# Reimagining Hair Science:
# A New Approach to Classify Curly Hair Phenotypes via New Quantitative Geometrical & Structural Mechanical Parameters

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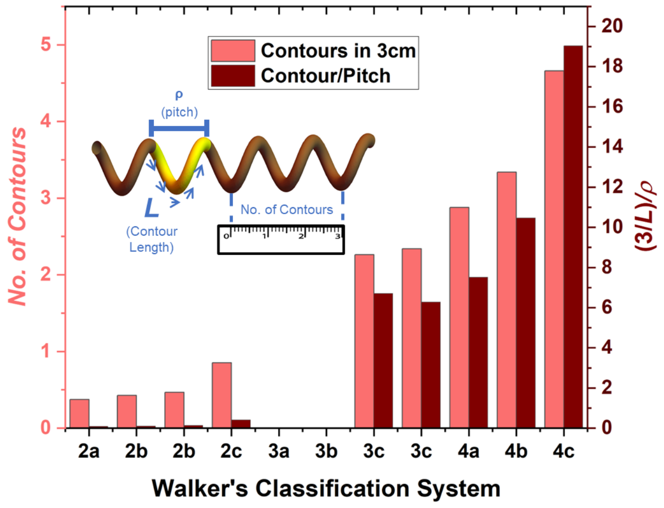
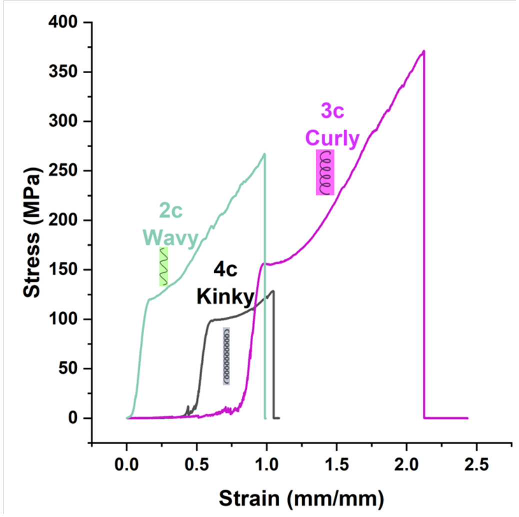
## CONSPECTUS

Hair is one of the key characteristics that classify us as mammals. It is a natural polymeric composite that is primarily composed of tight macro-bundles of keratin proteins, which are highly responsive to external stimuli, including pH, temperature, and ionic solvent content. The external responsive behavior displayed by hair is similar to the behavior displayed by hydrogels and other natural fibrous gel systems like collagen and fibrin. Hair and its appearance play a significant role in human society. It is a highly complex biocomposite system, which has been traditionally challenging to characterize and thus develop functional personal care products for consumers. Over the last few decades, a significant societal paradigm shift occurred among those with curly hair. They began to accept the natural morphological shape of their curls and style their hair according to its innate, distinct, and unique material properties. These societal and cultural shifts have given rise the development of new hair classification systems, beyond the

traditional and highly limited race-based distinction between Caucasian, Mongolian, and African. L'Oréal developed a hair typing taxonomy based on quantitative geometric parameters displayed among the four key curl patterns – straight, wavy, curly, and kinky. However, the system fails to capture the complex diversity of curly and kinky hair. Acclaimed celebrity hair stylist, Andre Walker, developed a classification system that is the existing gold standard for classifying curly and kinky hair, however the system relies upon qualitative classification measures, making the system vague and ambiguous to the full diversity of phenotypic differences. The goal of this research is to use quantitative methods to identify new geometric parameters, which will be more representative of curly and kinky hair curl patterns. These new parameters will therefore provide more information on the kinds of personal care product ingredients that will resonate best with these curl patterns, and thus maximize desired appearance and overall hair health. The goal is also to correlate these new parameters with its mechanical properties. This was accomplished by identifying new geometric and mechanical parameters from several types of human hair samples. Geometric properties were measured using scanning electron microscopy (SEM), photogrammetry, and optical microscopy. Mechanical properties were measured under tensile extension using a texture analyzer (TA) and a dynamic mechanical analyzer (DMA), which bears similarity to the common act of brushing or combing. Both instruments measure force as a function of applied displacement, thus allowing the relationship between stress and applied stretch ratio to be measured as a hair strand uncurls and stretches to the point of fracture. From the resulting data, correlations were made between fiber geometry and mechanical performance. This data will be used to draw more conclusions on the contribution that fiber morphology has on hair fiber mechanics and will promote cultural inclusion among researchers and consumers possessing curly and kinky hair.





**Related Published Work:**

[1] Shanina Sanders Johnson, **Michelle K. Gaines**, Mary J. Van Vleet, Kimberly M. Jackson, Cachetne Barrett, Davita Camp, Marisela De Leon Mancia, Lisa Hibbard, and Augusto Rodriguez; *Journal of Chemical Education* **2020** *97* (9), 3369-3373. https://doi.org/10.1021/acs.jchemed.0c00728

[2] Gaines, M. K. *Interfacial Chemical Properties in Polymer Biomimetic Materials and Hair*. Breakfast Club Seminar Series, Institute of Bioengineering and Bioscience, Georiga Institute of Technology. https://www.youtube.com/watch?v=Oo2PuEfqgfM&t=3s (accessed 2023-04-02).

[3] Gaines, M. K. Reimagining Hair Science: A New Approach to Classify Curly Hair Phenotypes via New Quantitative Geometrical & Structural Mechanical Parameters. In *Division of Presidental Events: Research at HBCUs Session*; Proceedings of the 2023 Spring Meeting of the American Chemical Society: Indianapolis, Indiana.

[4] *New ways to measure curls and kinks could make it easier to care for natural hair*. American Chemical Society Meeting Newsroom. https://www.acs.org/pressroom/newsreleases/2023/march/new-ways-to-measure-curls-and-kinks-could-make-it-easier-to-care-for-natural-hair.html (accessed 2023-04-02).

# INTRODUCTION

Hair is a key human phenotypic descriptor and is one of the key features that distinguishes humans as mammals. This natural polymeric composite is primarily composed of tight macro-bundles of keratin proteins, which are highly responsive to external stimuli, including pH, temperature, and ionic solvent content.[5] The external responsive behavior displayed in hair is similar to the behavior displayed in hydrogels and other natural fibrous gel systems like collagen and fibrin. Hair styling plays a significant role in human society by serving as a form of nonverbal social expression, political stance, and sexual attractiveness.[6,7] The development hair cosmeceuticals by the personal care industry is continuously changing in response to current cultural aesthetic trends.[8,9] Hair morphology can be distinguished by overall fiber shape or curl pattern. These categories include straight, wavy, curly, and kinky as pictured in Figure 1.[6,8,9] Kinky hair can be further sub-classified into two different morphologies: corkscrew shape or zig-zigged, Z-angle shape.[7] Kinky hair is sometimes referred to as coily hair and people with this hair type often possess a mixture of these hair morphologies on their scalp.

While hair science has greatly advanced in recent decades there is still a need for products that protect the natural mechanics of hair strands.[6,8,9] The Andre Walker hair typing system emerged from the start of the “Natural Hair Movement”, inspired from the widely acclaimed documentary by Chris Rock called *Good Hair*.[10,11] This movie inspired people with naturally wavy, curly, and kinky hair to style their hair in its natural morphological state, rather than process their tresses with chemically and thermally damaging products and techniques. Hence, consumers switched from purchasing relaxers and straightening tools, to hydrating creams and conditioning brushes, and influenced an entire industry to develop new consumer products that protected and showcased shiny, healthy, natural curls. The movement also led cosmetologists to learn new hair styling and maintenance techniques to create the most appealing natural hair styles. It has also inspired consumers to research the performance of newly developed styling products and which products best achieve a desired curly hair style.[8,12] This pushed the development of a

