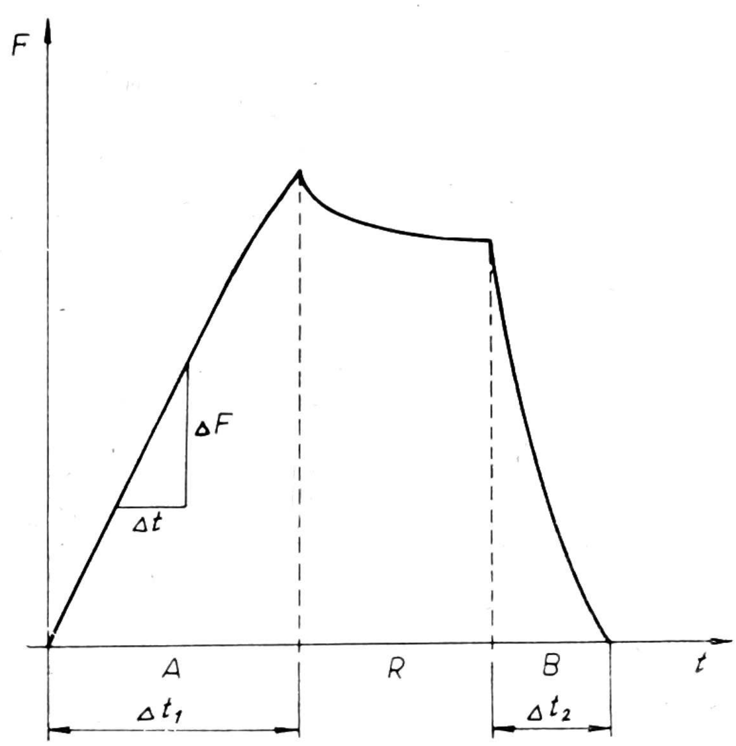

Fig. 1. Example of deformation curve — the dependence of force F on the time t: A — region of loading, R — region of relaxation, B — region of unloading

dulus E_f were calculated from the data of the record (Δt_1 and Δt_2 are time intervals; see Fig. 1) using equations (5,6):

$$D_E = \frac{\Delta t_2}{\Delta t_1} \tag{1}$$

$$E_f = \frac{E}{1 - \nu^2} = \frac{\Delta F}{\Delta t v d_p} \tag{2}$$

where E denotes Young's modulus of deformed tomato fruit (provided the body is homogenous, isotropic, elastic), ν Poisson's ratio, v deformation velocity and d_p plunger diameter.

Using linear regression analysis, statistically significant relations of different measured parameters were found for both series of tests and for all varieties. Equations of the type

$$X = A_i + B_i \cdot Y \tag{3}$$

were used, where A_i, B_i are the constants found by regression analysis of relations between parameters X and Y. The constants B_i are the slopes of lines described by equation (3).

RESULTS

The mean values of measured parameters are arranged in Table 2. Parameters F_c, D_c, and $\frac{F_c}{D_c}$ for the variety UC — 134-1-2 in Table 2 are charged with error, which results from the fact, that the fruit was damaged during its separation from the stem cracks in the area of the pedicel. These cracks only grew wider during the compression test, so that the maximum force F_c did not correspond to the proper cracking of the fruit.

The results of regression analysis of the relations between parameters as measured in test series A are given in Table 3. For each combination of parameters and each variety, in the order Olomoucké, Nova, VF — 65, and VE — 134-1-2, the dependences with statistical significance are denoted by * and ** for 5 and 1% level of significance, respectively. Significant dependences for the parameters in the test series B were found in similar manner.

Important relations in Table 3 are denoted by letters and numbers. The letters mark: T — trivial relations, A — relations of parameters describing fruit anatomy, H — relations of parameters concerning fruit firmness, S — relations of parameters describing bond strength between

