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Investigation into a practical approach and application of cotton fiber elongation

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Abstract

Background The strength of cotton fiber has been extensively studied and significantly improved through selective breeding, but fiber elongation has largely been ignored, even though elongation contributes to determining the energy needed to break fibers. Recent developments to calibrate the high volume instrument (HVI) for elongation has renewed interest in elongation. However, it is not understood how best to utilize yet another fiber property which has the potential to add to the complexity of fiber selection. To explore a practical approach to applying elongation, cotton samples were tested using single fiber methods, the Stelometer, and the HVI. Comparison of strength, elongation, and combined properties such as modulus were explored.

Results HVI testing was shown to be sensitive enough to characterize elongation differences but unlike single fiber testing it was unable to capture within-sample variation. Fiber bundle testing, like Stelometer and HVI was shown to reduce bias due to fiber selection.

Conclusion The use of secant modulus, an intrinsic material property, allowed for one value to represent both strength and elongation. Secant modulus was shown to contain more useful information than either elongation or work-to-break. Work-to-break was shown to be more influenced by a specific value of breaking force or elongation rather than the intrinsic behavior of the sample being tested. Exploring the influence of genetics and environment on elongation, and its interaction with other fiber properties, requires additional work. Secant modulus, by combining strength and elongation into one value, shows the potential to incorporate elongation values into fiber characterization without increasing the complexity of current fiber selection processes.

Keywords Cotton, Elongation, Tenacity, Work-to-break, Modulus

Background

Cotton (*Gossypium spp.*) requires significant mechanical handling and processing from harvesting through conversion to an end-product such as apparel and other textile goods. Advancements in processing rates and spinning speeds increase the mechanical stresses on cotton fiber. Mechanical processing can degrade the quality of the cotton through fiber breakage. Fiber breakage reduces fibers' length uniformity, resulting in a reduction in yarn strength and quality. Some fiber breakage during ginning is unavoidable to separate the lint from the seed and remove non-lint content; however, fiber breakage should be minimized as much as possible (Dever et al. 1988; Griffin, Jr. 1979; Hughs et al. 2013). Processing of cotton from fiber to finished goods will also result in fiber breakage (Krifa 2008; Robert and Blanchard 1997). Fibers are also broken during the testing processes, further confounding the characterization and understanding of fiber quality (Krifa 2006).

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Cotton samples with relatively long fiber length and high length uniformity result in more uniform yarns with higher strength (Smith et al. 2010; Wakeham 1955). The importance of fiber length in textile processing has made length one of the most critical fiber parameters in establishing cotton quality. Fiber strength has been assigned high importance because strong fibers will generally suffer less breakage and preserve the length parameters of the sample, resulting in yarns with improved uniformity and tensile properties (Farag and Elmogahzy 2009). The relationship between yarn strength and fiber strength is not simple (Pan et al. 2001). The failure of a yarn made by spinning staple fibers is normally due to fiber slippage and not fibers breaking within the yarn. This mechanism of failure means that several fiber properties interact to determine yarn strength: length, length uniformity, and fineness; as well as yarn parameters such as count, twist, and spinning system used (Fiori et al. 1954; Furferi and Gelli 2010; Zurek et al. 1987). Longer and finer fibers result in stronger yarns due to the increased number of fibers within the cross-section of a yarn as well as the increased surface area of contact among fibers, which increases the adherence among fibers due to friction (Campos et al. 2003).

Fiber bundle strength, as measured by the High Volume Instrument (HVI), is currently the only tensile property reported during cotton classification by the United States Department of Agriculture (USDA), therefore it is the most common tensile property used throughout the cotton industry (Hequet et al. 2014). Alternatively, the Stelometer (Rouse 1964) and Favimat (Foulk and Mcalister, III 2002) may also be employed to measure the tensile properties of cotton. All three methods are able to report both fiber strength and elongation, although elongation has not been widely utilized in the determination of fiber quality (Benzina et al. 2007; Mathangadeera et al. 2020).

As with most properties, the measurement of bundle strength and elongation is impacted by the distribution of tensile properties within the sample. Numerous studies have examined the complex relationship of single fiber tensile properties to bundle tensile properties and, ultimately, to yarn properties (Frydrych 1995; Koo and Suh 1999; Nachane and Krishna Iyer 1980; Orr et al. 1955). The Favimat single fiber tester allows for the distribution of tensile properties to be measured, although it is a time-consuming process. The Stelometer (ASTM D-1445 2021) uses a flat bundle of fibers secured across two clamps with a 3.2 mm (1/8 inch) gauge length, while the HVI (Taylor 1986) uses a tapered bundle of fibers with a 3.2 mm gauge length. Replicated bundle tests can be used to measure some level of variation of tensile properties within a sample; however, the true distribution of tensile properties is only able to be measured with single fiber testing.