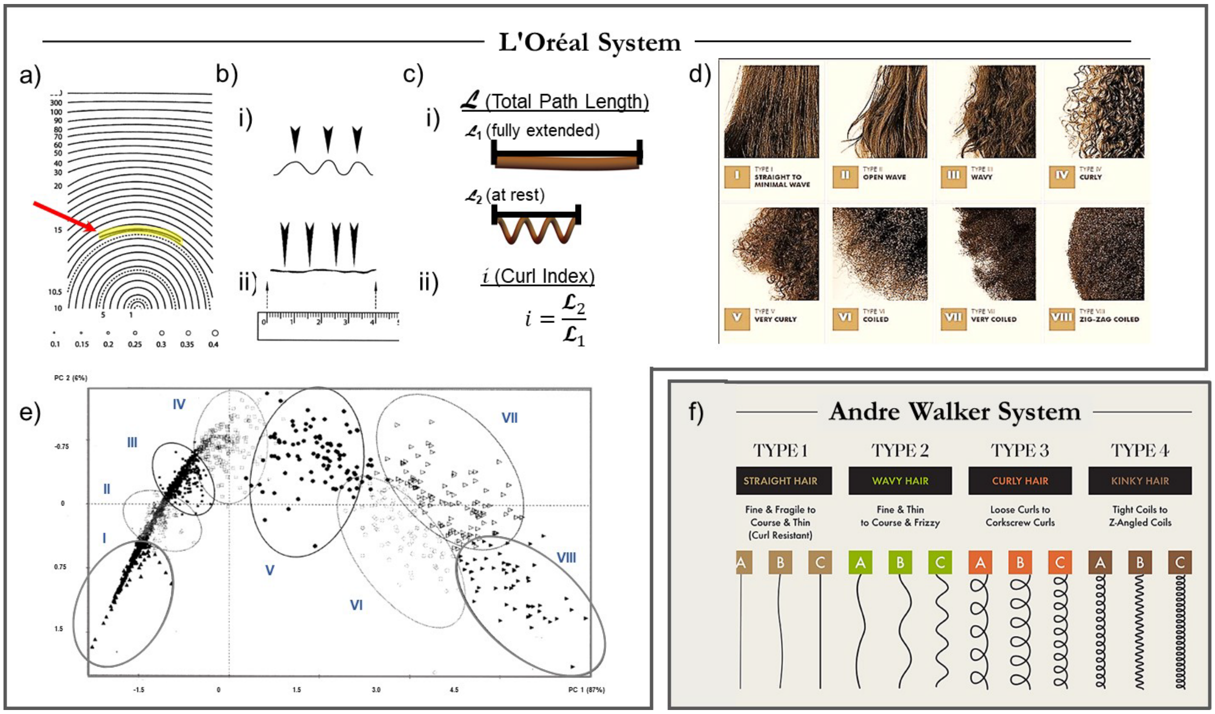


**Figure 1. L'Oréal and Andre Walker Hair Classification Systems:** (a-d) correspond to L'Oréal's naming scheme (I-VIII). (a) Template derived by Bailey & Schliebe used to measure curve diameter (*CD*).[15,16] The template is composed of concentric arcs ranging from miniscule to very large radii of curvature. The curvature of a hair fiber within a sample is matched to an arc on the template. Example shown, *CD* = 11. (b) Method for measuring (i) Number of waves (*w*) and (ii) number of twists (*t*). (c) Methodology for distinguishing (i) total path length ($\mathcal{L}$), where $\mathcal{L}_1$ represents a fully extended hair fiber to 6 cm and $\mathcal{L}_2$ represents the total path length of the fiber at rest and unperturbed. (ii) Curl index ($i$) is the ratio of $\mathcal{L}_1$ to $\mathcal{L}_2$ (d) Illustration of the eight-cluster partition on the PC1/PC2 plane that make up the eight categories of morphologies exhibited by human hair fibers (I-VIII). These results were derived by L'Oréal from principle component analysis and transformed into orthogonal components from linear combinations of the four parameters measured in a-c. (e) The principle component plot illustrates relation patterns between the parameters. (f) Andre Walker's hair typing system (Type 1a – Type 4c).[6,8-10] Types 1, 2, 3, and 4 refer to straight, wavy, curly, and kinky hair morphologies. Subtypes a-c are defined according to increasing fiber diameter within each hair type and increasing coarseness, respectively. Reprinted with permission from reference 13.

hair typing system, expanding the previously limited race-based distinctions, Caucasian, Mongolian, and African hair types.[9,12–15]

Andre Walker's claim to fame came when he became Oprah Winfrey's and Michelle Obama's personal hair stylist. His new hair typing system classified hair fibers according to their observable natural curl pattern and shape.[11,16] His system classified hair in the same four main categories (Types 1-4) for straight, wavy, curly, and kinky morphologies, respectively. His system also included three sub categories (a-c) that correspond to increasing hair diameter and thus increasing coarseness.[11,17] As pictured in Fig. 1f, Type 1 hair is perceived as bone straight, while Type 4c hair is perceived as tightly coiled and kinky. Those that use his system to classify their waves, curls, or kinks match their strands, as best they can, to the image of the strands pictured in Fig. 1f.

In 2007, L'Oréal published results from an extensive study, which characterized several physical properties in a large sample size of human hair (1000+). The samples came from an inclusive variety of people from diverse backgrounds across the globe.[13,15,18] L'Oréal's hair typing system has 8 categories (I-VIII), and most curly and kinky samples were categorized as Types V-VIII (Figure 1). L'Oréal's is recognized among the consumer products industry as the official standard for hair typing[6], used to guide the development of natural hair products targeting each distinct hair type.

While L'Oréal's system is widely accepted by the personal care industry and academics, consumers are often still left feeling perplexed and overwhelmed by the massive assortment of products available on the shelf.[8,19] Moreover, some argue that hair-typing is more divisive than helpful because it glamorizes more culturally accepted hair traits such as cohesion/shine, long lengths, less coils/kinks, and high strength.[16,20] Those opposed to hair-typing also feel that it shuns culturally rejected traits such as dullness, short lengths, shrinkage, and fragility. Others argue that the L'Oréal's typing system is a start in the right direction for addressing the question of how to best classify hair according to it innate material properties but still has too narrow a focus.[19,21] Developing a more inclusive and robust hair classification system has been challenging because curly hair display a vast range of phenotypic characteristics. Each phenotypic variable displays unique material properties, which thus produce different observable and desirable outcomes.[6,21]

Colete and coworkers from the Hair and Skin Research Lab in the Division of Dermatology at Groote Schuur Hospital and University of Cape Town, South Africa proposed a systems-thinking approach to comprehensively visualize holistic properties of curly hair.[19,21] This group also proposed a modified version of L'Oréal's hair-typing system, which classified hair according to curve diameter (*CD*) (Fig 1a).[22,23] Like L'Oréal, *CD* accurately distinguishes straight and wavy hair phenotypes (I-IV). The last two types (V & VI) possessed too tight a curl or kink to distinguish accurately against the *CD* template (Fig. 1a). Thus, the last two types were determined according to whether the hair strand fit completely within the curl meter (Type-V), or whether the strands displayed a zig-zag pattern and did not fit within the curl meter (Type-VI). This system captures straight, wavy, curly, and kinky hair phenotypic morphologies, as Walker's system does, with a little less specificity. Type-VI from Mkentane *et. al.*'s work corresponds to Walker's 4b hair type and would be categorized as kinky.

Here, we describe quantitative methods to identify new geometric parameters and material properties that account for more phenotypic differences in curly, and kinky hair. We propose that these parameters may form the basis of a new classification system, based on quantitative measurements. A more quantitative approach to hair-typing will guide formulation and selection of personal care products that best resonate with curl pattern to maximize desired appearance and overall hair health. We aim correlate these new parameters with the mechanical properties displayed by curly, and kinky hair fibers. Here, geometric properties including ellipticity ($\boldsymbol{e}$) and fiber diameter ($d$) were measured and compared across several hair samples with different curl patterns via scanning electron microscopy (SEM) and optical microscopy. New geometric parameters were identified and measured using optical photogrammetry and optical microscopy. Mechanical properties were measured under tensile extension using a texture analyzer (TA) and a dynamic mechanical analyzer (DMA). Our experiments connect hair geometry and morphology to resulting hair fiber mechanics. This research was performed primarily by Chemistry & Biochemistry undergraduate student researchers attending Spelman College, a small liberal arts Historically Black College or University (HBCU) women's undergraduate institution in Atlanta Georgia. This research deeply resonates with the Spelman student body and the Black community because the students and professors completing the research possess the same wavy, curly, and kinky hair researched here.

