Oat Grain/Groat Size Ratios: A Physical Basis for Test Weight

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ABSTRACT

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Market value of oat grain is largely determined by test weight or bulk density, yet little is known of the physical basis for test weight in oats. We have hypothesized that a larger sized groat relative to the oat grain (the kernel with the hull) would generate higher test weight oats because the groat is the densest structure in the oat grain. We tested this by measuring oat grain size and oat groat size by digital image analysis for 10 genotypes grown in 10 environments. We also measured other physical characteristics of the oats grains and groats including mean grain and groat mass, test weight, and groat percentage. We found that the groat/grain size ratio was highly correlated with test weight. Because the oat grain image area was nearly twice that of the groat, we suggest that there are significant amounts of empty space within the oat hull, which detracts from test weight. We also found that oat groat size distributions, like oat grains, fit bimodal distributions better than normal distributions.

Oat kernel size is of interest to the oat milling industry because grain size is an important component to consider when dehulling oats with an impact dehuller. Larger oat grains can be dehulled at slower rotor speeds than smaller oat grains (Ganssmann and Vorwerck 1995), presumably because an oat kernel with a larger mass will possess more energy of inertia when impacting the walls of the impact dehuller than smaller oat grains at the same rotor speed. Application of excessive mechanical energy in the dehulling of oat grains will result in excessive groat breakage, whereas application of insufficient energy will result in lower dehulling efficiency (Doehlert et al 1999; Doehlert and McMullen 2001). Many facilities dehulling oats for human consumption will separate kernels into streams of different grain sizes to optimize milling yield (Deane and Comers 1986; Ganssmann and Vorwerck 1995).

Studies completed at this laboratory have indicated that oat grains tend to form bimodal size distributions (Doehlert et al 2004a, 2005). This distribution pattern is probably caused by the architecture of the oat spikelet. Oat spikelets typically contain two grains, where the first or primary kernel is significantly larger than the secondary kernel (Doehlert et al 2002, 2005). Thus primary kernels may make up a subpopulation of larger sized grains and secondary kernels may make up a smaller grain size subpopulation in the apparent bimodal distribution. Deviations from the perfect bimodal distribution have been attributed to the presence of single-kernel and triple-kernel spikelets, as well as other sources of variation related to position of the spikelet on the panicle and variation among panicles (Doehlert et al 2002, 2005). Genotypic and environmental variation in kernel size has also been described (Doehlert et al 2002, 2004a).

None of the previously mentioned studies on oat kernel size have addressed the question of groat size, the groat being the oat caryopsis that is encased within the oat hull (composed of the lemma and palea). There are several reasons why groat size is of interest, especially in relation to the oat grain (with hulls) size. The groat is the grain portion flaked to generate old-fashioned style oat flakes. Groat size affects the maximum size of the flake that can be generated. Also, the mass of the groat relative to the mass of the oat grain is referred to as the groat percentage, and is the principal factor affecting milling yield. The size of the groat relative to the size of the oat grain may influence the test weight, also called the bushel weight, the hectoliter weight, or the bulk density of the oats. The value of oats sold on the open market is usually strongly affected by test weight (Ganssmann and Vorwerck 1995). Because the groat is denser than the hulls of the oat, oats with larger groat size relative to the grain may be of greater test weight. Also of interest is whether oat groat size distributions are bimodal, as are the oat grain size distributions (Doehlert et al 2004a, 2005).

In this study, we analyzed oat grain and groat size from 10 genotypes grown in 10 environments by digital image analysis, and compared sizes and oat grain/groat size ratios with other physical characteristics of the oats, including test weight. We also analyzed size distributions of the oat grains and groats and applied bimodal distribution analysis to groat distributions.