In recent years, there has been a renewed focus on using elongation in breeding programs (Benzina et al. 2007; Kelly et al. 2019) and the role of elongation in processing (Mathangadeera et al. 2020). Much of the renewed interest is due to the development of calibration procedures for the HVI elongation measurement (Delhom et al. 2020; McCormick et al. 2019). However, questions remain about how to apply an elongation measurement to provide the most utility and how to interpret elongation in light of other confounding factors such as measurement equipment, test parameters, variety, growing condition, and the interaction with other fiber properties. The HVI elongation measurement is the only practical approach to routine measurement of fiber elongation, but it must be understood how to implement the measurement. It is not known if the best approach is to utilize HVI strength and elongation independently or to consider strength and elongation together. Simply adding another measurement, elongation, would add to the existing burden of end-users being able to only manage a finite number of parameters. Fiori (1956) proposed two possible approaches to utilizing both strength and elongation in understanding the response of cotton samples to processing. One approach is a toughness index, while the other is the stiffness of the fiber. Toughness index is the work-to-break, or energy required to break the fiber(s). The stiffness of fiber can be assessed by examining the elastic properties of a fiber by calculating the secant modulus, E_s. The secant modulus is the slope of the line drawn from the origin to the breaking point on a force and elongation diagram for the fiber.

Most materials can be categorized as either brittle or ductile. Ductile materials experience both elastic and plastic deformation under loading. Elastic deformation is completely recoverable when the load is removed, while plastic deformation occurs when the yield stress has been exceeded, and plastic deformation results in permanent deformation of the material after the load is removed. Cotton does not exhibit plastic deformation during loading. Brittle materials do not exhibit plastic deformation and are generally considered to exhibit low rates of elongation under loading. Cotton fibers have a wide range of elongation, with approximately 10% elongation being near the upper end of expected elongation. However, the force–elongation loading of cotton is linear and can therefore be modeled as an elastic material complying with Hooke's Law (Eq. 1) (Benzina et al. 2007; Hearle and Sparrow 1979). Hooke's Law shows that a force applied to an elastic material will result in a change in length governed by a constant, k. The constant k can be calculated by dividing the force, F, by the change in length, x, which is also referred to as strain. The modulus of a material can be calculated by dividing stress (force divided by the cross-sectional area of the material being tested) with strain (Eq. 2). It is seldom practical to directly measure modulus for cotton fibers or fiber bundles due to challenges with accurately measuring stress or strain due to the variation in fiber cross-section and structure. However, because the stress–strain curves of cotton fibers are linear, tenacity and elongation at break can be used to approximate the secant modulus (Fiori et al. 1956).

$$F = k * x \quad (1)$$

F = Force.

x = displacement (change in length).

k is a material dependent constant.

$$E = \frac{\sigma}{\varepsilon} \quad (2)$$

E = Young's modulus.

σ = uniaxial stress (force per unit surface area).

ε = strain (change in length divided by original length).

Work-to-break is determined by the area under the force–elongation curve. The tenacity-elongation curve can be used in lieu of the force–elongation curve to account for the influence of fiber fineness. Since the tenacity-elongation curve is essentially linear, the area under the loading curve is calculated by dividing the product of tenacity and elongation in half.

The introduction of more fiber quality parameters may be useful in a breeding program where the improvement of specific traits is being pursued. The utility of elongation as an independent property in a breeding program has been demonstrated by multiple researchers (Benzina et al. 2007; Kelly et al. 2019). However, for practical use by processors, the introduction of an additional trait adds to the complexity of fiber selection and modeling the expected yarn properties from fiber properties (El Moghazy et al. 1990; Frydrych 1992; Yang and Gordon 2016).

It is proposed that normalizing breaking strength (tenacity) by breaking elongation to calculate the secant modulus would provide a measure with the combined utility of strength and elongation without resulting in additional parameters for consideration by end-users.

The reported study examines the use of both secant modulus and work-to-break when calculated using the breaking tenacity and elongation as an indicator of textile processing quality. Work-to-break has been studied and proposed as a combined measure of strength and elongation (Hsieh et al. 2000; Kelly et al. 2019; Mathangadeera et al. 2020; Sasser et al. 1991), but there have been no modern attempts to revisit the use of secant modulus. The study compares the distribution of single fiber testing results to bundle tests, examines the test results as an indicator of textile processing, and investigates approaches to incorporate elongation into fiber quality assessments.

This study was undertaken using cotton grown as part of the National Cotton Variety Trials (NCVT) over two crop years and in multiple locations (Zeng 2021), as well as the elongation calibration materials reported by McCormick and colleagues (2019). The samples have been characterized with a wide array of techniques for measuring tensile properties of strength and elongation and subjected to the stresses of textile processing via aggressive opening and cleaning. A large set of the 2018 NCVT samples were processed into ring-spun yarns and tested for skein strength.

Materials and methods

Thirty cotton samples were used in the primary fiber testing study; 14 samples were obtained from the 2017 crop year NCVT and 14 samples from the 2018 crop year NCVT. Two additional samples used in the testing are the high and low HVI elongation calibration materials (McCormick et al. 2019). The variety and growing location for the NCVT samples is shown in Table 1. Across both crop years, there are nine separate varieties and 14 growing locations across 10 states included in the sample set. Candidate samples were chosen to represent as wide a range of HVI elongation values as possible, and then samples with at least 100 g of material remaining after NCVT testing and processing were selected for inclusion in this study. Each sample was manually blended prior to testing to ensure uniform sub-sampling for each test.