## METHODS

Hair samples were collected from volunteers of varying age (20-50), gender, ethnicity (nationality), and washing/personal care attitudes. They were collected from fibers that were naturally shed from the scalp after combing, brushing, or other forms of physical manipulation. Each volunteer gave at least twenty strands of hair, 6 cm or longer, to allow for multiple experiments per sample. Samples were prepared by washing in 1% sodium lauryl sulfate solution with reverse osmosis water for twenty minutes. Next, they were rinsed and placed onto a drying rack to allow curls, waves, or kinks to naturally form as the hair strands dried. Hair strands dried for at least twelve hours before any experimentation (Figure S2).[13]

Geometric properties and fiber morphology were measured and evaluated using bright-field optical microscopy, scanning electron microscopy (SEM), and photogrammetry. All collected images were analyzed to extract desired parameters by using ImageJ and Blender, free and open-sourced 3D computer graphics modeling software.[24] Photogrammetry was employed to image and reconstruct the full 3D shape of individual hair samples. Samples were imaged via photogrammetry by collecting images of each hair strand from a range of angular perspectives, captured by circling a camera 360° around each hair fiber (Figure 2). Photogrammetry reconstruction was used to accurately measure the path length ($\boldsymbol{\mathcal{L}}$), as indicated by the red dotted line extending down the length of the hair fiber shaft (Fig.

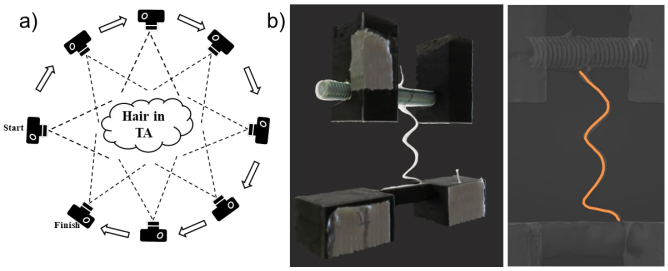


**Figure 2.** Photogrammetry. (a) Experimental design for capturing data for 3D rendering of hair fibers. (b) 3D render of a curly hair fiber mounted to the Texture Analyzer (TA).The fiber was imaged at zero displacement. (c) Fiber length measured in Blender (3D-modeling software) by tracing the path along the length the rendered 3D curve. Curve length of pictured fiber, 37.519 ± 0.454 mm. Figure S8 is the 3D render of the curly fiber at different angles, visualized in Sketchfab.

2b). $\boldsymbol{\mathcal{L}}$ was one of the parameters originally measured by L'Oréal.[13] Hair fiber diameter ($d$) was measured via bright-field optical microscopy under 20x, 50x or 63x magnification (Figure 3). Ellipticity ($\boldsymbol{e}$) is a key distinguishing parameter and is measured by the ratio of the lengths of the major and minor axes from the cross section of each hair strand. $\boldsymbol{e}$ was measured from images of hair sample cross-sections collected via SEM (see Supporting Information for details). Other newly identified geometric parameters, such as contour length ($L$), number of contours, and pitch ($\rho$) were measured from images collected off a standard camera and then analyzed using ImageJ (Figure 3).

Mechanical properties were measured using a texture analyzer (TA) (TA-XT, Stable Microsystems®) and a dynamic mechanical analyzer (DMA). Stress-strain curves were developed from force-displacement measurements collected from each hair strand in the TA. Hair strands were loaded between the grips by winding the ends of each strand around the top and bottom grips of the TA and DMA. Before each tensile test began, the initial displacement length was set to either 1, 3, or 6 cm, respectively. An example is shown in Fig. 2c, 3D rendered curly hair strand loaded in the TA and set at an initial displacement length of 3cm. Experiments concluded at the fiber's point of fracture. (Figure S8).

## GEOMETRIC FEATURES

### ***Hair Structure & Composition***

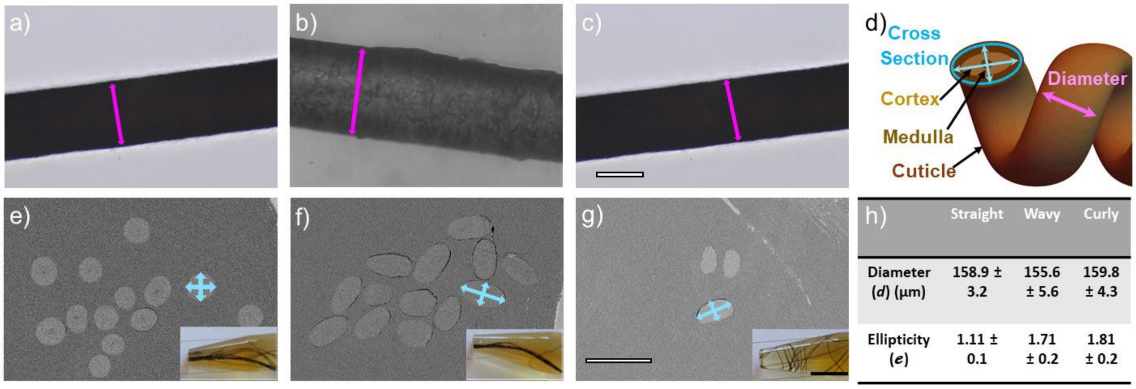
Hair is composed of three main components – medulla, cortex, and cuticle (Figure 3d).[5] The core of each hair fiber consists of the medulla, which is structurally similar to bone marrow, however it is predominantly present in only coarser hair fibers.[25] The cortex surrounds the medulla and provides the bulk of geometric structure, morphological shape, mechanical strength, and elasticity for hair fibers.[14] The cortex is composed of cortical anisotropic cells among a matrix of keratinized amorphous proteins. Each cortical cell is a macro-fibril composite of aggregated alpha-helical micro-fibrils. The inner-structure of micro-fibrils is made of keratin proteins, arranged in tight bundles of alpha-helical keratein fiber intermediate filaments that have been aggregated and arranged into micro- alpha-helices.[25] Human hair contains three types of cortical cells – paracortical, mesocortical, and orthocortical – each differing slightly in shape.[14,26] According to Wortmann *et. al.*, the structural arrangement of each type of cortical cell directly correlates to hair fiber shape, which originates from di-sulfide bond chemical crosslinking between cortical cells, keratinous amorphous matrix proteins, and the long-range order of the resulting crosslinked structures.[26] Wortmann and coworkers suggest that lateral phase segregation between the three cortical cells leads to curl formation in hair, implying that more homogeneous cortical cell arrangements underly wavy and straight phenotypes.[14,26]

The outer layer of hair is called the cuticle.[5] It protects the cortex from outside physical and chemical stresses and maintains a homeostatic internal environment. The cuticle is comprised of overlapping layers of cell sheaths that are individually anchored to the base of the cortex and arranged over each other like shingles on a roof.[14,26] Each cell sheath is composed of keratinized amorphous proteins and several types of lipids. The cuticle is made of five to eleven layers of sheathed cells, which can lift and lower in response to the hair fiber's environment. The natural degradation of cuticle sheaths coupled with their ability to reversibly lift away from the cortex when exposed to changes in humidity and moisture creates porosity within hair. Hair porosity is defined as the extent of reversible sheath cell opening and closing. Thus, the cuticle is responsible for maintaining hydration across each hair fiber.

### ***Diameter & Cross-Sectional Ellipticity***

The key variables most often reported in dermatological or anthropological studies of hair are fiber geometry (length, diameter, ellipticity, and degree of curl), emergence angle from the scalp, and fiber-to-fiber interactions.[27] Most studies have broadly reported that curlier hair had shorter lengths, were less dense, and had slower growth rates.[28] As for the other geometrical parameters, L'Oréal has used diameter ($d$) as a geometric descriptor to infer coarseness and thus “texture”, “handle”, and “feel”.[29] *d* has also been used to draw conclusions on fiber growth rate, trends in hair fiber density, to evaluate the scalp health.[28,30,31] Hair fiber diameter (*d*) was measured from samples donated by volunteers. The average *d* from those samples (~ 4 hair strands, per volunteer) are reported in Figure 3.[28] The results show little variation of *d* for each of main hair shape morphologies (straight, wavy, curly, respectively).

