Mechanical properties of maize kernel horny endosperm, floury endosperm and germ
Bo Wang and Jun Wang
Department of Biosystems Engineering, Zhejiang University, Hangzhou, PR China

ABSTRACT
Mechanical damage of maize kernel caused by external forces during processing is closely related to its internal mechanical properties. In this research, three main tissues’ (horny endosperm, floury endosperm and germ) mechanical properties of three maize varieties (Jinyu818, Zhengdan958 and Dafeng30) and five stages of moisture contents (11.78–34.73% w.b.) were evaluated using puncture test. Results showed that there was no (p > .05) or weak significant (0.01 < p < .05) difference between varieties, while significant moisture and tissue material effects were observed. For rupture force (F_{rp}), ultimate strength (\sigma_b), toughness (T_{rp}), initial firmness (F_{inf}), average firmness (F_{avf}), modulus of elastic (E), apparent modulus of elastic (AME), bioyielded force (F_{by}), bioyielded strength (\sigma_s) and penetration force (F_p), outer layer tissue (horny endosperm) of maize kernel at lower stage of moisture contents were higher than those of inner layer tissues (floury endosperm and germ) at higher moisture contents. While for bioyielded deformation (D_{by}) and rupture deformation (D_{rp}) values, results showed that inner layer tissues at with higher moisture content were the highest. Pearson’s correlation analysis showed that most of the parameters had a significant correlation (p < .01, r > 0.80) with each other. This study can be considered as a contribution towards further studying and minimizing the mechanical damage of the maize kernel when applying external force during and post harvesting.

Introduction
Maize (Corn, Zea mays L.) is widely grown in more than 160 countries nowadays, its flavor and nutrition make it utilized in making various dietary foods. To satisfy the enormous demands of maize, the design and development of equipment for mechanical harvesting, packaging and transport have received increasing attention. However, grain kernels with distinct internal structures are very susceptible to mechanical damage during these handling processes. A high percentage of damaged kernel not only result in considerable amounts of brokens and fines, but also reduce the market value of maize due to likely insect and microbial attack. Therefore, further understanding and minimizing mechanical damage have become extremely important issues. Application of high precision engineering technologies, such as multi-body modeling, internal damage simulation, and postharvest quality evaluation regarded the internal tissues have attracted more intentions. Evaluating the mechanical properties of maize kernel tissues is essential during applying these methods. However, there is still a clear knowledge gap between mechanical properties of maize kernel tissues and urgently needed parameters of the technological applications.

Different kinds of methods have been applied in evaluating the mechanical properties of agriculture products, but no standard method is available according to the published literature. The most common method is flat-plate compression test carried out with...
a universal testing machine or a texture analyzer. Previous related studies are abundant, which can be summarized as (1) using the shaped sample which has uniform geometry, but the characteristics of the individual kernel are lost\cite{7,8}, (2) or testing the whole sample whose mechanical properties are not modified, but geometry is irregular, which has been applied in studying cereal grain\cite{9,10} and tomato.\cite{11} Compression tests have also been carried out by many researchers on the whole maize kernel for evaluating the mechanical parameters such as break force and modulus of elastic.\cite{12} However, compression test provides a method to evaluate the mechanical properties of whole samples, so it is not suitable for determining the mechanical properties of maize kernel tissues. Puncture test is an alternative method for measuring the mechanical properties of agriculture products especially pony-size ones. It has been applied in determining the mechanical properties of various agriculture products, including gram\cite{13}, cherry\cite{14}, tomato\cite{15} and et al. Mechanical properties of maize kernel were also determined using puncture test by some researchers.\cite{16,17} However, as mentioned above, previous studies are mainly concerned on the whole maize kernel or horny endosperm only.

Actually, according to the anatomical characteristics of the maize kernel, it can be considered as a multibody system mainly consisting of horny endosperm, floury endosperm and germ (approximate 94% of the kernel composition), which have totally different mechanical properties and geometric shapes\cite{18}, they react differently to the application of external forces. However, according to the aforementioned studies, little information in details is available on the mechanical parameters of these tissues. Additionally, only a few parameters such as rupture force and break energy of the whole kernel were evaluated in these researches. As a matter of fact, many of other critical parameters can be obtained during a puncture test, some of which have been proved to have a closer correlation with internal damage (i.e. bioyield force and ultimate stress).\cite{11,19} Furthermore, moisture content and variety have been proved to be critical factors that significantly affect the mechanical properties of whole maize kernel.\cite{9} Nevertheless, little concerning is given to that of kernel tissues with different moisture contents and varieties.

To solve the above problems, the mechanical properties of maize kernel tissues should be further determined. Additionally, the relationship between the mechanical properties of maize kernel tissues and its varieties and moisture contents need to be found. Therefore, the objective of this paper is to (1) determine the mechanical properties of three maize kernels’ tissues (horny endosperm, floury endosperm and germ) of three varieties differ from horny endosperm content, (2) determine the three tissues’ mechanical properties under different moisture content (3) and analysis the effected of maize variety, tissue material and moisture content on tissues’ mechanical properties. To further provide essential data for further researching and minimizing the mechanical damage of the maize kernel.

**Materials and methods**

**Materials**

The experiments were conducted using three varieties of maize kernel namely Jinyu818 (flint corn), Zhengdan958 (middle type corn) and Dafeng30 (dent corn), which are normally cultivated in China. Dafeng30 has the lowest ratio of horny endosperm to floury endosperm, while Jinyu818 has the highest of that and Zhengdan958 is in-between. Jinyu818, Zhengdan958, and Dafeng30 kernel samples were harvested and shelled manually in August 2016 from Guiyang, Guizhou province, Jinan, Shandong province and Handan, Hebei province, China, respectively. Subsequently, kernels were packed in plastic bags by variety (three branches) and transported to the laboratory. Then, every branch of kernels was selected on the basis of uniformity, examined individually for stress cracks using a candling technique similar to that described by Singh et al.\cite{12}, absence of damage and blemishes. After that, each branch was randomly and equally divided into five groups (approximately 100 g per group) and packed in plastic bags retained for moisture conditioning and subsequent testing.
The initial moisture content of the maize kernel samples was determined using the oven method according to standard protocols (GB 5009.3–2016), the initial moisture content was about 27% (wet basis). Branches with the moisture content of 29.31 and 34.73% were conditioned by adding calculated amounts of distilled water according to the procedure reported by Seifi et al.\textsuperscript{[20]} While moisture contents of 11.78, 17.64 and 23.45% were obtained by drying the samples at different times (at 40°C) to minimize the drying damage.\textsuperscript{[21]} Samples were then transferred to separate double layered ziplock bags and tightly sealed, allowed to reach equilibrium by storing at 4°C in a refrigerator (Haier Co., Qingdao, China) for 1 week.