All samples were tested on the same HVI 1000 (Uster Technologies, Knoxville, TN) at the Agricultural Research Service in New Orleans, LA. HVI testing was carried out with five replications for micronaire and ten measurements of length, strength, and elongation. Elongation measurements on the HVI were calibrated per the procedure reported by Delhom et al. (2020). Calibration samples were tested prior to testing, in the middle of testing and at the end of testing to ensure there was no instrument drift during the testing of the sample set (Benzina et al. 2007). Breaking elongation values ranged from 4.92% to 10.50%. All HVI properties were measured and recorded, however color and leaf grade data are not included because the hand harvesting and tabletop ginning methods used in small-scale breeder trials have an overwhelming impact on those measurements. All samples were characterized for length and fineness, in the raw state and after two passes through the Shirley, using an AFIS PRO2 (Uster Technologies, Knoxville, TN) with three replications of 5 000 fibers each.

Samples from the 2017 NCVT were tested according to ASTM D-1445 (2021) with a Spinlab Stelometer 654

Table 1 NCVT sample varieties, years, and growing locations

Variety	Crop year	Growing location	HVI strength/ ($g·tex^{-1}$)	HVI elongation/%	HVI E_S/($g·tex^{-1}$)	HVI work to break/ ($N·m^2·kg^{-1}$)
DP 1612 B2XF	2017	Lamesa, TX	32.1	9.30	3.45	46.9
	2018	Lamesa, TX*	31.4	9.95	3.16	50.6
		Lubbock, TX	30.7	10.50	2.92	49.1
DP 1646 B2XF	2017	Altus, OK	33.3	9.14	3.65	47.8
		Portageville, MO	31.5	7.19	4.42	35.8
	2018	Lubbock, TX	29.5	9.85	3.00	45.6
		Lubbock, TX*	31.0	10.02	3.10	48.7
DP 1820 B3XF	2018	Keiser, AR	33.4	6.22	5.40	32.6
DP 358 RF	2017	Five Points, CA	43.5	6.80	6.42	46.4
FM 2574 GLT	2018	St. Joseph, LA	33.8	5.28	6.42	28.0
NG 4545 B2XF	2017	Altus, OK	33.5	5.86	5.74	30.8
		Lamesa, TX	29.0	7.58	3.91	34.4
		Lubbock, TX*	31.2	6.61	4.72	32.3
		Starkville, MS	32.4	6.61	4.91	33.6
	2018	Maricopa, AZ	31.7	5.21	6.09	25.9
		Portageville, MO	33.4	4.92	6.81	25.8
PHY 499 WRF	2017	Portageville, MO	40.0	7.74	5.18	48.6
		Starkville, MS	32.8	8.69	3.77	44.6
	2018	Lubbock, TX	32.2	9.95	3.24	50.3
PHY 764 WRF	2017	College Station, TX	38.2	7.39	5.21	44.3
		Lubbock, TX*	36.3	7.84	4.63	44.6
		Portageville, MO	31.4	8.95	3.52	44.1
		Stoneville, MS	41.5	7.03	5.99	45.8
	2018	Jackson, TN	37.5	7.42	5.06	43.6
		Keiser, AR	36.9	7.29	5.09	42.2
TAM KJ-Q14	2018	Florence, SC	37.5	6.45	5.83	37.9
		Keiser, AR	40.2	6.90	5.84	43.5
		Lubbock, TX*	40.4	7.42	5.45	47.0

*Indicates dryland (rainfed only) production, all other samples were produced with irrigation

(Uster Technologies, Knoxville, TN) with six replications. Single fiber testing was performed using a Favimat (Textechno Herbert Stein GmbH & Co., Monchengladbach, Germany). Samples from the 2017 NCVT were tested using a 13 mm gauge length with pre-tension determined by the vibroscope method from ASTM D1577-07, Option C (2018) per the method described by Delhom et al. (2010) and a 13 mm/min rate of extension. Samples from the 2018 NCVT and the elongation calibration cotton were tested using a 3.2 mm gauge length and 20 mm/min rate of extension as described by Mathangadeera et al. (2020). Measurements were taken on 300 fibers total from each of the 30 individual samples. The different gauge lengths were used to assess the impact of gauge length on comparing single fiber to bundle-fiber testing as well as examining the impact of fineness measurements on the result due to the role of fineness in determining the pretension and the normalization of the breaking force into tenacity.

The 30 samples were subjected to two passes through a Shirley Analyzer (Shirley Developments, Ltd., Stockport, UK) following ASTM D2812-12. The two passes through the lickerin and cleaning cylinder of the Shirley Analyzer were intended to mimic the potential for damage through opening and cleaning in a textile mill.

The NCVT provides for a spinning test in which two bobbins of 22 Ne ring spun yarns with a 4.1 twist multiple are produced for certain samples. Samples were processed on a custom draw frame and a modified SDL Atlas ring spinning machine (Rock Hill, SC) as reported by Manandhar and Delhom (2018). Yarn strength is reported via skein breaking (ASTM D1578-93 2016). A total of 342 samples from the 2018 NCVT were used in the yarn portion of the study, which represented 171 variety-location combinations that were produced, ginned, and tested with two field replications.

A second set of four cotton samples were used to examine the bias introduced by the difference in gauge lengths. These four samples were well blended HVI calibration cotton representing a range of length which are used in testing the responsiveness of HVI testing over a wide-range of fiber lengths (Table 2). These cotton samples were sorted into length groups using the Suter-Webb comb sorter according to ASTM D1440-07 (2019). Fibers from different mean length groups were analyzed for fineness using ASTM D1577-07, Option A (2018); in which 100 fibers from each of the length groups examined were counted out and weighed as a bundle and this measurement was replicated five times. The mean gravimetric fineness for each length group was used as the fineness for normalizing breaking force into tenacity as 100 fibers from each length group were tested on the Favimat using a 3.2 mm gauge length and 20 mm/min rate of extension as described by Mathangadeera et al. (2020).