MATERIALS AND METHODS

Plant Material

Ten oat (*Avena sativa* L.) cultivars (AC Assiniboia, Belle, CDC Boyer, Derby, Hytest, Jerry, AC Medallion, Otana, Triple Crown, and Youngs) were grown at five locations (Carrington, Edgeley, Fargo, Minot, and Williston in North Dakota) in 2000 and 2001. A seeding rate of 2.47×10^6 kernels/ha was used for all experiments. Herbicide treatments consisted of preemergence application of 3.93 kg/ha of propchlor and postemergence application at the three-leaf stage with a tank mix of 0.14 kg/ha of thifensulfuron, 0.07 kg/ha of tribenuron, and 0.14 kg/ha of clopyralid. Experimental units consisted of four rows spaced 0.3 m apart and 2.4 m long. The two center rows were harvested with a two-row binder and threshed with a plot thresher. Grain was cleaned using an air-screen cleaner to remove chaff.

Quality Analyses

Test weight was determined by weighing a fixed volume of grain from a test weight filling hopper (Seedburo Equipment Company, Chicago, IL). Bulk densities of groats were measured because sufficient volumes of groats were not easily prepared for the test weight determination. Groats were weighed and placed in a graduated cylinder. The cylinder was tapped several times to assure uniform packing before measuring the bulk volume of the groats. Groat percentage of field plot samples was determined with a compressed air dehuller (Codema, Eden Prairie, MN), correcting for hulled grain remaining after dehulling was described as the final groat percentage in Doehlert and McMullen (2001). Mean grain mass and mean groat mass were determined by counting the number of kernels in a 10-g sample. Kernels were counted with an automated seed counter (Seedburo).

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Digital image analysis was used to measure the length, width, and image area of individual oat grains and groats in samples. Details of the image gathering, analysis procedure, validation procedures, and resolutions were described previously in Doehlert et al (2004a). Means and variances were calculated from collected individual oat grain and groat measurements for each sample. Typically oat grain samples contained 250–400 kernels and groat samples contained 350–450 kernels.

Experimental Design and Statistical Analyses

Field plots were arranged in a randomized complete block design with three replicates. Analysis of variance was applied to data where genotypes were considered fixed, and environments were considered random. Analyses of variance were calculated with the Statistix computer package (Analytical Software, Tallahassee, FL), where the environment-by-replicate mean square was used as an error term to test the environmental effect, the genotype-by-environment interaction mean square was used to test the genotypic effect, and the genotype-by-environment interaction was tested with the residual mean square. Mean separation was evaluated by the least significant difference, which was also calculated by the Statistix software program using the previously described error terms. Correlations were calculated from phenotypic means within each environment and were pooled according to Steel et al (1997). The bimodality test used was described in an earlier report (Doehlert et al 2004a) and was used essentially in the same way for this study. The test was performed on each replicate of each genotype/location and compared the likelihood that the data fit a single normal distribution with the likelihood that every data point belongs to either of two normally distributed subpopulations, each with its own mean and variance. In what follows, "Prob1" refers to the probability that a particular kernel in a sample is in the first (smaller kernel size) subpopulation and the "bimodality coefficient" is a factor describing the fit of the bimodal model versus a normal distribution. Bimodality coefficients of >8.8 were considered to be significantly bimodal (Doehlert et al 2004a).

RESULTS

Analysis of variance indicated significant genotypic and environmental main effects and a significant genotype-by-environment interaction for all characteristics presented here (analysis of variance tables not shown). The genotype-by-environment interactions were primarily attributed to differences in crown rust resistance among the genotypes and has been discussed in previous reports (Doehlert et al 2004a, 2005). Genotypic means of linear measurements of oat grain and groat size are presented in Table I. Genotypes ranked differently in terms of oat grain size when compared with groat size. Youngs and AC Assiniboia had the largest oat grains as measured by grain image area. CDC Boyer oat grains were significantly smaller than Youngs oat grains, but CDC Boyer groats did not differ significantly in image area from Youngs groats. Also, even though Otana had larger oat grain image area, Jerry, Belle, and Hytest all had a larger groat image area than Otana. Genotypic rankings of oat grain width and groat width differed as well but there was less relative range to the values so less significance is attributed to these.