\textbf{Methods}

\textbf{Instrument system and experimental procedure}

The puncture test on every specimen was performed under laboratory conditions, followed by Blandino et al.\textsuperscript{[22]} As shown in Figure 1a, the measurements were made using an Instron universal testing machine (Instron Instrument Trade Co., Ltd., Shanghai, China) equipped with a 1 mm diameter flat-head stainless steel cylindrical probe, which was fixed by three-jaw chuck and attached to a load cell. The average values of the temperature and relative humidity of the laboratory where the tests were carried out were 25 ± 2°C and 50% ± 10%, respectively.

The experimental procedure was as follows: First, the conditioned individual kernel was polished along the mid-longitudinal face with a sharp razor blade to expose the horny endosperm, floury endosperm and germ with smooth surface\textsuperscript{[22]}; Then, it was glued on the base plate; After that, the probe was pressed into the kernel tissue at a penetration speed of 1 mm/min (quasi-static loading) over a depth of 1.25 mm based on our trial tests; Finally, the force-deformation curve (Figure 1b) displayed on the screen and the data was recorded. The sample was abandoned after the test for a certain tissue is down, 25 specimens (replications) were taken for every tissue and the mean value was reported.

\textbf{Analytical methods of mechanical parameters}

A large number of data can be obtained during the puncture test, but not all of them can be used for analysis, therefore, extraction and calculation of the data is necessary. Some of the parameters can be obtained through extraction and simple calculation of the key points on the curve shown in Figure 1b, including initial hardness, biouyed force, biouyed deformation, rupture deformation, rupture force, average hardness, toughness and penetration force in the tissue (Figure 1b and Table 1). However, other parameters have to be obtained through stress analysis and calculation combined with the direct parameters, such as modulus of elastic, biouyed strength and ultimate strength. The apparent modulus
of elasticity (AME) was calculated according to Boussinesq theory\cite{11,19,23}, in which the relationship between force $F$, deformation $D$, apparent modulus of elastic $AME$ and the diameter of the probe $d$ was given as follows:

$$F = AME \cdot D \cdot d$$  \hfill (1)

And the following relationship was also given:

$$AME = E/(1 - \mu^2)$$  \hfill (2)

where $E$ is Young’s modulus of elastic, $\mu$ is Poisson’s ratio, because the difficulty of determining the Poisson’s ratio of maize kernel’ tissues, in this study, Poisson’s ratio was assigned 0.35 according to the published studies.\cite{24,25} The bioyield strength and ultimate strength in the puncture case are calculated according to Boussinesq theory and published studies\cite{15}, which were given as formula (3) and formula (4), respectively. A list of symbols and abbreviations is given in Table 1.

$$\sigma_s = - \frac{4F_{by}}{\pi d^2}$$  \hfill (3)

$$\sigma_b = - \frac{4F_{rp}}{\pi d^2}$$  \hfill (4)

where $F_{by}$ and $F_{rp}$ are bioyielded force and rupture force, respectively, $\sigma_s$ and $\sigma_b$ are bioyielded strength and ultimate strength, respectively, the negative sign indicates different directions between $\sigma$ and $F$.

**Scanning electron microscope (SEM)**
The upper face of maize kernel horny endosperm, floury endosperm and germ specimens were scanned using a Hitachi SU-8010 scanning electron microscope. The kernels were polished to expose the mid-longitudinal face for the electron microscopy sections.

**Experiment design and statistical analyses**
To evaluate the mechanical properties of maize kernel’ tissues, a completely randomized experimental design with three factors was used. The factors evaluated were maize varieties (Jinyu818, Zhengdan958 and Dafeng30), tissue material (horny endosperm, floury endosperm and germ) and moisture content (11.78–34.73%). Analysis of variance (ANOVA) was performed on the data gathered from the different evaluations with a 95% level of significance. Pearson’s correlations

---

| Symbols or abbreviations | Description | Calculation |
|--------------------------|-------------|-------------|
| $F_{rp}$ (N) | Rupture force (force at the rupture point) |Shown in Figure 1b.|
| $D_{rp}$ (mm) | Rupture deformation (Deformation at the rupture point) |
| $T_{rp}$ (mJ) | Toughness (energy absorbed before the rupture point) |
| $F_{by}$ (N) | Bioyielded force (force at the bioyielded point) |
| $D_{by}$ (mm) | Bioyielded deformation (deformation at the bioyielded point) |
| $F_{avf}$ (N/mm) | Initial firmness (measured at the deformation of 0.015mm) |
| $F_{avf}$ (N/mm) | Average firmness (measured at the rupture point) |
| $F_{p}$ (N) | Penetration force (the average of measured forces at every 1 mm depth up to 1.25 mm depth after the rupture point) |
| $AME$ (MPa) | Apparent modulus of elastic |
| $E$ (MPa) | Modulus of elastic |
| $\sigma_s$ (MPa) | Bioyielded strength |
| $\sigma_b$ (MPa) | Ultimate strength |
Results

Mechanical properties of tissues of different varieties

Previous studies indicated that the mechanical properties of whole maize kernel are significantly different from varieties. In this experimentation, mechanical properties of three portions (horny endosperm, floury endosperm and germ) in three varieties which were different form horny endosperm to floury endosperm ratio were determined using puncture test.