Data analysis

Fiber quality testing and Shirley Analyzer samples were carried out in a complete randomized design. Spinning trials were carried out in a randomized complete block design, in which the samples were blocked by crop year. Statistical analyses were performed with Minitab 21.1 (Minitab, LLC, State College, PA). Results were considered statistically significant only for P-value ≤ 0.05. Means comparisons for analysis of variance was performed using Tukey's method and 95% confidence.

The calculation of secant modulus, E_S, will result in different units depending upon the instrumentation used and the units which the instrument reports the data using. A pure measurement of breaking force and tenacity will result in cN/tex, however, by convention, the cotton industry expects Stelometer and HVI testing to report tenacity as $g_f \cdot tex^{-1}$. The difference between cN and g_f is minimal as 1 g_{force} is equal to 0.98 cN. Modulus is traditionally reported using pressure units, however tensile properties of textile materials are reported as tenacity rather than using stress (pressure units) so the units of secant modulus should be considered to be the same as the tenacity measurement.

Table 2 HVI calibration cottons used for length group testing

Cotton	Upper half mean length/ mm	Strength/ $(g \cdot tex^{-1})$	Micronaire	Uniformity index
38	30.2	33.4	4.6	84.2
36	28.8	27.4	4.5	82.8
34	26.7	27.9	4.1	80.8
32	25.1	23.7	3.5	77.7

Results and discussion

As stated earlier, the samples chosen from the NCVT represented a wide range of tensile properties. The mean and within-sample variability were considered for the samples (Tables 3 and 4) as variation within the sample must be considered to properly understand the role of elongation. There is a wide range of within-sample variability for these properties, especially in comparison to the elongation calibration cotton. However, the elongation calibration materials were selected for their uniformity in elongation and then subjected to rigorous blending to improve the uniformity of properties as demonstrated by the low coefficient of variation within each sample. The calibration cotton serves as an ideal case for uniformity of tensile properties.

The mean HVI elongation was nearly the same for both the 2017 (7.6%) and 2018 (7.7%) samples, although the 2018 samples had a slightly broader range of elongation. The intra-sample variation for elongation, as measured by the HVI, tends to be higher than for other properties. The secant modulus variation is generally higher than the one for elongation but less variable than work-to-break, when considering the range of values for the samples in the study. Secant modulus is less variable than work-to-break as it is more consistent within a sample regardless of the specific breaking tenacity or elongation of a specific sub-sample.

Single fiber testing on the Favimat instrument allows the distribution of tensile properties within a sample to be captured. The Favimat instrument is inherently length biased as the fibers must be long enough to span both clamp surfaces and the desired gauge length. A longer gauge length, such as the 13 mm used for the 2017 NCVT samples, allows the linear density of each fiber to be determined using the vibroscope method (Gonsalves 1947). The use of the vibroscope allows each fiber to be normalized by a more precise linear density. The 2018 samples and calibration materials were tested using a 3.2 mm gauge length. The shorter gauge length allows more fibers to be sampled, however the breaking force is normalized to tenacity using an estimated value for linear density applied to all fibers equally. The 2017 NCVT samples tested with 13 mm gauge length were subjected to a pre-tension equal to 0.5 $cN \cdot tex^{-1}$ based on the fineness determined by the instrument. The 2018 samples tested using a 3.2 mm gauge length were subjected to a pre-tension 2 $cN \cdot tex^{-1}$ (Mathangadeera et al. 2020). Although the values of tensile properties are influenced by gauge length and cross-head speed, the within-sample

Table 3 Basic statistics of the HVI fiber properties for the samples

	Mic	UHML/mm	UI/%	Tenacity/(g·tex^{-1})	Elongation/%	E_S/(g·tex^{-1})	Work to break/(N·m^2·kg^{-1})
2017 NCVT							
Average	4.4	29.8	84.0	34.8	7.6	4.7	41.4
Minimum	3.5	26.6	79.5	29.0	5.9	3.5	30.8
Maximum	5.3	35.7	87.8	43.5	9.3	6.4	48.6
Intra-sample CV/%							
Average	3.2	2.4	1.2	4.3	5.4	7.8	5.8
Minimum	0.6	0.7	0.4	1.3	1.3	1.1	1.5
Maximum	13.9	6.7	1.9	7.5	17.3	17.4	18.9
2018 NCVT							
Average	4.7	30.5	83.4	34.3	7.7	4.8	40.8
Minimum	4.2	27.7	80.9	29.5	4.9	2.9	25.8
Maximum	5.3	34.0	86.3	40.4	10.5	6.8	50.6
Intra-sample CV/%							
Average	1.9	1.9	1.2	3.3	3.7	6.0	3.8
Minimum	0.8	0.4	0.6	1.2	1.6	3.3	0.9
Maximum	5.2	3.0	2.2	6.6	7.1	10.7	9.5
Elongation calibration cottons							
Low	5.1	29.2	80.0	33.4	5.2	6.4	26.9
Low CV/%	1.2	1.9	1.2	2.8	4.7	7.2	2.4
High	5.0	26.4	79.4	29.9	9.0	3.4	43.5
High CV/%	0.9	3.0	1.0	3.4	3.0	5.9	2.7