There are several limitations when using *d* to differentiate hair fiber geometry across phenotypes. The diameter of hair fibers can vary significantly from the root its tip, and the diameter of hair fibers can also vary across each person’s scalp.[30,32,33] Importantly, *d* does not capture the ellipticity ($\boldsymbol{e}$) of a hair fiber.[34] $\boldsymbol{e}$ is a measure of divergence of an ellipse from a circle. It is the ratio of lengths of the major and minor axes of the cross-section of each hair fiber (Figure 3).[30,33] $\boldsymbol{e}$ is a normalized value, and has been used to examine structural differences along the hair shaft in curly hair.[33,35] Most of the literature does not include comparatives studies  in hair fiber ellipticity ($\boldsymbol{e}$) and diameter across the different phenotypes. However, there were a few that compared medulla ellipticity, cuticle thickness, and fiber ellipticity across several phenotypes, and their findings agree with the measurements collected and shown in Figure 3.[36–39] The studies that have been conducted and reported $\boldsymbol{e}$ as a geometrical descriptor were mostly conducted on “Caucasian” hair samples, in the context of mitigating adult male hair loss.[29,33,40–44] Although one study conducted on “Caucasian” females reported a decrease in the length of the major axis, traveling along the hair shaft from root to tip. They also reported that the length of the minor axis remained constant.[33] Daniels et. al. conducted a comprehensive appraisal across the different phenotypes, and these results along with the results outlined here are in agreement with what has been reported in the literature.[32,37,38,45]

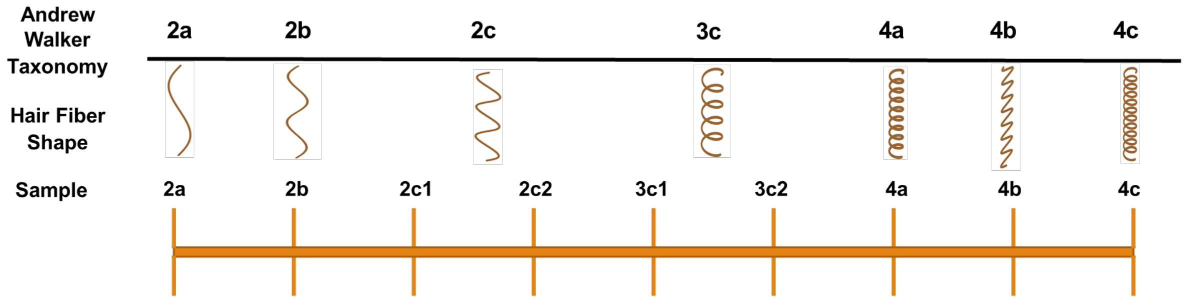


| h) | Straight | Wavy | Curly |
|---|---|---|---|
| Diameter ($d$) (μm) | 158.9 ± 3.2 | 155.6 ± 5.6 | 159.8 ± 4.3 |
| Ellipticity ($e$) | 1.11 ± 0.1 | 1.71 ± 0.2 | 1.81 ± 0.2 |

**Figure 3. Hair Fiber Ellipticity & Hair Diameter Measurements.** Bright-field optical microscopy and SEM images of hair fibers. (a-c) Average diameter ($d$) was measured from 3-5 strands of each hair sample, along multiple points along the length of each fiber. The samples shown are (a) straight, (b) wavy, and (c) curly hair fibers. According to Walker's taxonomy, they would be considered (a) Type-1, (b) Type-2b, and (c) Type-3c. (d) Hair fiber structure. (e-g) Scanning election micrographs of the cross-section of hair samples shown in a-c. Ellipticity ($\boldsymbol{e}$) is a measure of divergence of an ellipse from a circle. It is the ratio of lengths of the major and minor axes of the cross-section of each hair fiber. The inset (e-g) is an image of each sample of hair fibers vitrified in 1.5 mL vial of epoxy resin. Images were collected of each cross-section after clipping the tip of each sample vial. The scale bar in (a) and (c) is 50 μm, (b) is 80 μm, and (g) is 200 μm. The scale bar in the inset of (g) is 10 mm. (h) Summary table comparing average diameter to average ellipticity for each curl type.

### *New Geometric Parameters for New Classification System*

Several other geometrical parameters have been reported in the literature, and several comparative studies across phenotypes have been conducted.[37] There have been a few studies that have measured "fiber-to-fiber" interactions in "African" and "Caucasian" hair fibers in the context of braided hair styles.[29,46] "Emergence angle from the scalp" is the angle at which "living hair" inside the skin polymerizes and grows out of the follicle away from the scalp.[14,26] The shape of the follicle dictates the shape of the cross-section of each hair fiber (ellipticity, $\boldsymbol{e}$).[8,38] It is also an indication of the "degree of curl", although there are additional major contributors, i.e. cortical cell density and distribution, that play a major role in curl morphology.[14,26] As descriptive as these geometrical parameters are, many of the present studies reported in the literature have deemed the differences in phenotypic morphology as inconclusive. The reason may lay in the geometric parameters that were selected for comparison. Due to stark differences in dimensionality, it is no surprise that the geometric parameters used to characterize straight and wavy hair may not fully represent the geometric diversity of curly and kinky hair because straight and wavy hair exist in 2-dimensions, while the other phenotypes exist in 3-dimensions.



| | 2a | 2b | 2c1 | 2c2 | 3c1 | 3c2 | 4a | 4b | 4c |
|---|---|---|---|---|---|---|---|---|---|
| *L* (cm) | 8.047 | 7.031 | 3.523 | 3.523 | 1.326 | 1.283 | 1.043 | 0.899 | 0.634 |
| *No. of Contours* (3/*L*) | 0.373 | 0.427 | 0.851 | 0.851 | 2.262 | 2.338 | 2.876 | 3.337 | 4.659 |
| *ρ* (cm) | 4.38 | 4.436 | 2.10 | 2.10 | 0.337 | 0.373 | 0.383 | 0.3189 | .2448 |
| (3/*L*) / ρ Ratio | 0.085 | 0.096 | 0.410 | 0.410 | 6.70 | 6.27 | 7.50 | 10.45 | 19.04 |

**Table 1. Summary of New Geometric Measurements.** Summary of measurements collected on samples of straight (1), wavy (2a-c), curly (3a-c), and kinky (4a-c) hair. Measurements reported are the average taken from measurements collected off 12-15 strands from each sample of cleaned, dried hair fibers. Samples c1 and c2 signify 2 different samples from the same curl type.

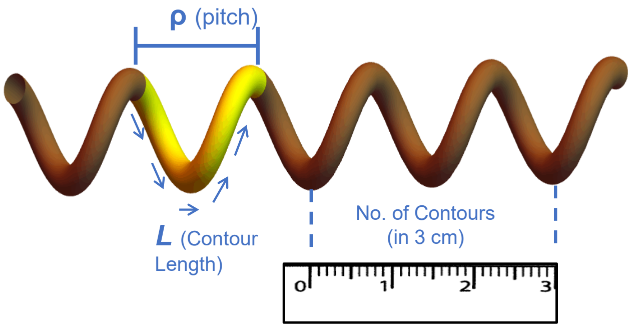


**Figure 4. Contour Length, Number of Contours, & Pitch Geometric Parameters, Summarized in Table 1.** The three key parameters measured, reported in Table 1 are *L*, *No. of Contours*,& *ρ*. Contour Length (*L*) – length in centimeters along one contour of a wavy or curly hair fiber. Number of Contours in 3 cm (*No. of Contours*) – number of *L* within a 3 cm distance, measured parallel to the direction of hair growth. Pitch (*ρ*) is the distance between the start and the end of one *L*, measured parallel to the direction of hair growth.

This leads into the present study, where new geometrical parameters were reported to capture the morphological differences between wavy, curly, and kinky hair. These new parameters were used to develop a quantitative taxonomy and was compared to Andre Walker's system. Figure 4 illustrates the methodology for measuring each of 4 new geometric variables – contour length (*L*), no. of contours (*3*/*L*), pitch (*ρ*), and no. of contours/pitch ratio ((*3*/*L*)/*ρ*). Table 1 depicts measurable trends for each of the 4 new geometric parameters across hair phenotypes. No. of contours was measured from the number of *L* per 3 centimeters. Measurements were collected from 2D images of clean/dry hair samples using Image J (Figure S2). The results show a continuous decrease in no. of contours and a continuous increase in the ratio (3/L/ρ).

These values are also depicted in Figure 5 and compared with the Andre Walker typing system. Figure 5 illustrates overall agreement of our results with the curl pattern categories and subcategories included in Walker's hair typing system. Importantly, Figure 5 also illustrates similar trends between the quantitative measurements obtained and the trends observed when estimating the no. of contours on a strand of hair, by counting the repeating contour lengths (*L*) observed within 3 cm. The latter methodology allows one to estimate their curl pattern themselves  against a ruler, without using any analytical techniques, an approach that can be readily extended to much larger sets of hair sample data in future studies.