The means and standard errors from 25 repeats of mechanical parameters of Zhengdan958, Jinyu818 and Dafeng30 maize kernel horny endosperm, floury endosperm and germ tissues obtained by the puncture test are shown in Figure 2. Rupture force and rupture deformation measured the breaking thresholds of the tissues when sustaining the external force, which indicated that the ability to resist damage. As can be observed from Figure 2a and 2b, horny endosperm had a higher rupture force (64.44, 71.11 and 73.95 N for Dafeng30, Jinyu818 and Zhengdan958, respectively) but lower rupture deformation (0.44, 0.41 and 0.41 mm for Jinyu818 and Zhengdan958, respectively) than that of floury endosperm (49.36 N, 60.11 mm and 27.38 N, 0.52, 0.66 and 0.44 mm for Dafeng30, Jinyu818 and Zhengdan958, respectively), furthermore, as the reproductive part of a maize kernel, germ had little ability to resist external forces (6.35, 6.34 and 9.51 N for Dafeng30, Jinyu818 and Zhengdan958, respectively) but strongest ability to deformation (0.56, 0.69 and 0.54 N for Dafeng30, Jinyu818 and Zhengdan958, respectively). The toughness defined as the energy required to crack of

Figure 2. Puncture test results of horny endosperm, floury endosperm and germ in Zhengdan958, Dafeng30 and Jinyu818 at the moisture content of 17.64%. Error bar indicates the standard deviation. Values with different letters in each parameter are significantly different according to the Duncan multiple range test at $\alpha = 0.05$. Values of $p$ smaller than 0.05 indicate a significant difference at the 95% confidence level.
the tissue, corresponded to the rupture force and rupture deformation, while ultimate strength expressed the maximum stress that maize kernel tissue can withstand when sustaining external force ignorance the effect of the contact area. As shown in Figure 2c and d, toughness and ultimate strength of horny endosperm (18.70, 18.36, 16.39 mJ and 82.05, 90.54, 94.16MPa for Dafeng30, Jinyu818 and Zhengdan958, respectively) were significantly higher than those of floury endosperm (5.861, 15.002, 5.850 mJ and 62.840, 76.228, 34.856MPa for Dafeng30, Jinyu818 and Zhengdan958, respectively) and germ (1.60, 2.19, 2.46 mJ and 8.08, 8.07, 11.11MPa for Dafeng30, Jinyu818 and Zhengdan958, respectively), indicated that horny endosperm was significantly more difficult to crack than floury endosperm and germ, further indicated that the maize kernel which has a higher proportion of horny endosperm (flint kernel) exhibited higher crack resistance.

Similar trends can be found on the bioyield parameters including bioyield force (Figure 2i), bioyielded deformation (Figure 2j) and bioyielded strength (Figure 2k), which were the parameters indicate the thresholds of initial rupture in the center of the material. As shown in Figure 2i, the significantly lower bioyielded strength of floury endosperm (approximate 70% of horny endosperm) and germ (approximately 10% of horny endosperm) indicated that the maize kernel with a higher proportion of horny endosperm was more prone to internal cracks. Results on germ in Figure 2i–k also indicated that germ was the most sensitive to internal cracks, agreed on the fact that damaged maize kernel has a poor germination rate. In addition, as shown in Figure 2g and h, modulus of elastic and apparent modulus of elastic, which were the most important parameters measured the stiffness of the testing tissues, were also observed the similar results. Indicated that the horny endosperm has a higher resistance to deformation compared with floury endosperm and germ in the elastic stage. However, there was little resistance to deformation when germ sustains the external force. Firmness, which characterized the resistance to deformation under a load up to the point of sudden fracture when contact with processing equipment. As shown in Figure 2e and f, the initial firmness and average firmness of horny endosperm were significantly higher than those of floury endosperm and germ in three varieties. The penetration force (Figure 2l) at the horny endosperm was higher than that of floury endosperm and germ. This indicated that cracks caused by external force propagated more easily in floury endosperm and germ.

Many similar results can be found by examining the previous literature. Singh et al. (1991) reported the individual flint and dent kernels’ modulus of elastic at moisture content of 17% are approximate 175, 130 MPa, respectively, which were higher than those of floury endosperm and germ but slightly lower than horny endosperm obtained from our study, may explained as that the mechanical properties of a whole kernel is a joint action of all tissues but the major contributor was the outer layer (horny endosperm). Furthermore, the ultimate strength was determined as about 38, 28 MPa for individual flint kernel and dent kernels, which is slightly lower than those of floury endosperm in this study, the reason may be that the connections among tissues more likely to break down. Shelef et al. (1969) carried out a puncture test on maize horny endosperm using a 0.41 mm diameter probe, the apparent modulus of elastic of was evaluated as 489 MPa at the moisture content of 14.38%. Other related literature such as reported by Massimo et al., in which mechanical properties of individual maize kernels was evaluated using puncture test with a 2 mm diameter flat-head probe, rupture force was reported as 215 N at moisture content of 10.20%, the higher value could be explained by its lower moisture content, larger probe diameter and puncture location (pericarp).

Statistical analysis shown in Figure 2 revealed that most evaluated parameters was not significantly (p > .05) or weak significant (0.01 < p < .05) influenced by varieties but significant (p < .01) different from tissue materials. In order to illustrate more clearly, ANOVA results of the rupture force and modulus of elastic are presented in Table 2. The left side of the line in Table 2 are comparisons between same tissues of same or different varieties, from which no significant difference (p > .05) of weak significant difference (0.01 < p < .05) were observed. However, on the right side of the line where significance levels of different tissues form the same or different varieties were compared, the results showed that modulus of elastic values are significantly different from tissue materials. In other words, varieties or has no or weak significant effect on the modulus of elastic of
Table 2. P values for the modulus of elastic (E) of maize kernel tissues from different varieties.