Genotypic rankings of oat grain test weight and groat bulk density were fairly consistent (Table II). Jerry and Hytest were among the top three for both oat grain test weight and groat bulk density, and Derby, Otana, and CDC Boyer had the lowest oat grain test weights and groat bulk densities. Genotypes also ranked similarly for mean oat grain mass and mean groat mass. AC Assiniboia and CDC Boyer were among the top three for both oat grain and groat mass, and Otana, Jerry, Derby, and Belle made up the lowest four genotypes for both oat grain and groat mass (Table II). AC Assiniboia and Hytest had the highest groat percentages, as determined by compressed air dehulling and Otana and Derby had the lowest groat percentages.

TABLE I
Genotypic Means of Oat Grain (with hull) and Oat Groat Linear Dimensions Measured by Digital Image Analysis

Genotype	Grain Image Area (mm^2)	Groat Image Area (mm^2)	Grain Length (mm)	Groat Length (mm)	Grain Width (mm)	Groat Width (mm)
AC Assiniboia	24.1a	11.6a	10.68bc	6.49a	3.03a	2.32ab
Belle	21.0d	10.7d	10.03d	6.20b	2.81g	2.27bc
CDC Boyer	23.3b	11.3ab	10.81b	6.53a	2.86ef	2.22c
Derby	22.8b	9.9e	10.64bc	5.97c	2.88e	2.21c
Hytest	21.2d	11.1b–d	9.38e	6.18b	2.99ab	2.33a
Jerry	20.4e	9.9e	9.26e	5.77d	2.94cd	2.27bc
AC Medallion	22.2c	10.8cd	10.13d	6.12b	2.94cd	2.27bc
Otana	21.3d	8.5f	10.17d	5.28e	2.82fg	2.13d
Triple Crown	22.8b	10.8cd	10.50c	6.25b	2.90de	2.26bc
Youngs	24.6a	11.2bc	11.11a	6.43a	2.95bc	2.29ab

[a] Values are means of three replicates from each of 10 environments in North Dakota. Values in the same column with the same letter do not differ significantly at $P < 0.05$ (mean separation LSD).

TABLE II
Genotypic Means of Some Physical Characteristics of Oat Grain and Groats

Genotype	Grain Test Wt (g/L)	Groat Bulk Density (g/L)	Mass/Grain (mg)	Mass/Groat (mg)	Groat Percentage
AC Assiniboia	485bc	773cd	35.8a	27.1a	73.3ab
Belle	480b–d	795ab	28.5d	22.6de	71.5ab
CDC Boyer	453ef	759e	33.5bc	26.0ab	70.2bc
Derby	432fg	762de	28.7d	20.8e	63.7d
Hytest	529a	790ab	32.1c	25.0bc	74.1a
Jerry	497b	801a	29.2d	21.4e	70.6a–c
AC Medallion	470c–e	769de	32.2c	24.3b–d	69.9bc
Otana	413g	763de	24.7e	16.5f	60.0d
Triple Crown	463c–e	782bc	32.1c	23.7cd	69.8bc
Youngs	456d–f	771c–e	34.0b	24.3b–d	67.7c

[a] Values are means of three replicates from each of 10 environments in North Dakota. Values in the same column with the same letter do not differ significantly at $P < 0.05$ (mean separation LSD).

The groat/grain area ratios and the groat/grain length ratios were remarkably consistent in ranking (Table III). The correlation coefficient for these characters was 0.98 ($P < 0.01$). Rankings of the groat/grain width ratios were less consistent and the correlation coefficient with the groat/oat area ratio was only 0.62 ($P < 0.01$). The groat/grain mass ratio was surprisingly inconsistent with the groat percentage, which was supposed to be a nearly identical measure. The difference is likely due to the aspiration involved in the groat percentage measurement, whereas the groat/oat mass ratios were determined from hand-dehulling and separation from hulls. During mechanical dehulling, small groats and broken groats may be removed by the aspiration process, whereas no such loss occurs in hand-dehulling. The genotypic rankings of groat/grain test weight ratios (Table III) were largely consistent with the rankings of the bulk densities themselves (Table II).