Table 4 Average single fiber tensile data

	Breaking force/cN	Tenacity/(g·tex^{-1})	Elongation/%	E_S/(g·tex$^{-1)}$	Work-to-break/(cN·cm)
2017 NCVT, 13 mm gauge length					
Average	5.0	25.7	8.9	2.9	0.30
Minimum	4.0	20.7	6.4	2.2	0.19
Maximum	7.6	42.1	11.5	4.6	0.43
Intra-sample CV/%					
Average	40.5	42.4	35.5	36.2	56.0
Minimum	25.3	30.1	31.4	31.4	40.4
Maximum	48.1	50.1	41.3	43.7	66.8
2018 NCVT, 3.2 mm gauge length					
Average	5.8	34.4	19.4	2.0	0.19
Minimum	4.8	28.1	10.1	1.1	0.11
Maximum	7.4	43.7	28.4	4.3	0.25
Intra-sample CV/%					
Average	40.2	40.2	36.1	38.7	56.2
Minimum	32.5	32.5	32.1	34.0	43.8
Maximum	49.0	49.0	39.8	49.4	66.9
Elongation calibration, 3.2 mm gauge length					
Low	7.6	44.6	11.0	4.1	0.14
Low CV/%	39.6	0.40	37.4	37.5	39.6
High	6.9	40.7	15.4	2.6	0.18
High CV/%	38.4	38.4	32.1	33.6	54.7

variation is consistent for both gauge lengths for the NCVT samples.

The 2017 NCVT samples, tested with a 13 mm gauge length, had a correlation coefficient of 0.621 ($P=0.018$) between Favimat and HVI tenacity but a weak and non-significant correlation between Favimat and HVI elongation, work-to-break, and secant modulus. However, there was a significant correlation ($R=0.640$, $P=0.014$) between Favimat tenacity and HVI secant modulus which parallels the relationship between Favimat and HVI tenacity.

Although single fiber testing of the 2017 NCVT samples was conducted with 13 mm gauge length, the samples were also tested with the Stelometer flat bundle method using a 3.2 mm gauge length (Table 5). The Stelometer bundle testing resulted in nearly the same average elongation (7.4%) as the HVI testing of the same samples (7.6%). However, the range of values was slightly narrower for the Stelometer than the HVI. The Stelometer differs from the HVI in the use of a flat bundle in which all fibers span across both jaws, while the HVI tapered bundle does not necessarily result in all fibers spanning both jaws. The Stelometer breaks each bundle in the middle, while the HVI varies the exact location of the break on the tapered bundle in order to standardize the amount of fiber being tested (Naylor et al. 2014). The Stelometer normalized the breaking force into tenacity by weighing the broken bundle of fibers, while the HVI uses micronaire and optical density techniques to estimate the linear density of the tapered beard. Although elongation values were similar between the two methods there was poor correlation between the methods ($r=-0.261$, $P=0.368$). Similarly, although the tenacity measurements were not similar between the HVI and Stelometer, they were highly correlated ($r=0.741$, $P=0.002$). The HVI reported substantially higher values than the Stelometer. The difference in fiber tenacity measurements between Stelometer and HVI is well documented (Taylor 1982).

The 2018 NCVT samples were tested on the Favimat with a 3.2 mm gauge length which enables a greater percentage of fibers to be sampled. The shorter gauge length allows testing of fibers up to 10 mm shorter than when a 13 mm gauge length is used. The longer fibers may represent a bias towards more mature and well-developed fibers which were able to maintain a longer length through the ginning process. The shorter fibers may represent a larger portion of less mature fibers and fibers which have already been damaged during harvesting and ginning. There was poor correlation between Favimat and HVI tenacity ($r=0.333$, $P=0.245$), but excellent correlation for elongation ($r=0.977$, $P\leq 0.001$). There were strong correlations between HVI secant modulus and Favimat measurements for work-to-break ($r=-0.889$, $P\leq 0.001$), tenacity ($r=0.605$, $P=0.022$), elongation ($r=-0.950$, $P\leq 0.001$), and Favimat secant modulus ($r=-0.825$, $P\leq 0.001$). Correlations between Favimat measurements and HVI work-to-break were not as strong as for secant modulus.

Although gauge length differences among the single fiber testing of the 2017 and 2018 samples result in a biased selection of fibers to be tested, the results for tenacity and secant modulus were not appreciably impacted. However, elongation and the work-to-break, which is directly reported by the Favimat instrument, were highly impacted. A longer gauge length will translate into a greater amount of fiber extension for the same percent elongation which impacts the area under the force elongation curve. Therefore, the proper interpretation of work-to-break data requires knowledge of the gauge length used.