|                | Dafeng30-FP | Jinyu818-FP | Zhengdan958-FP | Dafeng30-HP | Jinyu818-HP | Zhengdan958-HP | Dafeng30-G | Jinyu818-G | Zhengdan958-G |
|----------------|-------------|-------------|----------------|-------------|-------------|----------------|-------------|-------------|--------------|
| Dafeng30-FP    | 1           | 0.0396*     | 0.1751 NS      | 1.95648e-008** | 7.4447e-008** | 3.843e-016** | 1.14646e-005** | 8.67657e-006** | 2.59229e-005** |
| Jinyu818-FP    | 1           | 0.1264 NS   | 1              | 1.01426e-007** | 2.3306e-008** | 3.99456e-008** | 4.87635e-007** | 3.49963e-013** | 2.37159e-022** |
| Zhengdan958-FP | 1           | 2.3306e-008** | 2.3306e-008** | 1.46926e-007** | 6.76135e-018** | 2.88806e-022** | 1.95345e-022** | 3.87403e-023** | 2.65735e-023** |
| Dafeng30-HP    | 1           | 0.0572 NS   | 0.0572 NS      | 1           | 0.4542 NS   | 1              | 0.6413 NS   | 0.0156*     | 1            |
| Jinyu818-HP    | 1           | 0.6413 NS   | 0.0555 NS      | 0.0156*     | 1           | 1              | 0.0555 NS   | 0.0156*     | 1            |
| Zhengdan958-HP | 1           | 0.0156*     | 1              | 1           | 1           | 1              | 1           | 1           | 1            |

Symbols and abbreviations: FP (floury endosperm), HP (horny endosperm) and G (germ).
NS is non-significant.
* is significant at the 0.05 level (1-tailed).
** is significant at the 0.01 level (2-tailed).
the tissues within our experimental range. Combining the contrary results were given by previous studies on mechanical properties of the individual kernel\textsuperscript{[12]}, which are significantly affected by their varieties, which may indicating that the differences in mechanical properties of the whole maize kernel are not caused by the differences of its tissues material, but caused by their proportion.

Since there were no significant differences among different varieties for most mechanical parameters, we can assume that sample acquisition and manipulation were carried out in a repeatable way and had no influence on the observations. Therefore, further analysis and discussion on the mechanical behavior of different moisture content were investigated by using only the Zhengdan958 (middle type).

**Mechanical properties of tissues with different moisture contents**

The rupture force, rupture deformation, ultimate strength, toughness, initial firmness, average firmness, modulus of elastic, apparent modulus of elastic, bioyielding force, bioyielding deformation, bioyielding strength and penetration force of the horny endosperm, floury endosperm and germ as a function of moisture content ranging from 11.78 to 34.73\% w.b. are presented in Figure 3. The above-mentioned parameters varied significantly ($p < .01$) between tissue materials and moisture contents.

**Figure 3a** shows that rupture force decreased approximately 70\% (from 99.83 to 34.78N, 42.22 to 11.14N, 15.25 to 3.76N for horny endosperm, floury endosperm and germ, respectively) as moisture content increased from 11.78 to 34.73\%, and horny endosperm was slightly higher than that of germ (approximately 3 times) and floury endosperm (approximately 7.5 times) in rupture force within the experimental range. This indicated that smaller force was necessary to rupture the floury endosperm and germ at higher moisture stages. As can be observed from **Figure 3i** and **l**, bioyielding force (from 77.83 to 25.71N, 29.44 to 6.64N, 10.21 to 2.45N for horny endosperm, floury endosperm and germ, respectively) and penetration force (from 35.30 to 10.46 N, 13.68 to 2.54 N, 4.523 to 0.57 N for horny endosperm, floury endosperm and germ, respectively) also showed the same trend. Which indicated that a lower external force was needed to cause and propagate a crack especially in floury endosperm and germ. Similar trend was also found in ultimate strength (**Figure 3c**, from 117.11 to 44.28, 53.75 to 14.18, 19.42 to 4.76 MPa for horny endosperm, floury endosperm and germ, respectively), toughness (**Figure 3d**, from 18.39 to 12.10, 6.85 to 2.93, 3.73 to 1.20 m\textsuperscript{J} for horny endosperm, floury endosperm and germ, respectively), initial firmness (**Figure 3e**, from 277.18 to 47.69, 118.63 to 24.63, 26.52 to 5.94 N/mm for horny endosperm, floury endosperm and germ, respectively), average firmness (**Figure 3f**, from 311.24 to 59.31, 134.05 to 22.13, 29.41 to 6.17 N/mm for horny endosperm, floury endosperm and germ, respectively), modulus of elastic (**Figure 3h**, from 441.15 to 65.83, 100.8 to 29.25, 22.95 to 4.37 MPa for horny endosperm, floury endosperm and germ, respectively), apparent modulus of elastic (**Figure 3h**, from 502.74 to 75.02, 114.05 to 33.34, 26.16 to 4.97 MPa for horny endosperm, floury endosperm and germ, respectively), bioyielding strength (**Figure 3c**, from 99.09 to 32.74, 37.49 to 8.46, 13.00 to 3.12 MPa for horny endosperm, floury endosperm and germ, respectively). Contrary results were presented in **Figure 3b** and **j**, rupture deformation (**Figure 3b**, from 0.30 to 0.69 mm, 0.31 to 0.54 mm and 0.49 to 0.73 mm for horny endosperm, floury endosperm and germ, respectively) and bioyielding deformation (**Figure 3j**), from 0.19 to 0.429 mm, 0.18 to 0.35 mm and 0.26 to 0.45 mm for horny endosperm, floury endosperm and germ, respectively) increased as the moisture content increased for tissues, less deformation was needed for horny endosperm than for floury endosperm (approximately 90\%) and germ (approximately 70\%). Which indicated that maize tissues with lower moisture content had higher hardness and therefore had higher resistance to deformation and capacity to bear the load.