Correlation analysis of oat and groat size analyses (Table IV) indicated that the groat/grain image area ratio and the groat/grain length ratio were positively and significantly correlated with test weight and groat percentage. Oat grain length was negatively and significantly correlated with test weight but was not significantly correlated with groat percentage. Groat image area and mean groat mass were positively correlated with groat percentage. Groat percentage was significantly correlated with test weight.

Oat grain size distributions generally showed patterns resembling bimodal or multimodal distributions (Figs. 1 and 2). Size distributions of oat grain and groats for the cultivars CDC Boyer, AC Medallion, and Hytest grown at Edgeley (Fig. 1) and Williston (Fig. 2) in 2001 are shown. These data are typical of all genotypes and locations, which essentially showed the same trends. Although data used for analysis of variance were means from individual plots, for illustrative purposes, all three replicates from a genotype/environment were pooled. This was permissible because the replicate effect within genotype/location was not significant (analysis of variance not shown). Figures indicate clearly that not only were groats smaller than oat grains, but their range of sizes was smaller than that of oat grains. Distributions appeared by visual inspection to be less bimodal than the oat grain size distributions.

Bimodal analysis of oat grain and groat distributions (Table V) indicated that the bimodal coefficients were all well above the threshold of 8.8, and thus all the distributions could be better described by a bimodal distribution than by a normal distribution. The grand mean of oat grain bimodal coefficients (74.3) was greater than the grand mean of groat bimodal coefficients (54.6), strengthening the visual impression that the groat distributions were less bimodal than the oat grain size distributions. The Prob1 values, which indicate the numerical proportion of kernels in the putative subpopulation with smaller sized kernels, also appeared to differ between oat grains and groats. The grand mean of Prob1 for oat grains was 0.460, whereas the grand means of Prob1 for groats was 0.627.

Thus groats appeared to have greater numbers in the smaller kernel size subpopulation than did the oat grains. The bimodal analysis calculated mean image area values for oats and groats in subpopulations 1 and 2 of the putative bimodal population. It is interesting to note that oat groat/grain area ratios for subpopulation 1 (grand mean 0.533) appeared to be larger than the oat groat/grain area ratio for subpopulation 2 (grand mean 0.488).

DISCUSSION

The relatively high correlation of oat groat/grain size ratios with test weight provides insight into a possible physical basis for test weight in oats. The oat grain and groat image areas, while being only two-dimensional measures, are presumably correlated to the actual volume of individual grains and groats. These volumes do not appear to have been ever studied closely. Because the groat is denser than the hull, a greater proportion of the oat grain volume composed of groat would contribute to greater test weights. Data in Table I indicates that the oat grain image area is about twice that of groat. Whereas, the hull would be expected to make up some of the difference in size, some the remainder may consist of empty space. Empty space within oat grains would most certainly contribute to lower test weight of the oats. Thus thin, tight fitting hulls would appear to contribute to high test weight and would be reflected by high groat to oat grain size ratio.

Because a large groat relative to the hulls would contribute to a high groat percentage, one might expect test weight to be related to groat percentage. Indeed, this study as well as a number of other studies (Stoa et al 1936; Atkins 1943; Bartley and Weiss

TABLE IV
Correlations of Oat Grain (with hull) and Groat Characteristics with Test Weight and Groat Percentage[a]

Characteristic	Test Wt	Groat Percentage
Grain image area	–0.278*	0.036
Groat image area	0.526**	0.719**
Groat/grain area ratio	0.856**	0.823**
Grain length	–0.630**	–0.205
Groat length	0.316*	0.540**
Groat/grain length ratio	0.868**	0.768**
Grain width	0.582**	0.446**
Groat width	0.758**	0.549**
Groat/grain width ratio	0.439**	0.380**
Grain width/length ratio	0.801**	0.368**
Groat bulk density	0.626**	0.439**
Mean grain kernel mass	0.452**	0.593**
Mean groat mass	0.588**	0.692**
Groat/grain mass ratio	0.604**	0.685**
Groat percentage	0.694**	–

[a] *,** Significant at $P < 0.05$ and $P < 0.01$.