Table 2

Mean values of measured parameters

Parameter	Unit	Olomoucké	Nova	VF-65	UC-134-1-2
D_m	—	2.72 ± 0.12**	2.87 ± 0.12**	2.46 ± 0.13**	2.73 ± 0.15**
d	mm	47.3 ± 1.1	33.5 ± 0.5	31.3 ± 0.49	$38.9 \pm 0\ 6$
V	10^{-43}m	0.48 ± 0.03	0.315 ± 0.12	0.358 ± 0.017	0.364 ± 0.017
E_o	N	$13.6 \pm 0{,}7$	7.67 ± 0.38	7.45 ± 0.47	13.62 ± 0.56
S	10^{-62}m	33.3 ± 2.2	9.48 ± 0.26	19.2 ± 1.1	24.1 ± 1.3
σ	MPa	0.454 ± 0.025	0.831 ± 0.045	0.434 ± 0.033	0.595 ± 0.029
F_c	N	31.3 ± 3.3	51.5 ± 2.9	83.4 ± 7.7	$44.8^* \pm 7.1$
D_c	mm	9.01 ± 0.32	10.2 ± 2.9	9.9 ± 0.27	$9.25^* \pm 0.47$
F_c/D_c	Nm^{-1}	3370 ± 320	5030 ± 270	9800 ± 1460	$4450^* \pm 470$
C	—	4.18 ± 0.21	4.46 ± 0.25	3.98 ± 0.23	4.2 ± 0.29
t_w	mm	3.62 ± 0.11	4.48 ± 0.09	4.48 ± 0.09	4.69 ± 0.1
t_s	mm	0.045 ± 0.005	$0{,}055 \pm 0.007$	0.067 ± 0.009	0.041 ± 0.005
E_f	MPa	0.59 ± 0.01	0.64 ± 0.01	0.72 ± 0.01	0.83 ± 0.01
D_E	—	0.67 ± 0.03	0.57 ± 0.01	0.62 ± 0.02	0.56 ± 0.03

* Fruit was cracked during the tearing before the compression test.
** In columns are mean values plus minus the mean error.

fruit and stem, and R — relations of parameters of non-destructive test. These relations can be further divided into two groups according to the number of asterisks far all the varieties together.

I — relations with 8 asterisks,

II — relations with n asterisks, if the relation $5 \leqq n \leqq 8$ is valid.

The relations of the group I are statistically significant in view of a 1% level of significance for all four tomato varieties under study. This cannot be said about the relations of the group II, nervertheless, these relations seem to by typical, too. In this case, at least one variety exhibits statistically significant dependence in view of a 1% level of significance and at least 3 varieties of statistically significant dependence in view of the 5% level of significance.

The results of the linear regression analysis are shown in Fig. 2. The primary parameters describing anatomy of fruit, maturity stage, and colour are in circles, the other parameters are in rectangles. Different parameters are connected by lines expressing the relations found by regression analysis: solid lines denote the relations of the group I, dashed ones the relations of the group II. Decreasing dependence is marked by the typical double-arow on its respective line.

The values of the slopes B_i obtained for relations (3) as found between the thickness of skin and the other parameters are arranged in Table 4. The absolute value of the slope B_i indicates the steepness of the dependence (see eq. (3)).

Table 3

Map of results of regression analysis

	D_m	d	V	F_o	S	σ	F_c	D_c	$\frac{F_c}{D_c}$	C	t_w	t_s
D_m		★	★★		★★	★★ ★★ ★	H'_1 ★★ ★★ ★★ ★★	★★	T_3 ★★ ★★ ★★ ★★	T_1 ★★ ★★ ★★ ★★	★★	A ★★ ★★ ★★ ★★
d			T_2 ★★ ★★ ★★ ★★	★★ ★★	A_2 ★★ ★★ ★★ ★★	★★ ★		★★	★	★★	A_3 ★★ ★★ ★★	★★
V				★★ ★	A'_2 ★★ ★★ ★★ ★★	★★ ★★	★	★ ★★	★		A'_2 ★★ ★★ ★★ ★★	★
F_o					S'_1 ★★ ★	S_1 ★ ★★ ★★ ★	★	★		★★		
S						S_2 ★★ ★ ★★ ★★	★	★			★ ★	
σ							H-S ★★ ★ ★★	★★ ★★	★★ ★ ★	S_3 ★★ ★★ ★★	★★ ★★	★ ★★ ★
F_c								H_2 ★★ ★★ ★★	H_1 ★★ ★★ ★★ ★★	H_2 ★★ ★★ ★★ ★★	★ ★ ★	H_3 ★★ ★★ ★★ ★★
D_c									★★	★ ★★	★	★
$\frac{F_c}{D_c}$										H_3 ★★ ★★ ★	★★	H_4 ★★ ★★ ★ ★★
C											★★ ★	A'_1 ★★ ★★ ★★ ★
t_w												
t_s												