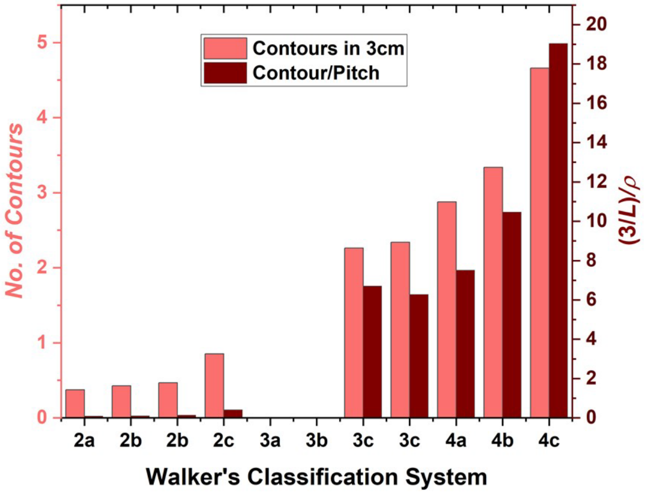


**Figure 5. Comparison between Number of Contours and Contour Length to Pitch Ratio.** Graphical representation of new parameters, *No. of Contours* & (*3*/*L*)/ρ, taken from Table 1, were identified in this work and compared against Andre Walker's hair-typing system. (Left) *No. of Contours* represents the number of *L* within a 3 cm distance, measured parallel to the direction of hair growth (Fig. 3). (Right) (*3*/*L*)/ρ is a derivative of curl index (*i*), L'Oréal, which describes the extent of curling observed in curly and kinky hair. Samples for Types 3a and 3b could not be collected. Image describes two methods for classifying hair fibers according to curl pattern. (*3*/*L*)/ρ requires quantitative measures to determine (Right). Measurements correlate evenly with results reported on the right side, where *no. of contours* was estimated by manually counting number of *L* observed against a ruler (3cm) (Left).

‘Contours in 3cm’ is a visualization analysis that supports the contour/pitch method; by including this form of classification we see the hair samples behave as hypothesized, where the number of contours (curls) in 3cm increases, comparably with increasingly curly hair phenotypes. The contour length/pitch ratio is used to classify hair based on how curls naturally form and how tight the curls are. and By using this method, all hair phenotypes are more quantitatively distinguished.

## MECHANICAL PROPERITES

Prior literature consistently report straight and wavy hair as being stronger than curly and kinky hair.[47–49] These prior studies reported that Young’s modulus ($E$), tensile strength ($\sigma$) and fracture point decrease with increasing degree of curliness, while friction coefficient increases with degree of curliness. Hair breakage and damage from mechanical manipulation has been widely reported and commonly experienced by people with curly and kinky hair. These conclusions remain true for hair fibers that are dry, wet, or coated with products.[47,50–53] These reasons motivate research and development by the cosmetic industry of new products to strengthen and fortify the structure of curly hair.[6,9] The results in our current study display similar trends, and also a few other mechanical parameters that are unique to curly and kinky hair.

### *Uncurling Force*

Colete and coworks were the first to report on the interrelationship between hair fiber morphology and mechanical behavior on dry hair samples with different curl patterns. In their work, they describe the presence of two tensile forces that contribute to the overall strength of hair fibers – uncurling force ($\sigma_u$) and elastic tensile strength ($\sigma_\varepsilon$). $\sigma_u$ is analogous to the decrimping force measured in wool.[54] One of the key observations made by Colete and coworkers was that overall stress response decreased with increasing hair fiber curliness, meaning that curlier hair fibers exhibit a time-delay before the onset of elastic stress in response to fiber extension (strain). Also reported were negligible values for $\sigma_u$ when measured on straight and wavy hair samples (natural and processed hair). Colete *et. al.* reported a direct correlation between with fiber viscoelasticity and degree of curliness (decreasing curve diameter).[55]

The results in the current study coincide well with Colete *et. al.* and depict several notable differences in mechanical response between samples with slight morphological differences in hair fiber geometry. Stress-strain behavior was collected off a texture analyzer (TA) and is summarized in Figure 6. Region I is the Toe Region (coined by Colete *et. al.*), and it describes the stress-strain behavior when a fiber is uncurled ($\sigma_u$). Region II is the elastic region where elastic modulus ($E$) is determined. Regions II – IV are

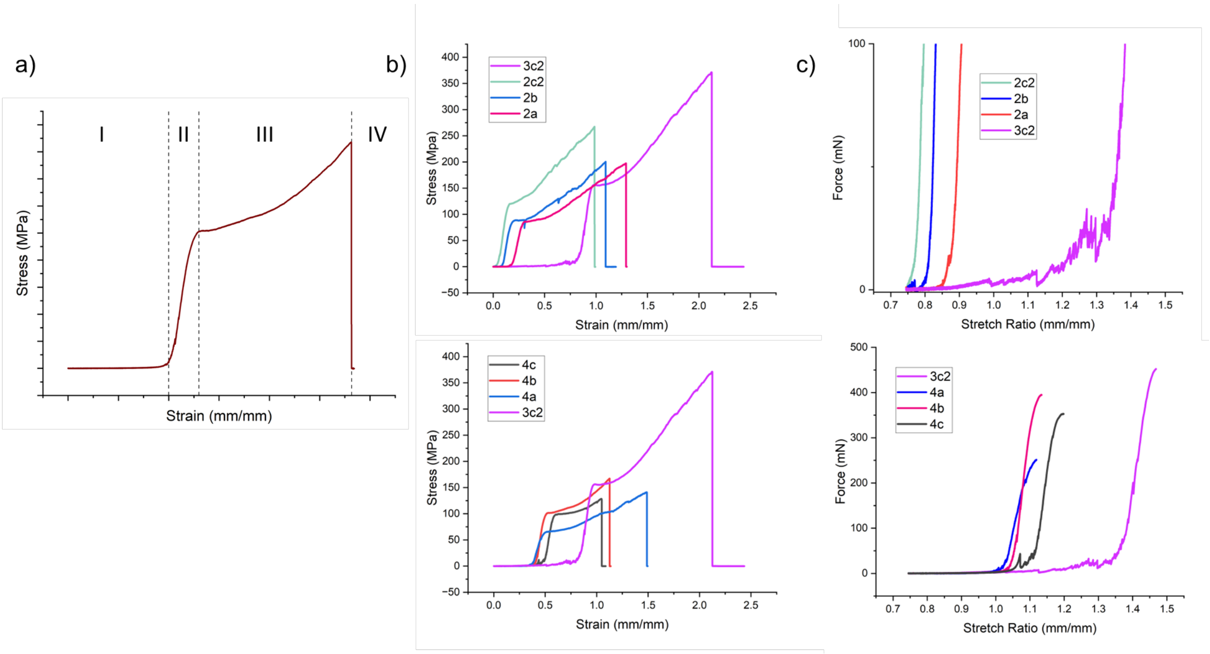


**Figure 6. Mechanical Properties.** (a) Example stress-strain graph for a curly or kinky hair fibers. I – Toe Region, the tensile force required to uncurl the natural curve morphology of a curly and kinky hair fiber ($\sigma_u$). The toe region is virtually absent for straight and wavy hair samples (Types 1 & 2). II – Elastic region, used to determine the elastic modulus of the hair strand. III – Plastic Region, plastic deformation, permanently stretching the hair past its maximum tensile stress ($\sigma_{max}$) thus causing permanent damage to the cortex. IV – Fracture Force, the maximum force the hair strand can endure before fracture. (b) Stress-strain data of hair samples. (Top) compares mechanical behavior of wavy hair against a curly 3c sample. (Bottom) compares mechanical behavior of kinky hair against a curly 3c sample. (c) Stretch ratio highlighting Region I in hair samples. (Top) compares stretch ratio of wavy hair against a curly 3c sample. (Bottom) compares stretch ratio of kinky hair against a curly 3c sample.

the regions captured in a typical stress-strain curve for a fiber. DMA can measure mechanical behavior at higher resolution and was used to measure force-displacement response with increased precision. The stress-strain behavior of wavy and curly hair samples is shown in Figure 6b, where the stress-strain behavior of sample 3c was compared against wavy samples (top – 2a-c) and kinky samples (bottom – 4a-c). Sample 3c shows evidence of the widest Toe Region (Region I) and thus the largest $\sigma_u$. Past studies have demonstrated a correlation between *CD* and with Young's modulus.[50] This work is in agreement with those results.