TABLE III
Genotypic Means of Ratios of Groat to Oat Grain Physical Characteristics

	Ratios				
Genotype	Area	Length	Width	Mass	Bulk Density
AC Assiniboia	0.485b	0.609bc	0.768bc	0.761bc	1.60d
Belle	0.511a	0.620b	0.808a	0.795a	1.66cd
CDC Boyer	0.486b	0.606bc	0.776bc	0.776ab	1.68cd
Derby	0.439d	0.565e	0.771bc	0.722d	1.79b
Hytest	0.526a	0.660a	0.779b	0.781ab	1.50e
Jerry	0.489b	0.625b	0.772bc	0.736cd	1.62cd
AC Medallion	0.487b	0.610bc	0.773bc	0.761bc	1.64cd
Otana	0.402e	0.522f	0.757c	0.664e	1.90a
Triple Crown	0.474bc	0.597cd	0.782b	0.741cd	1.69c
Youngs	0.458cd	0.582de	0.779b	0.716d	1.70bc

[a] Values are means of three replicates from each of 10 environments in North Dakota. Values in the same column with the same letter do not differ significantly at $P < 0.05$ (mean separation LSD).

1951; Pomeranz et al 1979; Doehlert et al 1999) indicated this. However other studies have disputed this. Greig and Findlay (1907) suggested little relation between test weight and milling yield. Zavitz (1927) suggested that test weight was more influenced by kernel shape than by meaningful quality characteristics. Because groat percentage is a ratio of mass, one can envision an oat grain with loose-fitting but thin hulls that would have a high groat percentage and a low test weight. In contrast, an oat grain with tight-fitting but thick hulls might have a low groat percentage but a high test weight. Results presented here suggest that oats with larger groats, especially relative to the oat size, are most likely to have higher groat percentage (Table IV).

The strong negative correlation of oat grain length with test weight is very interesting, especially considering that oat grain length was not significantly correlated with groat percentage (Table IV). A number of other studies have made a similar suggestion (Love 1914; Zavitz 1927; Barbee 1935; Bruckner et al 1956; Root 1979; Forsberg and Reeves 1992; Doehlert et al 1999). Cutler (1940) illustrated this concept by showing that test weight of a given oat sample could be increased 20–45% by clipping off the tips of oat grains, by mechanically rubbing, and polishing the oat grains. It would appear that the tips of the oats may frequently extend beyond the length of the groat, so that the tips may largely encase only air. Thus the clipping of empty tips would decrease empty volume within the oat grain and act to improve test weight. Because the tips of the hulls affect the grain volume much more than they would affect the grain mass, such a factor might not affect groat percentage at all, which is consistent with our observation.

Test weight can be considered to be affected by two factors: kernel density and a packing factor. Kernel density would be equal to the mean kernel mass divided by the mean volume of the individual oat grains. A packing factor would be determined by the interstitial space, or the space between kernels when they are packed in a container. The packing factor could be conveniently expressed as an interstitial space ratio, or the ratio of the interstitial volume to the total volume. To the knowledge of the authors, neither oat grain densities nor interstitial volumes of packed oats have been reported in the literature. From this study, we would assume that increased groat/oat grain area ratio would be affecting the grain density; that is, oat grains with larger groats relative to the total grain size will have more mass per grain volume. Symons and Fulcher (1988) showed a strong correlation between the width/length ratio of oat grains and test weight, and suggested that larger width/length ratios represented more spherical kernels that could pack more efficiently. Here, we also found the oat width/length ratio to be significantly correlated with test weight (Table IV). The oat grain width/length ratio was also correlated with the groat/oat area ratio, suggesting that oat grains with higher width/length ratios may also be denser than longer kernels. Thus, a portion of the correlation of oat grain width/length ratio with test weight may be due to the association of the grain width/length ratio with grain density. An earlier study from this laboratory (Doehlert et al 2004b) concluded that packing efficiency may be a relatively minor factor affecting bulk density. We tested effects of size and shape of kernels on packed volume of grain. We separated oats into fractions of different sizes and found that the summation of the volumes of the fractions did not differ from the volume of the original sample. Thus the packing efficiency of the fractions did not differ from the packing efficiency of the mixture. We concluded that certain shapes of oats are associated with higher test weight because the grains are denser, not because of any effect on packing. This controversy may require direct measurement of interstitial volumes to resolve.