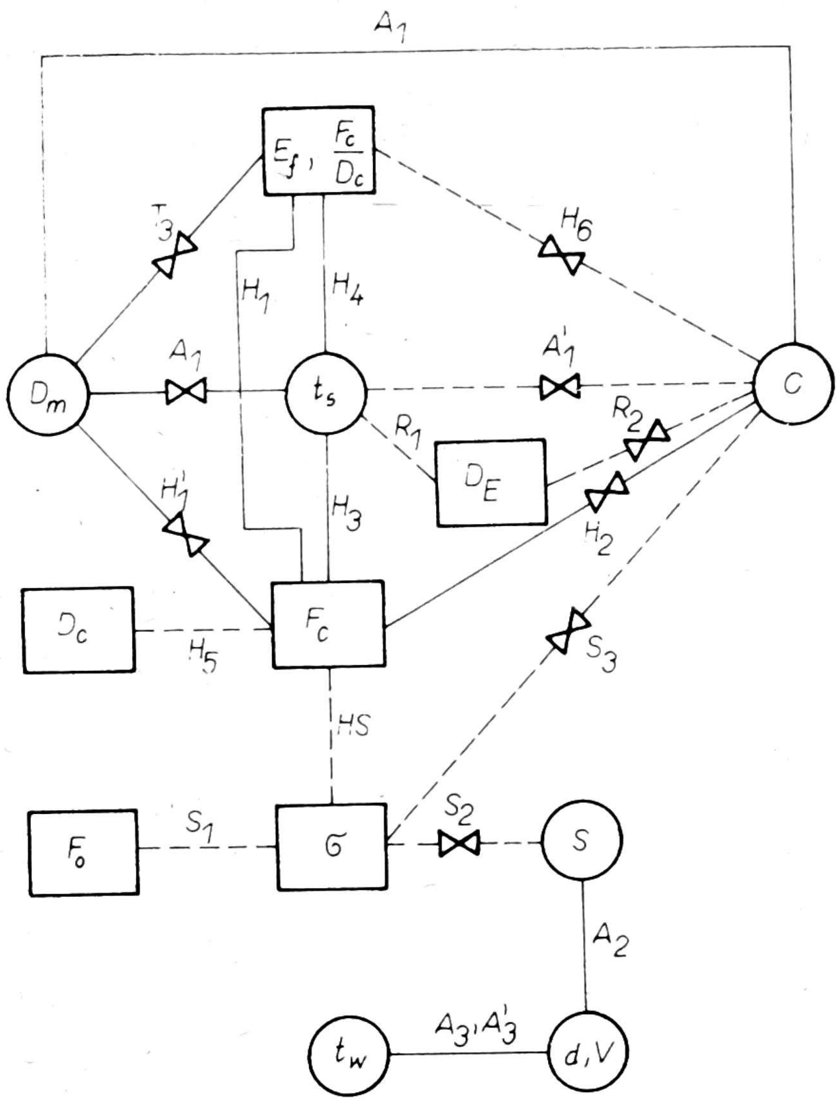

Fig. 2. Map of obtained relations among different parameters (see text)

Table 4

The slope of some measured parameters

Variety	Slopes *Bi*				
	x t_s / *y* C	*x* t_s / *y* D_m	*x* F_c / *y* t_s	*x* F_c/D_c / *y* t_s	*x* E_f / *y* t_s
Olomoucké	—0.011	—0.018	493	50900	0.82
Nova	—0.017	—0.0345	320	34800	0.99
VF-65	—0.024	—0.045	551	60000	2.16
ΠC-34-1-2	—0.0046	—0.018	1464	97100	1.24

DISCUSSION

The relationships among individual parameters are not simple, they represent a complex structure, as can be seen in Fig. 2. We can observe the relations in chains, some of which form closed loops joined to each other in different ways; e.g. the parameter of colour *C* is connected with other parameters by six different relations of the group I and II. Certain regularity, of course, does appear in this complicated structure in Fig. 2. It has been stated for every closed loop that the sense of the change of any parameter occurring in it does not alter along the "path" of the loop. Let us demonstrate this phenomenon on the example of the loop unfolded into the line $C \rhd\lhd F_c \rhd\lhd D_m \rhd\lhd t_s \rhd\lhd C$. Provided that the initial parameter C increases, then, as a result of decreasing dependence C—F_c, the value of F_c decreases, D_m increases, t_s decreases, and C increases. The congruency of the sense of changes of the parameter C before and after its movement round the loop is evident. Described regularity consists in the presence of an even number of double-arrows in every closed loop.