Up to now, relatively little information is available on the effect of moisture content on mechanical properties of maize kernel horny endosperm, floury endosperm and germ, so it is difficult to make comparisons. There are some papers as related to the effects of moisture content on mechanical properties of whole maize kernel. Shelef et al.\textsuperscript{[25]} reported the apparent modulus of elastic of individual maize kernel ranged from 889 to 165 MPa as moisture content increased from 0.73 to
21.88%. Results conducted by Singh et al.\textsuperscript{[12]} showed that the observed values of ultimate strength, modulus of elasticity, modulus of toughness decreased and ranged from 8–82 MPa, 8–44 mJ, respectively as the moisture content increased from 6 to 34%. Also, there are some papers related to moisture content and mechanical properties of other cereal grains. Yang et al.\textsuperscript{[27]} showed that the rupture force, toughness, apparent modulus of elastic and modulus of elastic decreased as the moisture content increased. Gezer et al.\textsuperscript{[28]} and Aydin\textsuperscript{[29]} have reported that the rupture force of hazelnut decreased with increase in moisture content.

**Pearson’s correlation analysis**

The Pearson’s correlation coefficients (r) between parameters of the testing tissues obtained from the puncture test are summarized in Table 3 to understand their relationships. Most of the parameters were correlated with each other, as has been concluded by other researchers.\textsuperscript{[11]}

Rupture force was most highly correlated with ultimate strength (r = 0.978), satisfied the mathematical relationship between rupture force, probe diameter and ultimate strength in Eq. (10), where the ultimate strength was mainly influenced by rupture force when the probe diameter was constant. A strong relationship was also found between rupture force and most of the other parameters, indicated that it could be used as a representative parameter for mechanical properties. However, weak correlations were presented between rupture force and rupture deformation (r = −0.281), bioyield deformation (r = −0.342), similar trend was also found between bioyield force and rupture deformation (r = −0.285), bioyield deformation (r = −0.341). Similar results have been reported by Sirisomboon et al.\textsuperscript{[11]} These indicated that force thresholds and deformation thresholds are nearly independent parameters. Among the parameters from the puncture test, the rupture deformation had the highest correlation with
Table 3. Pearson’s correlation coefficients (r) among the mechanical properties of maize kernel tissues obtained from the puncture tests.

|     | $F_{rp}$ | $D_{rp}$ | $\sigma_b$ | $T_{rp}$ | $F_{inf}$ | $F_{avf}$ | $E$ | $AME$ | $F_{by}$ | $D_{by}$ | $\sigma_s$ | $F_p$ |
|-----|----------|----------|------------|----------|----------|----------|-----|-------|----------|----------|------------|-------|
| $F_{rp}$ | 1        | -0.2821**| 0.978**    | 0.7267** | 0.6491** | 0.8243** | 0.793** | 0.9116** | -0.3416** | 0.9049** | 0.782** |
| $D_{rp}$ | 1        | -0.2532**| -0.0275   | -0.3934**| -0.4653**| -0.393** | -0.285**| 0.5812** | -0.2842** | -0.178** |
| $\sigma_b$ | 1        | 0.765**  | 0.6483**   | 0.8268** | 0.79**   | 0.79**   | 0.9243**| -0.3361**| 0.9175**  | 0.7885** |
| $T_{rp}$ | 1        | 0.4839** | 0.5459**   | 0.5978** | 0.5978** | 0.752**  | -0.1697**| 0.7562**  | 0.7133**  | -0.178** |
| $F_{inf}$ | 1        | 0.7848** | 0.7904**   | 0.6494** | -0.5031**| -0.5134**| 0.8395**| 0.6776**  | 0.6251**  | 0.596**  |
| $F_{avf}$ | 1        | 0.8604   | 0.8604**   | 0.8362** | -0.4863**| -0.4863**| 0.7998**| 0.6251**  | 0.6251**  | 0.596**  |
| $E$    | 1        | 0.9237** | 0.8059**   | 0.8059** | -0.4863**| -0.4863**| 0.7997**| 0.6251**  | 0.6251**  | 0.596**  |
| $AME$  | 1        | 0.9237** | 0.8059**   | 0.8059** | -0.4863**| -0.4863**| 0.7997**| 0.6251**  | 0.6251**  | 0.596**  |
| $F_{by}$| 1        | -0.3407**| 0.9902**   | 0.9902** | 0.9902** | 0.9902** | 0.9902**| 0.9902**  | 0.9902**  | 0.9902** |
| $D_{by}$| 1        | -0.3417**| -0.2664**  | -0.2664**| -0.2664**| -0.2664**| -0.2664**| -0.2664**| -0.2664**| -0.2664** |
| $\sigma_s$ | 1        | 0.7545** | 0.7545**   | 0.7545** | 0.7545** | 0.7545** | 0.7545**| 0.7545**  | 0.7545**  | 0.7545** |

The mechanical parameters are $F_{rp}$ (rupture force), $D_{rp}$ (rupture deformation), $\sigma_b$ (ultimate strength), $T_{rp}$ (toughness), $F_{inf}$ (initial firmness), $F_{avf}$ (average firmness), $E$ (modulus of elastic), $AME$ (apparent modulus of elastic), $F_{by}$ (bioyieled force), $D_{by}$ (bioyieled deformation), $\sigma_s$ (bioyieled strength), $F_p$ (penetration force).

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
bioyielded deformation \((r = 0.581)\) and was followed by initial firmness and average firmness \((r = 0.465)\). The ultimate strength of the testing tissue was found correlated significantly with bioyielded strength \((r = 0.918)\), indicated that the susceptibility to breakage increased as the stress cracks appear in the kernel. Toughness did not correlate with deformation at the rupture point and deformation at the bioyield point but correlated well with the rupture force and the bioyield force. Initial firmness was found correlated well with modulus of elastic and apparent modulus of elastic \((r = 0.7904)\), followed by bioyielded force \((r = 0.649)\) and bioyielded strength \((r = 0.648)\), these results may be explained as that initial firmness, modulus of elastic, apparent modulus of elastic, bioyielded parameters represent the relationship between the force and deformation of the tissues in the maize kernel under the small strain in elastic stage, indicated that all of the above parameters represents the elastic properties. Furthermore, modulus of elastic and apparent modulus of elastic correlated well with bioyielded force \((r = 0.806)\), bioyielded strength \((r = 0.7904)\), satisfied their relationships in mathematics that presented at Eq. \((9)\), indicated that the material of the tissues of maize kernel shows elasticity property before yielding. The penetration force of the tissues and the ultimate strength correlated best \((r = 0.789)\), followed by rupture force \((r = 0.782)\), bioyielded strength \((r = 0.754)\) and toughness \((r = 0.713)\), all these parameters were the thresholds for different degrees of damage, indicated that penetration force may represent the thresholds that the external force could continues to damage the tissues.