Like oat grain distributions, oat groat image area distributions resembled bimodal distributions more than normal distributions (Figs. 1, 2, Table V). Differences in the Prob1 values between oat grains and groats (Table V) would suggest that there were changes

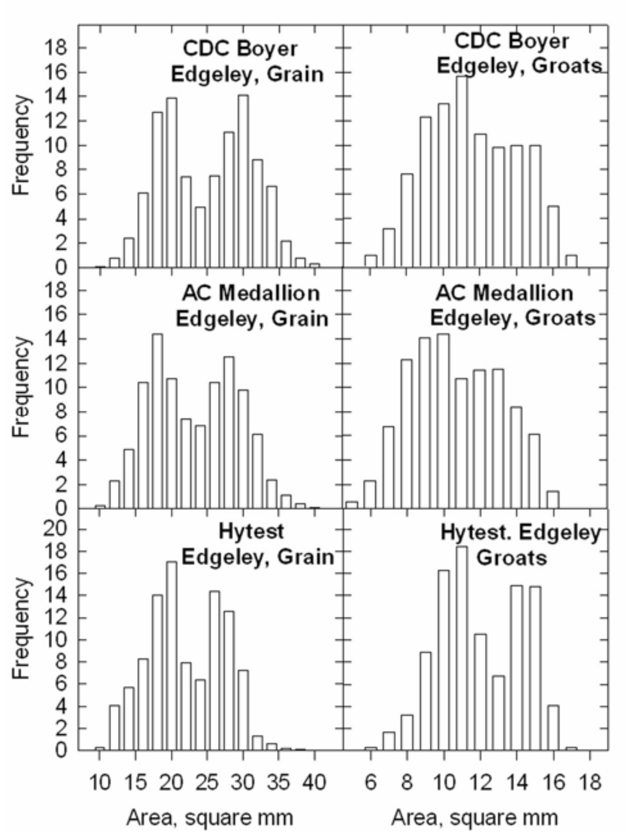

Fig. 1. Histograms of oat grain and groat size distributions for Hytest, AC Medallion, and CDC Boyer oats grown at Edgeley, ND, in 2001.

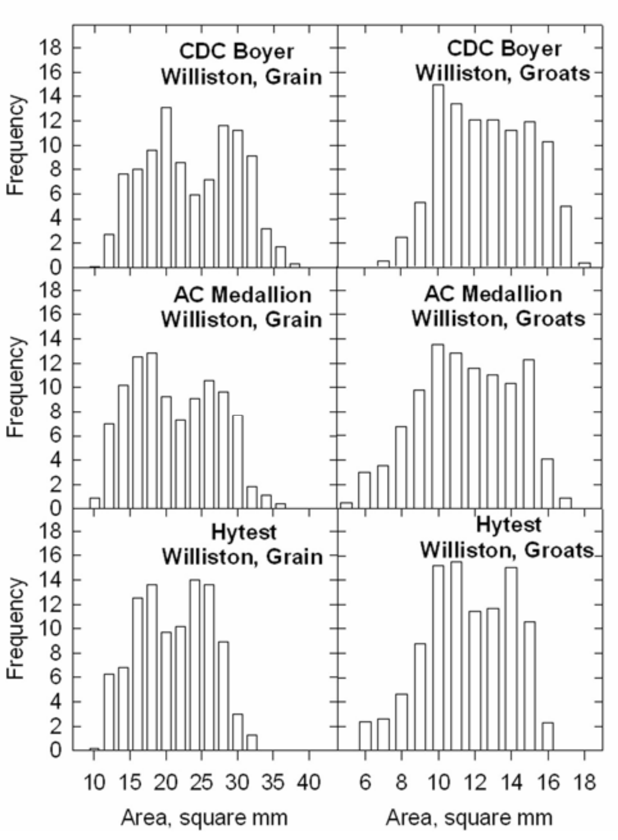

Fig. 2. Histograms of oat grain and groat size distributions for Hytest, AC Medallion, and CDC Boyer oats grown at Williston, ND, in 2001.