### *Stretch Ratio*

Stretch ratio is a new parameter reported in this study to further describe the mechanical behavior of the hair samples in Region I. Stretch Ratio was calculated using Equation I.

$$\frac{\varepsilon_0+\Delta\varepsilon}{\mathcal{L}} \qquad \text{(I)}$$

$\varepsilon_0$ is initial displacement (mm), i.e. the displacement recorded at time = 0 seconds. $\Delta\varepsilon$ is displacement (mm), and $\boldsymbol{\mathcal{L}}$ is total path length (mm). The stretch ratio depicts the extent of stretching that each hair fiber endures during a tensile test. Figure 6c compares the extent of hair fiber stretching between a curly 3c sample, wavy hair (2a-c), and kinky hair (4a-c). Stretch Ratio is 1.0 when $\varepsilon_0$ equals $\boldsymbol{\mathcal{L}}$, which depicts the mechanical behavior of a straight hair fiber. Wavy hair samples depicted stretch ratios < 1.0, which generally indicate $\boldsymbol{\mathcal{L}} > \varepsilon_0$. Each of the kinky hair samples consistently reported $\boldsymbol{\mathcal{L}} < \varepsilon_0$, which captures some of extent of initial curliness for each of the hair samples.

## SUMMARY AND OUTLOOK

The present study reported several distinguishing geometric and mechanical features of curly and kinky hair. Although these studies were performed on a small sample size, it serves as a proof-of-concept for correlating the newly reported parameters with existing quantitative

(L'Oréal) and qualitative (Andre Walker) hair typing systems. Before drawing more concrete conclusions that serve as foundation for a new hair-typing system, these proof-of-concept studies should be extended to larger sample sizes and populations. Compared to L'Oréal and Walker's systems, this proof-of-concept is more inclusive-based and has the potential to provide specifically descriptive labels for hair typing. The reported system also shows promise in its use among lay persons without access to microscopy or image processing software. This system allows people to objectively classify their own hair by simply selecting a hair strand and counting the number of coils in a fixed (perturbed and unperturbed) length of 3 cm. With continued development, this system can be used in a variety of different ways, including assisting in product development and creating products specifically for different hair phenotypes.

While outside the scope of the present work, it is also prudent to acknowledge the rich history of theoretical and computational studies on hair, in which the individual strands are often treated as elastic rods due to the presence of a single dimension (strand length) being much longer than the other two material dimensions (cross-sectional axes).[56] Like the many experimental studies on hair, theoretical investigations have spanned length and complexity scales, with some representative works including the curl response of a single hair to the force of gravity, the role of friction and strand interactions when combing several strands of hair, and the dynamics many interacting strands in the simulation of entire heads of hair.[57–59] In future studies, the geometry and intrinsic elasticity of single strands studied in these experiments will be compared to theoretical descriptions. Further experimentation will investigate using photogrammetry to develop a 3D model of hair as individual strands and in cohesive and non-cohesive hair bundles. Additional future studies will include more cross-sectional geometry analysis via SEM, cuticle sheathing and porosity analysis, and the material properties of hair fibers after being exposed to some commercial products.[4] These investigations contribute to the growing body of research which seeks to understand the complex multiscale material properties of human hair. In general, this work also highlights the diverse structures and properties of wavy, curly and kinky hair.

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# SUPPORTING INFORMATION

## Reimagining Hair Science: A New Approach to Classify Curly Hair Phenotypes via New Quantitative Geometrical & Structural Mechanical Parameters

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## GLOSSARY

- Curl Pattern: Shape or morphology of a hair fiber.
- Straight: fibers follow the shape of a straight line.
- Wavy: fibers follow the shape of a sine wave. Also referred to an "S-curl" because hair fibers are shaped like the letter "S".
- Curly: fibers follow the shape of a corkscrew with a large curve diameter ($CD \geq 1$).
- Kinky: fibers follow the shape of a corkscrew with a small curve diameter ($CD < 1$) and fibers are shaped like the letter "Z" and follow a zig-zag pattern.
- Coarseness: Term that describes hair fiber diameter within a subcategory (Andre Walker's system). This term is also used to loosely used to describe hair fiber rigidity and

its resistance to manipulate into hair styles. It is also described as having a firm and fibrous texture to the touch.

- Fineness: The antonym of Coarseness. It is described as having a soft and cottony texture to the touch.
- Curve diameter (*CD*): Parameter derived from L'Oréal's hair classification taxonomy that represents the extent of curvature that a hair fiber displays when at rest. Bailey & Schliebe modified the existing template developed by Hrdy, of concentric arcs ranging from miniscule to very large radii of curvature. The curve diameter (*CD*) is measured by matching a hair fiber to an arc on the template.
- Fracture Point: The stress of a fiber just before it breaks.

## METHODS

### ***Optical Microscopy***

After the hair was washed and dried, we took one strand from each sample group. The strand was sandwiched between two slides and taped down on the edge of the slide to ensure the hair was flat for imaging. For each slide five different images were taken at 50x and 20x, three images were taken using dark field. Multiple images were taken to ensure if the strand had varying widths they were represented in the diameter measurement.

#### Diameter of Hair (D)

Took images of hair on an optical microscope at 20x, 50x, and 63x.  From these images, ImageJ was used to measure from one edge of the hair strand to the other edge. For each image three diameter measurements were taken totaling in at least 15 diameter measurements that were averaged for every hair sample group.

### Contour Length (L)

“The path length of one period in the helix” The length from the start of a curl to the end of it. This measurement was taken using ImageJ. After hair was placed on the drying rack and allowed to dry for at least 12 hours an image was taken with ruler for scale. For each rack one contour length measurement was taken for every strand on the rack, there were 12-15 strands on each rack. From these measurements we were able to find a contour length for the sample group.


DM- 50x Obj - 2-Image Export-07.tif (16.7%)

8.67x23.00 inches (2752x2208); RGB; 23MB

Scale 20x:

Per pixel (0.227 um x 0.227 um)

Image size (2752 x 2208)

Image size scaled (624.70um x 501.22 um)

Scale 50x:

Per pixel (0.091um x 0.091um)

Image size (2752 x 2208)

Image size scaled (249.88um x 200.49um)

**FIGURE S1. Methodology for measuring fiber diameter.** Optical microscope images were analyzed in ImageJ to measure fiber diameter. The yellow line represents fiber diameter.

### Pitch (ρ)

The length of one helix from peak of curl to next peak. Measured using the same technique as contour length using image J.

### Total Path Length (L)

“The total path length of the hair between the two grips, so this would be equal to n*L, where n is the number of periods along the length of hair between the grips” Total path length was measured by multiplying the number of periods, the number of peaks, in an approximately 3 cm length of hair by the naturally curly length of hair.