**Discussion**

**Effect of tissue material on mechanical properties**

Comparing the mechanical properties of maize kernel horny endosperm, floury endosperm and germ, the rupture force, ultimate strength, toughness, initial firmness, average firmness, modulus of elastic, apparent modulus of elastic, bioyielded force, bioyielded strength, and penetration force of horny endosperm were higher than those of floury endosperm and germ tissues within the experimental range. While the bioyielded deformation and rupture deformation of germ and floury endosperm were higher than those of horny endosperm. This phenomenon could be explained by the differences among their structures and compositions. Morphology of maize kernel tissues was shown in Figure 4, for both species, as can be observed from Figure 4a, the horny endosperm cells are more sharply polyhedral and larger than the floury endosperm cells and germ cells, the surfaces of the starch granules are angled because they are closely packed, the arrangement of cells is compact and dense. On the contrary, as shown in Figure 4b and c, the typical shape of the cells of the floury endosperm are approximately polyhedral in shape and filled with spherical starch granules, sparse and loose cells arrangement can be observed in germ tissues. Besides, previous studies have indicated that the molecules in the protein film in the maize kernel endosperm are preferentially oriented\cite{30}, powerful intermolecular binding forces were expected due to this special structural arrangement in protein. The ratio of starch to protein has been reported to be 11:1 in floury endosperm and 6:1 in the horny endosperm.\cite{11} Furthermore, cracks which developed in the floury endosperm act as notches for the horny endosperm. Therefore, less applied force was needed to break inner tissue (germ and floury endosperm) of the kernel than outer tissue (horny endosperm), and the corresponding mechanical parameter of inner tissue was lower than that of outer tissue. Blandino et al.\cite{22} reported the rupture force and toughness of individual kernel with pericarp tissue is even higher than those of horny endosperm in their study, furthermore, Gunasekaran et al.\cite{31} reported that cracks firstly originate at the center of the kernel and propagate radially outward when suffered thermal stress. Moreover, similar characteristics were also observed in many other agricultural products such as tomato fruit\cite{32}, cherry\cite{19} and hazelnut.\cite{33}
Effect of kernel varieties on its mechanical properties

In this study, the mechanical parameters of maize kernel tissues, including rupture force, rupture deformation, ultimate strength, toughness, initial firmness, average firmness, modulus of elastic, apparent modulus of elastic, biowyelled force, biowyelled deformation, biowyelled strength and penetration force, no significant or weak significant differences in the above mentioned parameters were observed in three varieties (Jinyu818, Zhengdan958 and Dafeng30) within our experimental range. Interestingly, these results were entirely different from those reported by Li et al.\textsuperscript{8}, who tested the mechanical properties of tomato fruit tissues (exocarp, mesocarp and locular gel tissues) but significant difference between two varieties (Fenguan906 and Jinguang28) was observed, while were very similar to studies published by Güner et al.\textsuperscript{34}, who have evaluated the rupture deformation and rupture force of hazelnut kernel, concluded that variety has no significant effect on kernel and shell’s mechanical properties. This may be explained by the different failure forms between kernel tissue material and fruit tissue material. The failure of fruit tissue under compression loading occurred mainly due to the cell wall rupture caused by great compression force.\textsuperscript{18} However, as shown in Figure 5, the stress crack of maize kernel tissues did not occur across the cell walls, but along the boundary of starch granules by the breakdown of middle connection of the granules in an unpredictable manner. Moreover, analysis of variance statistics in the previous study has indicated that the above-mentioned stress crack characteristics were independent of the kernel variety at 95% level of significance.\textsuperscript{31} Therefore, maize kernel tissue ruptured in a different way compared with fruit tissues, and variety had no or weak significant effect on its mechanical parameters within our experimental range. From this, we may conclude that the differences in mechanical properties for the individual maize kernel were not caused by the mechanical differences of its tissues, but caused by tissues proportions.

Effect of moisture content on its mechanical properties

As can be seen from the obtained mechanical properties of maize kernel tissues at different moisture content levels, the parameters involved in this study decreased heavily as the moisture content increased except for biowyelled deformation and rupture deformation. Indicated that the mechanical behavior of kernel tissue was strongly dependent on its moisture content. This phenomenon may be explained as that when moisture content increased, water molecules entered the polymeric chain units, which were close to each other, the chains were forced to rearrange their relative positions, resulted in mechanical properties variation of the tissue. In addition, the friction coefficient decreased with an increase in water content\textsuperscript{35}, also, crack initiation and propagation would be affected by the levels of moisture present in the system. Consequently, the resistance to deformation and crack decreased with an increase in moisture content of the kernel. The same trend on mechanical properties of many cereal grains and fruits have been reported on wheat\textsuperscript{9}, cashew nut\textsuperscript{36} and individual maize kernel.\textsuperscript{12}

Figure 4. SEM micrographs of maize kernel horny endosperm, floury endosperm and germ (x1200). (a) The micrograph of horny endosperm; (b) the micrograph of floury endosperm; (c) the micrograph of germ.
Conclusion

In this research, the mechanical properties of maize kernel horny endosperm, floury endosperm and germ tissues of three varieties and five different stages of moisture content were determined using puncture test respectively. The main results can be summarized as follows. The variety had no significant or weak significant effect on the mechanical parameters of horny endosperm, floury endosperm and germ. The higher rupture force, ultimate strength, toughness, initial firmness, average firmness, modulus of elastic, apparent modulus of elastic, bioyielded force, bioyielded strength and penetration force values were obtained for outer layer tissue (horny endosperm) of maize kernel compared with inner layer tissues (floury endosperm and germ), while for bioyielded deformation and rupture deformation values were obtained as higher at inner layer than outer layer.