Oescribed the celar-cut relationship between parameters occurring in a closed loop suggests that the relations between parameters can be estimated by putting the known relations together in chains, e.g. on the basis of the relations A_2 and A_3 it may be assumed that the value S will increase with the increasing value t_w etc.

Fig. 2 shows a number of trivial relations or of such that are to be expected, as H_6, H_2, H_1, etc. Apart from the relations of this kind, there are some non-trivial, important dependences summarized in Table 2.

1. The value of maximum stress in the area of junction between fruit and plant σ depends on the colour and firmness of the fruit as a whole F_c.

2. All measured rheologic and mechanical parameters of tomato fruits depend on the skin thickness t_s.

The relation found between σ and F_c suggests that the fruit firmness and the bond strength between fruit and stem depend on the properties common for both tissues. With increasing value of the fruit colour — from green to dark red — the fruit firmness and the bond strength between fruit and stem are decreasing. That means that during ripening not only is the fruit firmness decreasing, but the fruits are also easier to pick.

The dependences of rheological parameters on the skin thickness show that the skin plays an important role in the development of mechanical parameters of the tomato fruit as a whole. In view of the fact that the linear regression analysis of data did not show any statistically significant dependences of rheological and mechanical parameters on the soft wall thickness and on the fruit diameter, it seems that the viscous elastic ball with firm skin 4 may be a suitable model of tomato fruit with regard to its mechanical properties.

Table 4 shows, for different varieties, the degree of dependences of the skin thickness on the fruit colour and maturity stage, as well as the dependences of rheological and mechanical parameters F_c, D_c, F_c/D, E_f on the skin thickness. The values of the slopes B_i as found out from the relation (3) are by order the same for all varieties.

Mechanical harvest of tomatoes requires varieties with increased fruit firmness. The above analysis of relationships between individual parameters shows that the breeding of varieties with these properties may bring about some other unfavourable properties, genetically and anatomically bound with high firmness of fruits. It can be, above all, a stronger bond between fruit and plant and, therefore, a more difficult harvest of these fruits. Disproportion between the bond strength of fruit and stem and the firmness of the soft fruit tissue results in damaging fruits directly at harvest by tearing out a part of tissue together with the pedicel (US — 134-1-2). According to the results of measuring, firmer varieties should exhibit firmer and thicker skin; that is probably not suitable in view of maintaining good consuming and processing quality. Hence, it is evident that a complex investigation of mechanical properties of plants should be involved in tests used under the breeding programme for the selection of suitable plants, which ought to carry fruits not only firm, but also easy to harvest and retaining, besides other consuming or processing mechanical properties.

CONCLUSION

A number of parameters, describing fruit anatomy, fruit firmness, rheological properties, bond strength of fruit and plant, and stage of fruit ripeness, were measured in four tomato varieties. Using linear regression analysis of these parameters a complex of statistically significant relationships between these parameters was found. Besides other results, it was shown, that the firmness of fruit and its elasticity modulus depend significantly on the skin thickness, which is getting thinner during the process of ripening. This conclusion confirms the hypothesis that the firmness of the tomato fruit is determined by the skin firmness. It was found further that with increasing fruit firmness the strength of bond between fruit and plant is increasing, too. These and other results were discussed from the viewpoint of selection work in breeding tomato varieties apt for mechanical harvesting.

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WSTĘPNE BADANIA WŁAŚCIWOŚCI MECHANICZNYCH POMIDORÓW

Streszczenie

Przeprowadzono pomiary niektórych cech mechanicznych czterech odmian pomidorów.

Na drodze analizy regresji liniowej znaleziono związki między parametrami opisującymi anatomię owocu, jego twardością i siłą związania z rośliną. Rezultaty analizy mają pogłębić wiadomości o mechanicznych cechach pomidorów.

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ВСТУПИТЕЛЬНЫЕ ИССЛЕДОВАНИЯ МЕХАНИЧЕСКИХ СВОЙСТВ ТОМАТА

Резюме

Посредством регрессивного анализа данных, измеренных для четырех сортов томатов, были найдены связи между параметрами, описывающими анатомию плода, его прочность и силу связывания с растением. Результаты анализа могут углубить сведения о механических свойствах плода томата.

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