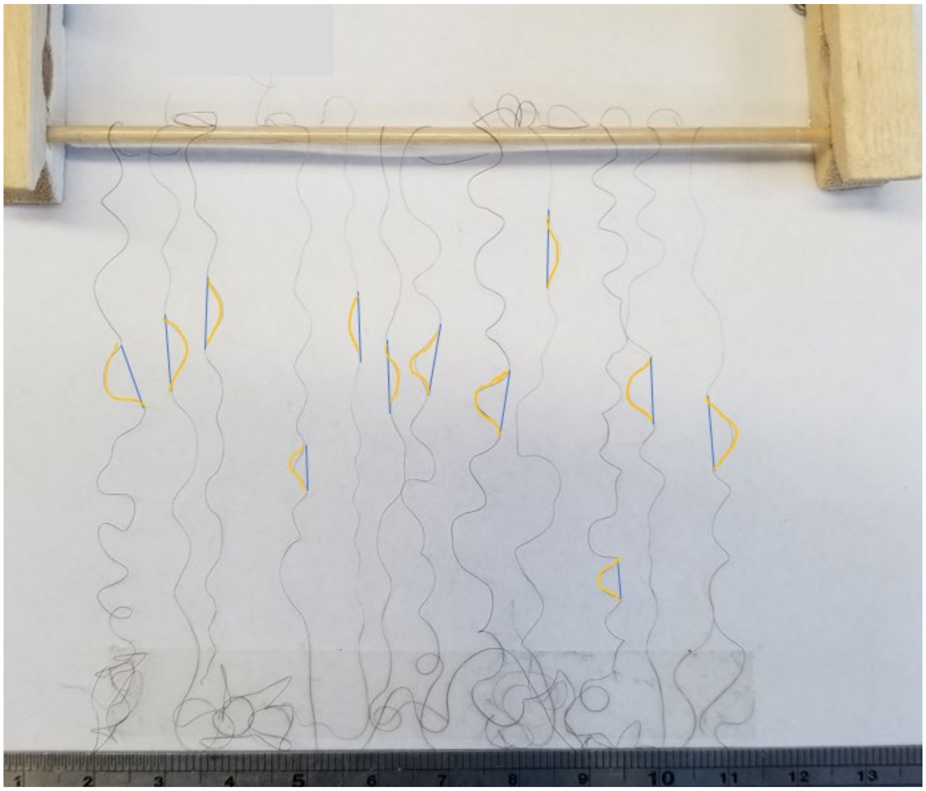


**FIGURE S2. Methodology for measuring pitch and contour length.** Hair fibers from one sample on the drying rack after washing. The ends are taped down to secure. An example of how pitch and contour length were measured in Image J. The yellow lines are the contour length measurements, the blue lines are the pitch measurements.

### *Force TA*

After the hair was washed and allowed to dry testing on the Texture Analyzer could being. Originally all hair sample types were tested at three different length (1.5cm, 3cm and 5cm) we choose these lengths to see if there was an ideal length that could be used for further testing.

The first round of testing was performed on synthetic hair in order to ensure the procedure we had come up with could produce similar results on synthetic hair. Once the procedure was fine tuned enough to give precise results we started testing on human hair.

Note: the grips used to run the hair experiments were customized designed using CAD and 3D printed in the lab.

Our produce of force displacement tests on human hair using the Texture Analyzer:

A length of hair longer than 8 cm was secured to the top grip using double sided tape and duct tape. The hair was than wrapped around the top rod three times and pulled tight enough to secure but not tight enough for the hair to store any force (stress). The hair was then wrapped around the bottom grip 3 times as well, tightened and secured using doubled sided tape and duct tape. Before securing the hair to the bottom of the grip, we always ensured that the force reading was at 0g so that the readings once the experiment started would be unbiased.

The testing jog rate (speed at which the grips were displacing) remained unchanged between each test as did the any other testing parameters. Jog rate was .1 mm/sec

When running tests the hair was monitored to ensure that no slipping was occurring and that the test ran to completion. The tests were considered complete once the hair snapped due to force.

** testing produce for the texture analyzer

Once the computer and TA were turned on the and the two griped were attached force was always calibrated. To calibrate force we started with a 1000kg weight, calibrated it then moved to a 100kg weight to fine tune the TA and ensure calibration was accurate. Once force was calibrated height was calibrated. To calibrate height we programed the TA set the distance to zero when the two grips were touching each other. By calibrated height we ensure the staring position of the grips were the same throughout all experiments.

## SCANNING ELECTRON MICROSCOPY

**Sample preparation for Scanning Electron Microscopy (SEM):** Several strings of hair were threaded through a small hole on the bottom of a 1.5 ml Eppendorf microtube and then sealed using PELCO® Pro C300 Cyanoacrylate Glue (Ted Pella) and allowed to harden overnight. In the first step the hair was fixated using aqueous Glutaraldehyde 25% which was allowed to infiltrate overnight. After removing the excess solution the samples were post-fixed in 4% aqueous Osmium tetroxide solution overnight as well. The samples were then washed 3 times using DI water before dehydration.

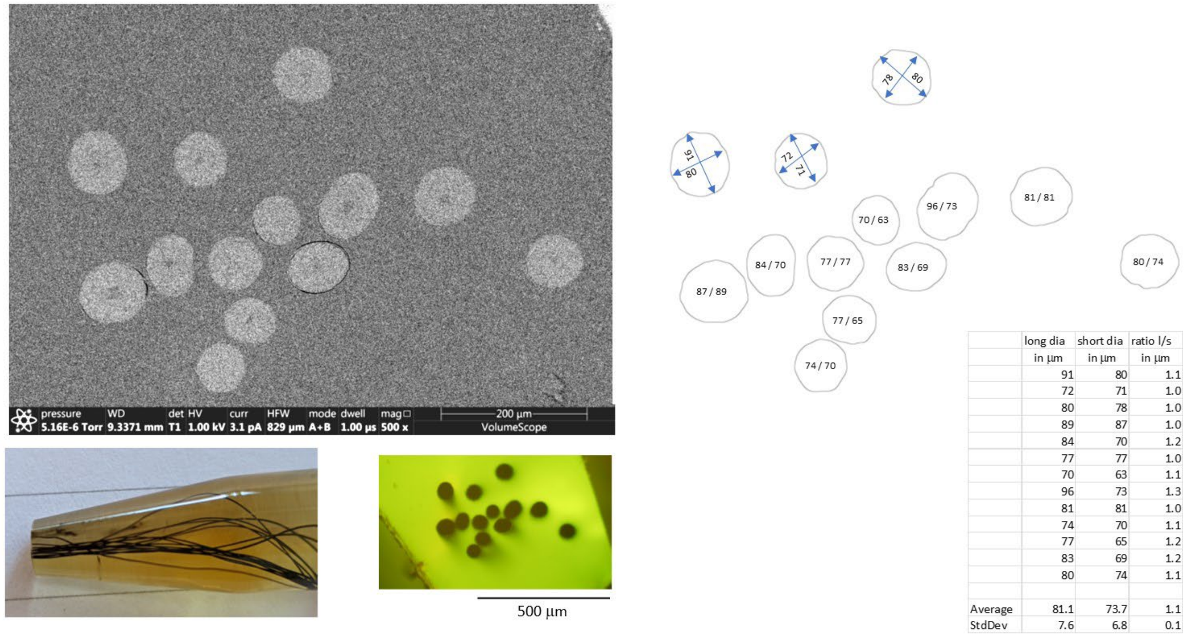
Dehydration was performed using Ethanol/Water mixtures, starting at 10% EtOH content increasing to 100% EtOH in 10% increments. For each dehydration step the samples were allowed to sit for at least 30 minutes. The samples were then washed twice with 100% EtOH and the EtOH was then replaced by acetonitrile.

Embedding was done using Araldite 502 (Ted Pella) starting with a 25% Epon/Acetonitrile solution, which was allowed to sit for 2 hours. Subsequently the solution was replaced with 50% Epon/Acetonitrile and 75% Epon/Acetonitrile solutions, which were allowed to infiltrate for 4 hours each. In a last step the solution was replaced by 100% Epon and allowed to infiltrate overnight. Crosslinking was done at 60°C for 2 days.

The thus obtained embedded hair samples were then cross sectioned using ultramicrotomy. About 1 mm disks were cut off close to where the hair was affixed with the Cyanoacrylate Glue in the first step and glued onto Thermo Scientific VolumeScope™ Pin Stubs (Ted Pella) using the same Cyanoacrylate Glue. After hardening the samples were trimmed around the area where the hair was located, removing as much epoxy as possible and the surface was faced using freshly prepared glass knives until it appeared shiny i.e. smooth. Before imaging in the SEM the samples were sputter coated depositing an about 20 nm thick gold layer, which was removed by ultramicrotomy to expose the cross sections of the respective hair.

SEM was performed using a ThermoFisher VolumeScope II. Due to the heavy Osmium tetroxide stain the hair appears bright in the images which were acquired in backscatter mode (T1 detector) at 1kV acceleration voltage and 3.1 pA beam current.