A sample set of four HVI calibration cotton were used to investigate the impact of biased fiber selection for the two different gauge lengths. The Suter-Webb comb sorter was used to separate the fibers into groups of fibers of similar length. As shown in Table 6, groups of fibers with a mean length from 14.3 to 39.7 mm in length were tested for fineness and tensile properties. Three of

Table 5 Stelometer results for the 2017 NCVT sample averages

	Tenacity/(g·tex^{-1})	Elongation/%	E_5/(g·tex^{-1})	Work-to-break/(cN·cm)
Average	25.5	7.4	3.5	0.28
Minimum	19.8	5.8	1.6	0.20
Maximum	39.3	8.8	6.5	0.48
Intra-sample CV%				
Average	6.3	6.8	11.1	7.3
Minimum	1.5	2.8	4.3	2.8
Maximum	13.7	17.0	29.9	12.8

Table 6 Average results of single fiber testing by fiber length group

Cotton	Mean length/mm	Elongation/%	Breaking force/cN	Work-to-break/(cN·cm)	Tenacity/(cN·tex^{-1})	Gravimetric fineness/dtex
38	39.7	11.7	7.4	0.14	52.8[a]	1.40[e]
	33.4	11.5	6.7	0.12	43.0[b]	1.55[d]
	27.0	12.0	7.0	0.13	41.9[b]	1.66[c]
	20.7	11.9	6.4	0.13	36.7[b]	1.74[b]
	14.3	11.4	7.1	0.14	37.4[b]	1.91[a]
36	39.7	11.8[ab]	5.9	0.11	43.4[a]	1.35[e]
	33.4	13.0[a]	6.2	0.13	42.4[a]	1.45[d]
	27.0	12.4[ab]	6.2	0.13	40.7[ab]	1.53[c]
	20.7	12.5[ab]	5.6	0.12	29.5[c]	1.89[a]
	14.3	11.0[b]	5.6	0.11	35.4[bc]	1.59[b]
34	33.4	9.3	5.6[ab]	0.09	41.6	1.35[d]
	27.0	9.4	5.5[ab]	0.09	33.8	1.64[a]
	20.7	9.0	4.8[b]	0.08	35.3	1.37[c]
	14.3	8.0	5.4[ab]	0.08	37.1	1.47[b]
32	33.4	11.5	5.6	0.11	37.0[bc]	1.51[b]
	27.0	11.1	5.1	0.10	29.4[d]	1.72[a]
	20.7	11.9	5.2	0.11	39.2[b]	1.32[c]
	14.3	12.0	5.1	0.10	55.0[a]	0.93[d]

Means that do not share a letter are significantly different, where no letter is present there are no differences

the four samples did not show any statistical differences among fibers from the various length groups for fiber elongation or breaking force. Breaking force and elongation differences were most likely attributable to the highly variable nature of single fiber testing and the use of only 100 fibers per length group. No significant differences were found among length groups for work-to-break, further reinforcing that the differences among the 2017 and 2018 samples were due to the gauge length and not the biased fiber selection. There were statistical differences in fiber tenacity, by length group, for three of the four samples. However, the differences in tenacity are attributable to differences in fineness. All samples were shown to have significant differences in fineness by length group.

Overall, the data in Table 6 shows that differences among fiber lengths are mostly attributable to fineness, and in turn fiber maturity which is the development of the secondary cell wall. Careful fiber selection is needed, regardless of the gauge length used, to ensure that fibers from across fiber length groups are utilized in testing to minimize the impact of fiber maturity.

The strong significant correlations between the 2018 NCVT Favimat testing and HVI secant modulus is indicative that the secant modulus may capture more information than work-to-break since it is capturing an intrinsic material property instead of the product of the extension of the fiber. In addition to gauge length, the specific fibers from within a sample which are being tested exert a significant influence over the work-to-break value, in that a strong fiber or particularly elastic fiber in a sample will greatly increase the area under the force–elongation curve, while secant modulus could be the same within a sample for both weak and strong fibers. Figure 1 is a plot of 15 randomly selected fibers from DPL 1612 B2XF grown in Lubbock, TX in 2018. Even when fibers are weak and break early, the slope (secant modulus) of the force–elongation curve tends to be similar to stronger fibers while the area under the curve (work-to-break) would vary significantly.

A single value to explain both tenacity and elongation is only of value if it has demonstrated utility. To assess the utility of secant modulus the 30 samples were subjected to simulated processing through the Shirley Analyzer. The lickerin and card cylinder of the Shirley Analyzer mimic the opening and carding process of textile processing. It has been previously reported that elongation can be used as a predictor of how well a cotton sample will maintain its length distribution during processing (Mathangadeera et al. 2020) and it has been previously proposed to use secant modulus to evaluate processing efficiency (Fiori et al. 1956), but this has not been demonstrated using HVI-derived values for secant modulus.

Samples were tested for length parameters before and after processing (Table 7). The Shirley Analyzer, similar to carding machines, removes non-lint content, and some