TABLE V

Genotypic Means from Bimodal Analysis of Kernel Image Area Derived from Digital Image Analysis[a,b]

Coefficient	Grain Area1 (mm^2)	Groat Area1 (mm^2)	Grain Area2 (mm^2)	Groat Area2 (mm^2)	Groat/Grain Area1 Ratio	Groat/Grain Area 2 Ratio	Grain Prob1	Groat Prob1	Grain Bimodal Coefficient	Groat Bimodal Coefficient
AC Assiniboia	19.3a	10.1a	29.3a	14.0ab	0.527c–e	0.479de	0.521a	0.615b	51.9ef	65.5ab
Belle	17.3bc	9.5bc	24.6e	12.7de	0.557ab	0.517ab	0.522a	0.654ab	42.1f	43.2cd
CDC Boyer	17.6b	9.6a–c	27.6b	13.7ab	0.549a–c	0.496b–d	0.433cd	0.598b	79.1b–d	59.4ab
Derby	16.8c	8.5d	26.8c	12.3ef	0.505e	0.458e	0.404de	0.604b	116.0a	62.1ab
Hytest	16.9c	9.7a–c	25.3d	13.4bc	0.573a	0.531a	0.494ab	0.625ab	61.6de	65.0a
Jerry	15.7d	8.4d	24.2e	12.1f	0.535b–d	0.500b–d	0.452b–d	0.584b	93.5bc	70.5ab
AC Medallion	17.0c	9.3c	26.8c	13.5bc	0.547a–c	0.505bc	0.469bc	0.643ab	78.5b–d	61.2ab
Otana	15.9d	7.5e	24.4e	10.2g	0.471f	0.422f	0.374e	0.599b	95.6b	25.3e
Triple Crown	17.6b	9.6a–c	26.8c	13.0cd	0.545b–d	0.488cd	0.434cd	0.649ab	76.0cd	55.7bc
Youngs	19.3a	9.9ab	29.6a	14.1a	0.518de	0.480de	0.494ab	0.698a	48.8ef	38.3de

[a] Analysis calculated mean kernel image areas of two putative subpopulations (1 and 2) within the sample of kernels. Prob1 is the probability that any given kernel in the sample is in subpopulation 1 and gives relative sizes of the two subpopulations. The bimodal coefficient provides an estimate as whether the size distributions are better described by a normal or bimodal distribution pattern. Bimodal coefficients of >8.8 are considered significantly bimodal. Values are means of three replicates from each of 10 environments in North Dakota.

[b] Values in the same column with the same letter do not differ significantly at $P < 0.05$ (mean separation LSD).

in the assignments of kernels to the first and second subpopulation before and after dehulling. It is interesting that the oat groat/grain area ratio for subpopulation 1 appeared larger than subpopulation 2. The subpopulation 2 includes the larger sized kernels and is presumably derived from the primary kernels of the two-kernel spikelets. Previous analyses had suggested that primary kernels had lower groat percentage than secondary kernels (Doehlert et al 2002, 2005) and that smaller kernels within a sample had greater bulk densities and groat percentages (Doehlert et al 2004a,b). The suggestion that kernels from subpopulation 1 have a greater oat groat/grain size ratio than oats from subpopulation 2 is consistent with the observed correlation of the oat groat/grain ratio test weight. This conclusion is dependent on the assumption that the larger sized groat population is derived from the larger sized grain population, for which we have no direct evidence.

Here we suggest that the oat groat/grain size ratio provides one aspect for the physical basis of test weight in oats. It is interesting, considering the importance of test weight in determining value in oats, that so little attention has been paid to physical characteristic associated with this important trait. Many breeders may already intuitively understand many of the concepts presented here when they select for lines with plump kernels, minimizing the amount of hull overlapping the groat on the tips. Further characterization of this trait may allow oat breeders to more easily select for high test weight oats.

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