The mechanical parameters of horny endosperm, floury endosperm and germ obtained at five moisture stages were significantly different. Rupture force, ultimate strength, toughness, initial firmness, average firmness, modulus of elastic, apparent modulus of elastic, bioyielded force, bioyielded strength and penetration force decreased heavily as the moisture content increased but bioyielded deformation and rupture deformation was on the contrary. The Pearson’s correlation analysis showed that most of the parameters were significantly correlated with each other. The maize kernel can be regarded as a multibody system, and the obtained mechanical parameters and thresholds of maize kernel horny endosperm, floury endosperm and germ tissues can be used for further studying and minimizing the mechanical damage. Additionally, the obtained data can also be used for a better understanding of mechanical properties of maize kernel as a multibody system.

Acknowledgments

The authors acknowledge the financial support of the National Key Research and Development Program of China through Project 2016YFD070190402.

Funding

This work was supported by the National Key Research and Development Program of China [2016YFD070190402].
References

[1] Lizhang, X.; Yaoming, L.; Zheng, M.; Zhan, Z.; Chenghong, W. Theoretical Analysis and Finite Element Simulation of a Rice Kernel Obliquely Impacted by a Threshing Tooth. Biosyst. Eng. 2013, 114(2), 146–156. DOI: 10.1016/j.biosystemseng.2012.11.006.

[2] Maoguo, X.; Daolin, Z.; Chunming, L. Analysis of Influence Factor on Corn Threshing Performance. J. Agric. Mechanization Res. 2015, 1, 188–191.

[3] Tanaš, W.; Zagajski, P. Mathematical Modeling of the Amount of Grain Damage during Combine Harvesting. J. Res. Appl. Agric. Eng. 2010, 55(2), 110–112.

[4] Mestres, C.; Matencio, F.; Louisalexandre, A. Mechanical Behavior of Corn Kernels: Development of a Laboratory Friability Test that Can Predict Milling Behavior. Cereal Chem. 2011, 72(6), 652–657.

[5] Herak, D.; Kabutey, A.; Divisova, M.; Simanjuntak, S. Mathematical Model of Mechanical Behaviour of Jatropha Curcas. L. Seeds under Compression Loading. Biosyst. Eng. 2013, 114(3), 279–288. DOI: 10.1016/j.biosystemseng.2012.12.007.

[6] Blandino, M.; Sacco, D.; Reyneri, A. Prediction of the Dry-Milling Performance of Maize Hybrids through Hardness-Associated Properties. J. Sci. Food Agric. 2013, 93(6), 1356–1364. DOI: 10.1002/jsfa.2013.93.issue-6.

[7] Alamar, M. C.; Vanstreels, E.; Oey, M. L.; Moltó, E.; Nicolai, B. M. Micromechanical Behavior of Apple Tissue in Tensile and Compression Tests: Storage Conditions and Cultivar Effect. J. Food Eng. 2008, 86(3), 324–333. DOI: 10.1016/j.jfoodeng.2007.10.012.

[8] Li, Z.; Li, P.; Yang, H.; Liu, J.; Xu, Y. Mechanical Properties of Tomato Exocarp, Mesocarp and Locular Gel Tissues. J. Food Eng. 2012, 111(1), 82–91. DOI: 10.1016/j.jfoodeng.2012.01.023.

[9] Ponce-García, N.; Ramírez-Wong, B.; Torres-Chávez, P. I.; Figueroa-Cáceres, J. D. D.; Serna-Saldivar, S. O.; Cortez-Rocha, M. O. Effect of Moisture Content on the Viscoelastic Properties of Individual Wheat Kernels Evaluated by the Uniaxial Compression Test under Small Strain. Cereal Chem. 2013, 90(6), 558–563. DOI: 10.1094/CCHEM-12-12-0166-R.

[10] Ponce-García, N.; Ramírez-Wong, B.; Torres-Chávez, P. I.; Figueroa-Cáceres, J. D. D.; Serna-Saldivar, S. O.; Cortez-Rocha, M. O.; Escalante-Aburto, A. Viscoelastic Properties Evaluation of Conditioned Wheat Kernels and Their Doughs Using a Compression Test under Small Strain. J. Sci. Food Agric. 2016, 97(4), 1235–1243. DOI: 10.1002/jsfa.2017.97.issue-4.

[11] Sirisomboon, P.; Tanaka, M.; Kojima, T. Evaluation of Tomato Textural Mechanical Properties. J. Food Eng. 2012, 111(4), 618–624. DOI: 10.1016/j.jfoodeng.2012.03.007.

[12] Singh, S. S.; Finner, M. F.; Rohatgi, P. K.; Buelow, F. H.; Schaller, M. Structure and Mechanical Properties of Corn Kernels: A Hybrid Composite Material. J. Mater. Sci. 1991, 26(1), 274–284. DOI: 10.1007/BF00576063.

[13] Sasikala, V. B.; Ravi, R.; Narasimha, H. V. Textural Changes of Green Gram (Phaseolus Aureus) and Horse Gram (Dolichos Biflorus) as Affected by Soaking and Cooking. J. Texture Stud. 2011, 42(1), 10–19. DOI: 10.1111/jts.2011.42.issue-1.

[14] Sirisomboon, P.; Pornchoaloempong, P. Instrumental Textural Properties of Mango (Cvmam Docmai) at Commercial Harvesting Time. Int. J. Food Prop. 2011, 14(2), 441–449. DOI: 10.1080/10942910903226058.

[15] Li, Z.; Lv, K.; Wang, Y.; Zhao, B.; Yang, Z. Mechanism and Structural Properties of Corn Kernels: Softness Parameter, Water Absorption and Hardness. Food Rev. Int. 2012, 28(2), 105–113. DOI: 10.1080/10498850.2011.570731.

[16] Singh, S. S.; Finner, M. F.; Rohatgi, P. K.; Buelow, F. H.; Schaller, M. Structure and Mechanical Properties of Corn Kernels: A Hybrid Composite Material. J. Mater. Sci. 1991, 26(1), 274–284. DOI: 10.1007/BF00576063.