Sample 1 – “My”



| | long dia | short dia | ratio l/s |
|---|---|---|---|
| | in µm | in µm | in µm |
| | 91 | 80 | 1.1 |
| | 72 | 71 | 1.0 |
| | 80 | 78 | 1.0 |
| | 89 | 87 | 1.0 |
| | 84 | 70 | 1.2 |
| | 77 | 77 | 1.0 |
| | 70 | 63 | 1.1 |
| | 96 | 73 | 1.3 |
| | 81 | 81 | 1.0 |
| | 74 | 70 | 1.1 |
| | 77 | 65 | 1.2 |
| | 83 | 69 | 1.2 |
| | 80 | 74 | 1.1 |
| | | | |
| Average | 81.1 | 73.7 | 1.1 |
| StdDev | 7.6 | 6.8 | 0.1 |

**FIGURE S3. Scanning Electron Microscopy of Cross Sections of Straight Hair Fibers.** Describes the steps taken to measure the cross section of collected straight hair fibers. The ellipticity (***e***) was measured from the ratio of major to minor axes for each fiber. ***e*** = 1.1 for samples pictured, which confirms that straight hair depicts minimal divergence from an ellipse, which agrees with existing findings.

Sample 3 – 2A AU

| | long dia in µm | short dia in µm | ratio l/s in µm |
|---|---|---|---|
| | 64 | 37 | 1.7 |
| | 65 | 36 | 1.8 |
| | 68 | 32 | 2.1 |
| | 69 | 37 | 1.9 |
| | 65 | 36 | 1.8 |
| | 63 | 35 | 1.8 |
| | 42 | 30 | 1.4 |
| | 50 | 37 | 1.4 |
| | 56 | 32 | 1.8 |
| | 54 | 48 | 1.1 |
| | 54 | 36 | 1.5 |
| | 68 | 35 | 1.9 |
| | 60 | 30 | 2.0 |
| | | | |
| Average | 56.2 | 33.3 | 1.7 |
| StdDev | 8.1 | 4.6 | 0.3 |

**FIGURE S4. Scanning Electron Microscopy of Cross Sections of Wavy Hair Fibers.** Describes the steps taken to measure the cross section of collected wavy hair fibers. The ellipticity (***e***) was measured from the ratio of major to minor axes for each fiber. ***e*** = 1.7 for samples pictured, which confirms that wavy depicts about 60% more divergence from an ellipse than straight samples, which agrees with existing findings.

## MECHANICAL PROPERTIES

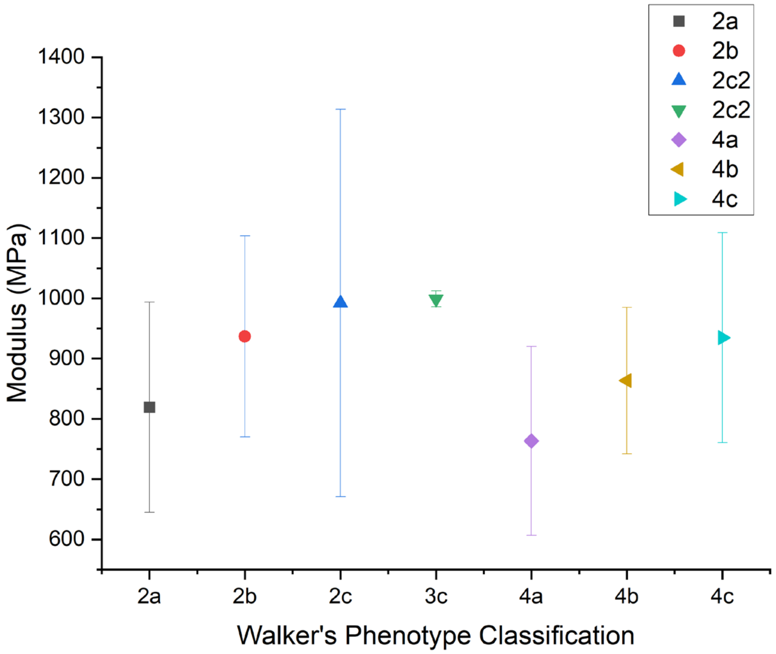


**FIGURE S5. Young's Modulus.** Preliminary elastic modulus measurements of hair samples measured via the texture analyzer (TA). Young's modulus was measured from the slope of the elastic region ($\sigma_\varepsilon$) of each stress-strain curve, which is an indicator of fiber tensile strength.

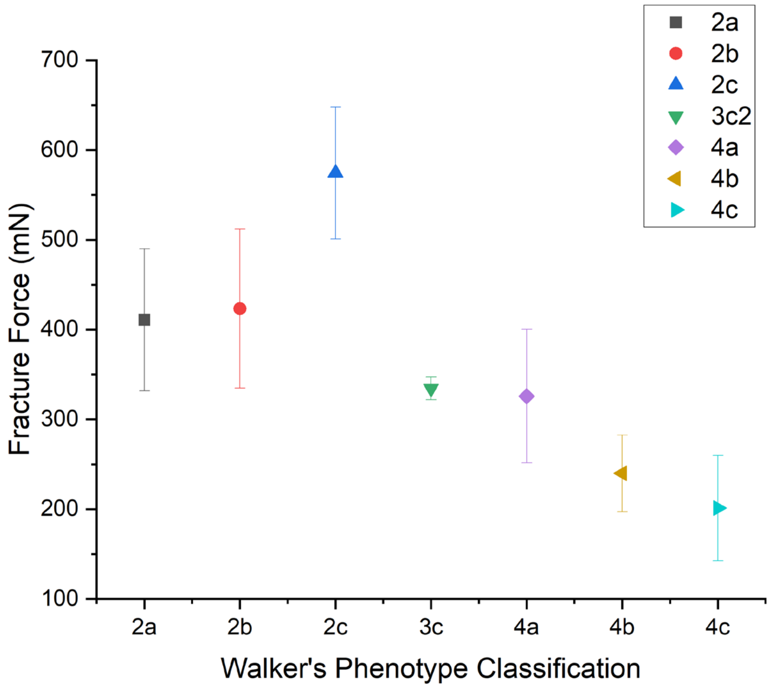


**FIGURE S6. Fracture Force.** Preliminary measurements of the force measured at the point-of-fracture for each of the hair samples. The force measured when each fiber broke, was deemed the point-of-fracture.

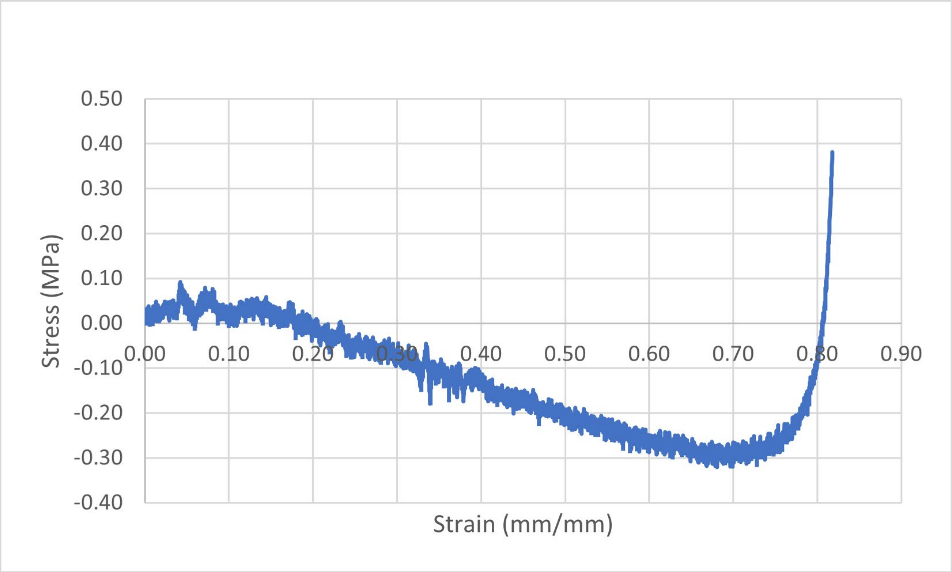


**FIGURE S7. DMA Analysis of Curly Hair Sample.** Dynamic mechanical data highlighting the toe region of the stress-strain curve for a curly hair sample. The toe region signifies the uncurling force ($\sigma_u$) or the force needed to uncurl a fiber until straight. The sample pictured is 3c1.

**FIGURE S8. Supporting Video of Photogrammetry 3D Rendering.**

https://urldefense.com/v3/__https://sketchfab.com/3d-models/220721-human-hair-759cbbf4f2c9494789fa9008eaf93dee__;!!ATJcLOt_!xpAWPt4fk_OPyLddaPOdu5iFgKAu_zadGlRwvLLL9Uo0N-dsM1lT3jYSC4tUjVLvCx5hKqpIQYjC9SSiWHu68mY$