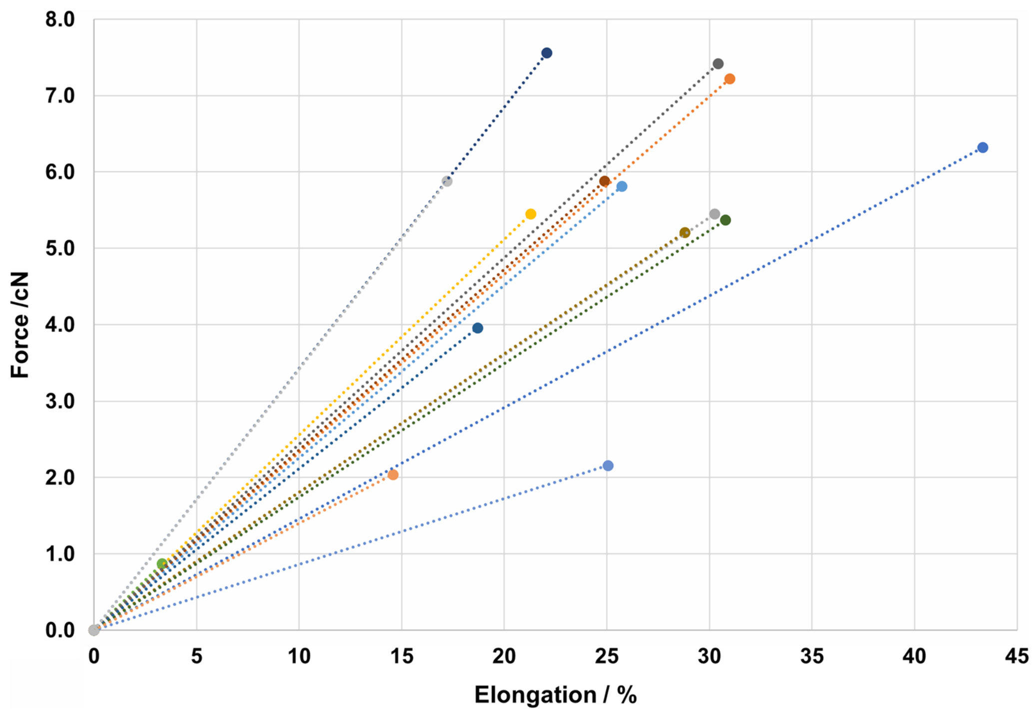

Fig. 1 The force elongation curve of 15 randomly selected fibers from DPL 1612B2XF cotton grown in 2018

Table 7 Change in AFIS fiber properties after processing

	Average	Maximum	Minimum
Ln/mm	− 0.84	1.27	− 3.56
Ln CV/%	1.42	9.06	− 4.30
SFCn/%	2.34	9.30	− 4.50
L5%n/mm	− 0.60	1.02	− 1.78
Lw/mm	− 0.78	− 2.54	1.02
Lw CV/%	0.07	3.07	− 1.77
SFCw/%	1.03	3.24	− 1.43
UQLw/mm	− 0.43	1.02	− 1.78
Neps/g^{-1}	21.9	231	− 108

short fibers will inevitably be removed with the non-lint content. Additionally, the card cylinder of the Shirley Analyzer may create as well as remove fiber entanglements known as neps as well as break fibers. The creation and removal of neps can obfuscate some changes in length during processing. Longer, finer, and less mature fibers tend to create neps during aggressive processing (van der Sluijs and Hunter 2016). In general, fiber length, as measured both by number and weight, decreased during processing while short fiber contents increased and the coefficient of variation of the length distributions confirming that the processing tended to damage the cotton fibers.

The changes in length properties during simulated processing were diverse with not all samples suffering reductions in length. However, the change in mean length was significantly correlated with fiber strength ($r = -0.437$, $P = 0.016$) and secant modulus ($r = -0.319$, $P = 0.046$) but not elongation or work-to-break. No changes in fineness or maturity were observed (data not shown) and no relationships between fiber damage and fineness or maturity were found. Tenacity is related to maturity and fineness, as shown in Table 6, however the AFIS lacks the sensitivity to detect small differences in maturity due to a narrow dynamic range (Paudel et al. 2013) and the samples used represent well-developed and mature samples.

In order to determine if either HVI secant modulus or work-to-break provided an advantage over the use of tenacity and elongation independently, the data from 341 samples of the 2018 NCVT were studied. These samples were all tested on the same calibrated HVI and then processed into ring spun yarns and skein strength and elongation were tested. As shown in Fig. 2a, HVI elongation was well correlated with skein elongation ($P \le 0.001$) but not skein tenacity (Fig. 2b). The HVI secant modulus demonstrated a weak but highly significant relationship ($P \le 0.001$) with skein strength, as did work-to-break. Secant modulus and work to break had