[17] Sasikala, V. B.; Ravi, R.; Narasimha, H. V. Textural Changes of Green Gram (Phaseolus Aureus) and Horse Gram (Dolichos Biflorus) as Affected by Soaking and Cooking. J. Texture Stud. 2011, 42(1), 10–19. DOI: 10.1111/jts.2011.42.issue-1.

[18] Sirisomboon, P.; Pornchoaloempong, P. Instrumental Textural Properties of Mango (Cvmam Docmai) at Commercial Harvesting Time. Int. J. Food Prop. 2011, 14(2), 441–449. DOI: 10.1080/10942910903226058.

[19] Li, Z.; Lv, K.; Wang, Y.; Zhao, B.; Yang, Z. Multi-Scale Engineering Properties of Tomato Fruits Related to Harvesting, Simulation and Textural Evaluation. LWT - Food Sci. Technol. 2015, 61(2), 444–451. DOI: 10.1016/j.lwt.2014.12.018.

[20] Gaytán-Martínez, M.; Figueroa-Cárdenas, J. D.; Reyes-Vega, M. L.; Rincón-Sánchez, F.; Morales-Sánchez, E. Microstructure of Starch Granule Related to Kernel Hardness in Corn. Rev. Fitotecnia Mex. 2006, 29(42), 135–139.

[21] Shandera, D. L.; Jackson, D. S. Corn Kernel Structural Integrity: Analysis Using Solvent and Heat Treatments. Cereal Chem. 2002, 79(2), 308–316. DOI: 10.1094/CCHEM.2002.79.2.308.

[22] Sandhu, K. S.; Singh, N.; Malhi, N. Some Properties of Corn Grains and Their Flours I: Physicochemical, Functional and Chapatti-Making Properties of Flours. Food Chem. 2007, 101(3), 938–946. DOI: 10.1016/j.foodchem.2006.02.040.

[23] Blahovec, J.; Jeschke, J.; Houška, M. Mechanical Properties of the Flesh of Sweet and Sour Cherries. J. Texture Stud. 2010, 26(1), 45–57. DOI: 10.1111/j.1745-4603.1995.tb00783.x.

[24] Seifi, M. R.; Alemardani, R. The Moisture Content Effect on Some Physical and Mechanical Properties of Corn (Sc 704). J. Agric. Sci. 2010, 2(4), 125. DOI: 10.5539/jas.v2n4p125.

[25] Sheng, S. Y.; Wang, L. J.; Li, D.; Mao, Z. H.; Adhikari, B. Viscoelastic Behavior of Maize Kernel Studied by Dynamic Mechanical Analyzer. Carbohydr. Polym. 2014, 112(2), 350–358. DOI: 10.1016/j.carbpol.2014.05.080.

[26] Blandino, M.; Mancini, M. C.; Peila, A.; Rolle, L.; Vanara, F.; Reyneri, A. Determination of Maize Kernel Hardness: Comparison of Different Laboratory Tests to Predict Dry-Milling Performance. J. Sci. Food Agric. 2010, 90(11), 1870–1878. DOI: 10.1002/jsfa.4027.

[27] Johnson, K. L.; Contact Mechanics; Cambridge univ. Press: Cambridge, 1985.

[28] Gustafson, R. J.; Thompson, D. R.; Sokhansanj, S. Temperature and Stress Analysis of Corn Kernel—Finite Element Analysis. Trans. ASAE. 1979, 22(4), 955–960. DOI: 10.13031/2013.35133.
[25] Shelef, L.; Mohsenin, N. N. Effect of Moisture Content on Mechanical Properties of Shelled Corn. Cereal Chem. 1969, 46(3), 242–253.

[26] Balastreire, L. A.; Herum, F. L.; Blaisdell, J. L. Fracture of Corn Endosperm in Bending Part II: Fracture Analysis by Fractography and Optical Microscopy. Trans. ASAE. 1982, 25(4), 1062–1065. DOI: 10.13031/2013.33668.

[27] Yang, Z.; Sun, J.; Guo, Y. Effect of Moisture Content on Compression Mechanical Properties and Frictional Characteristics of Millet Grain. Trans. Chin. Soc. Agric. Eng. 2015, 31(23), 253–260.

[28] Gezer, I.; Haciseferoğlu, H.; Demir, F. Some Physical Properties of Hacılığlı Apricot Pit and Its Kernel. J. Food Eng. 2003, 56(1), 49–57. DOI: 10.1016/S0260-8774(02)00147-4.

[29] Aydin, C.; Physical Properties of Hazel Nuts. Int. Agrophys. 2002, 25(2), 115–121.

[30] MacMasters, M. M.; Hilbert, G. E. Glutinous Corn and Sorghum Starches. Ind. Eng. Chem. 1944, 36(10), 958–963. DOI: 10.1021/ie50418a022.

[31] Gunasekaran, S.; Deshpande, S. S.; Paulsen, M. R.; Shove, G. C. Size Characterization of Stress Cracks in Corn Kernels. Trans. ASAE. 1985, 28(5), 1668–1672. DOI: 10.13031/2013.32496.

[32] Rančić, D.; Quarrie, S. P.; Pečinar, I. Anatomy of Tomato Fruit and Fruit Pedicel during Fruit Development. Microsc. Sci. Technol. Appl. Educ. 2010, 2, 851–861.

[33] Delprete, C.; Sesana, R. Mechanical Characterization of Kernel and Shell of Hazelnuts: Proposal of an Experimental Procedure. J. Food Eng. 2014, 124, 28–34. DOI: 10.1016/j.jfoodeng.2013.09.027.

[34] Günür, M.; Dursun, E.; Dursun, I. G. Mechanical Behaviour of Hazelnut under Compression Loading. Biosyst. Eng. 2003, 85(4), 483–491. DOI: 10.1016/S1537-5110(03)00089-8.

[35] Horabik, J.; Molenda, M. Grain Pressure in a Model Silo as Affected by Moisture Content Increase. Int. Agrophys. 2000, 14(4), 385–392.

[36] Swain, S.; Gupta, J. Moisture Related Mechanical Properties of Drum-Roasted Cashew Nut under Compression Loading. J. Crop Weed. 2013, 9(1), 164–167.