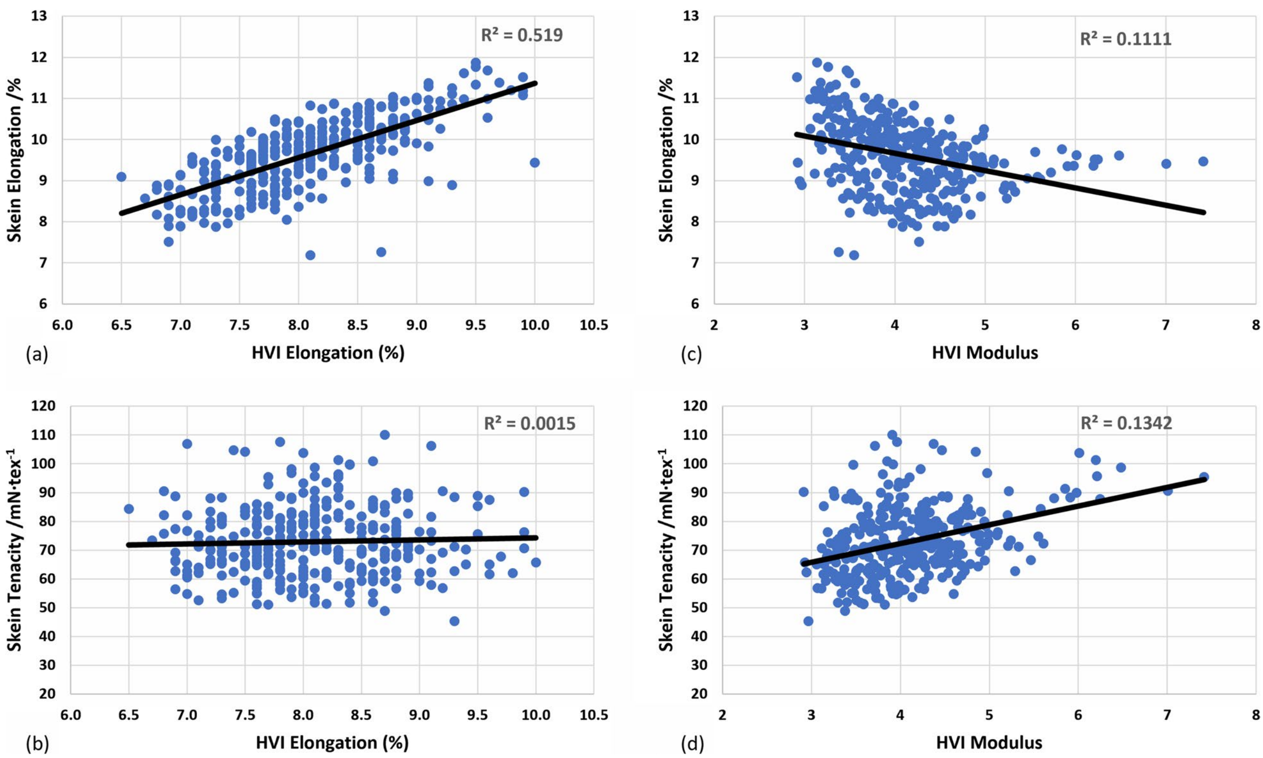

Fig. 2 **a** HVI Elongation (%) vs Skein Elongation (%). **b** HVI Elongation (%) vs Skein Tenacity (mN/tex). **c** HVI Modulus vs Skein Elongation (%). **d** HVI Modulus vs Skein Tenacity (mN/tex)

a highly significant ($P \leq 0.001$) correlation with skein elongation, but HVI elongation was the best single predictor. The small-scale processing of the NCVT samples limited yarn testing to skein tests and it is expected that single-end testing may yield improved relationships similar to that reported by Fiori et al. (1956).

Conclusion

To properly characterize the tensile properties of cotton it is required to account for the elongation as well as the tenacity of the fibers. The addition of an additional fiber property adds to the existing complexity of selecting samples based on numerous traits. There is potential, especially for fiber processors, to be able to combine both tenacity and elongation into one value. A combined measure would not increase the existing level of complexity. Numerous researchers have demonstrated the potential for breeding programs to improve the elite germplasm being developed by considering elongation as a stand-alone property and it would appear that for breeding efforts elongation and tenacity should be considered independently as the potential benefits of independent trait selection are worth the added complexity. However, for fiber processing, there are interactions among fiber traits which reduce the value of relying on single fiber traits for selection. Additionally, fiber processors are limited in the number of traits which can realistically be considered when selecting samples for processing and predicting the response of the material to processing. The interaction of various fiber traits also obfuscates the impact of individual traits.

The use of HVI testing to characterize the elongation properties provides adequate sensitivity to differences in fiber behavior as to be of value to the textile mill but does not fully capture the within sample variation of tensile properties like single fiber testing. However, the application of bundle testing, such as the HVI, reduces bias due to fiber selection. The use of secant modulus as a measurement of an intrinsic bulk parameter of a cotton fiber shows potential. Secant modulus and fiber strength both demonstrated significant correlation with changes in fiber length properties during processing, unlike elongation or work-to-break. This correlation indicates that secant modulus contains more useful information than either elongation alone or work-to-break. Secant modulus is measurable for a sample even when an individual fiber exhibits a difference in breaking strength or elongation than the other individual fibers within a sample. Work-to-break is heavily influenced by the specific value of breaking force and/or elongation of the individual fiber(s) being tested and not the intrinsic behavior of the sample. Bundle fiber methods, such as the HVI, are more immune from the influence of outlier fibers with exceptionally high or low values, unlike single fiber testing due to the averaging of the fibers being represented. Bundle fiber methods also reduce the potential for bias due to fiber selection.

The influence of genetics and environment on elongation, as well as the interaction of other fiber properties with elongation requires further study. However, the introduction of calibration materials and procedures for HVI allows for wide-scale use of the HVI elongation measurement which will be necessary as further investigations are carried out.

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Author contributions
Delhom CD conceived the methodology, constructed the cotton populations, conducted the formal analysis of the data, and wrote the manuscript. Wanjura JD, Pelletier MG, Holt GA, and Hequet EF aided in the conceptualization of the experiment. Hequet EF assisted with the curation of resources for the study. Wanjura JD, Pelletier MG, and Hequet EF aided in the data analysis and interpretation. All authors read, revised, and approved the manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

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Not applicable.

Consent for publication
All authors have reviewed the manuscript and given their consent for publication.

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Not applicable.

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