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 ethnicity-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 coily (kinky). However, the system fails to capture the complex diversity of curly and kinky/coily hair. Acclaimed

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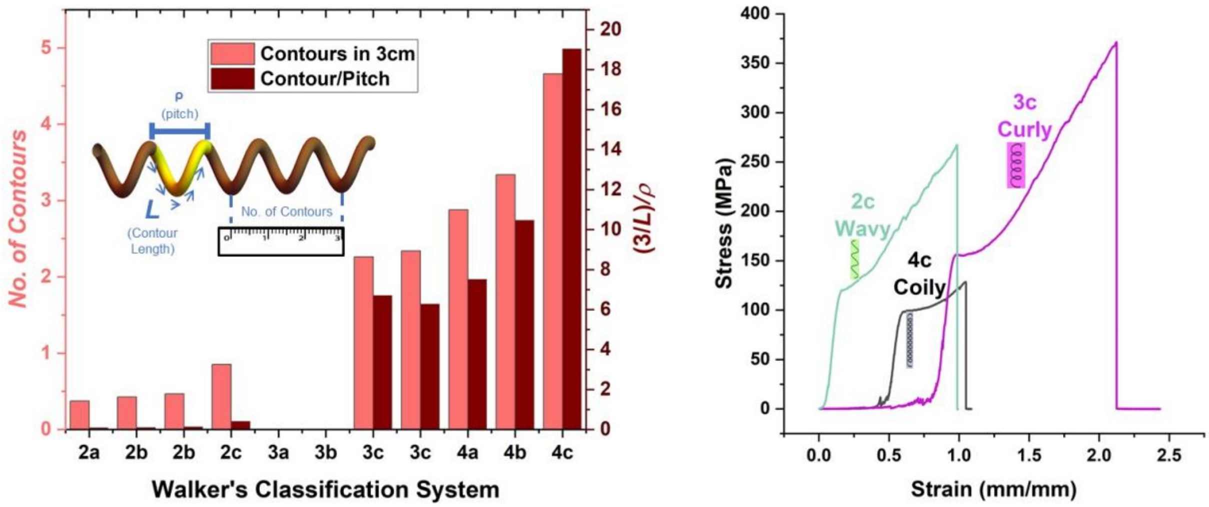
celebrity hair stylist, Andre Walker, developed a classification system that is the existing gold standard for classifying curly and kinky/coily hair, however the system relies upon qualitative classification measures, making the system vague and ambiguous to the full diversity of phenotypic differences. The goal of this research is to use quantitative methods to identify new geometric parameters, which will be more representative of curly and kinky/coily 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/coily hair.



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1. INTRODUCTION

Hair is a key human phenotypic descriptor and is one of the key features that distinguishes humans 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.[1] 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. The styles in which hair is displayed plays a significant role in human society by serving as a form of nonverbal social expression, political stance, and sexual attractiveness.[2] As a result, hair cosmeceutical development in the personal care industry is constantly changing because it is driven by current cultural aesthetic trends in society.[3,4] There are four key categories or curl patterns that distinguish hair morphology according to overall shape of the hair fibers. These include straight, wavy, curly, and coily (kinky) and are pictured in Figure 1.[2–4] Coily and kinky hair can be differentiated according to their morphological shape. Coily hair fibers depict corkscrew shape, while kinky hair fibers depict a zig-zigged, Z-angle shape. The terms coily and kinky are sometimes mentioned interchangeably because people with kinky and coily hair often possess a mixture of these hair morphologies on their scalp.

While hair science has greatly evolved and improved in recent decades there is still a need for products that protect the natural strength and elasticity of hair strands.[2–4] 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*.[5,6] This movie influenced the culture by inspiring people with naturally wavy, curly, coily, and kinky hair to style their hair in its natural morphological state, rather than continue to process their tresses with chemically and thermally damaging products and techniques. This change meant consumers switched from purchasing relaxers and straightening tools, to hydrating creams and conditioning brushes. It influenced an entire industry to develop new consumer products that protected and showcased shiny, healthy, natural curls. The movement also generated a new demand of cosmetologists to learn new hair styling and maintenance techniques to create the most appealing natural hair styles for their clients. This movement also generated significant interest for consumers to learn about how these newly developed styling products perform, so they could ascertain which products they ought to select in order to achieve a desired curly hair style.[3,7] This push for new information led to the development of a hair typing system, which included more hair textures than the previously limited ethnicity-based distinctions, Caucasian, Mongolian, and African hair types.[4,7–10]

Andre Walker's claim to fame came when he became Oprah Winfrey's and Michelle Obama's personal hair stylist. As a hair specialist, he established a new hair typing system that classified hair fibers according to their observable natural curl pattern and shape.[6,11] His system classified hair in the same four main categories (Types 1-4) for straight, wavy, curly, and kinky/coily morphologies, respectively. His system also included three sub categories (a-c) that correspond to increasing hair diameter and thus increasing coarseness.[6,12] 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 the curl pattern of 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.[8,10,13] L'Oréal's hair typing system has 8 categories (I-VIII), and most curly and kinky-coily samples were categorized as Types V-VIII (Figure 1). L'Oréal's is

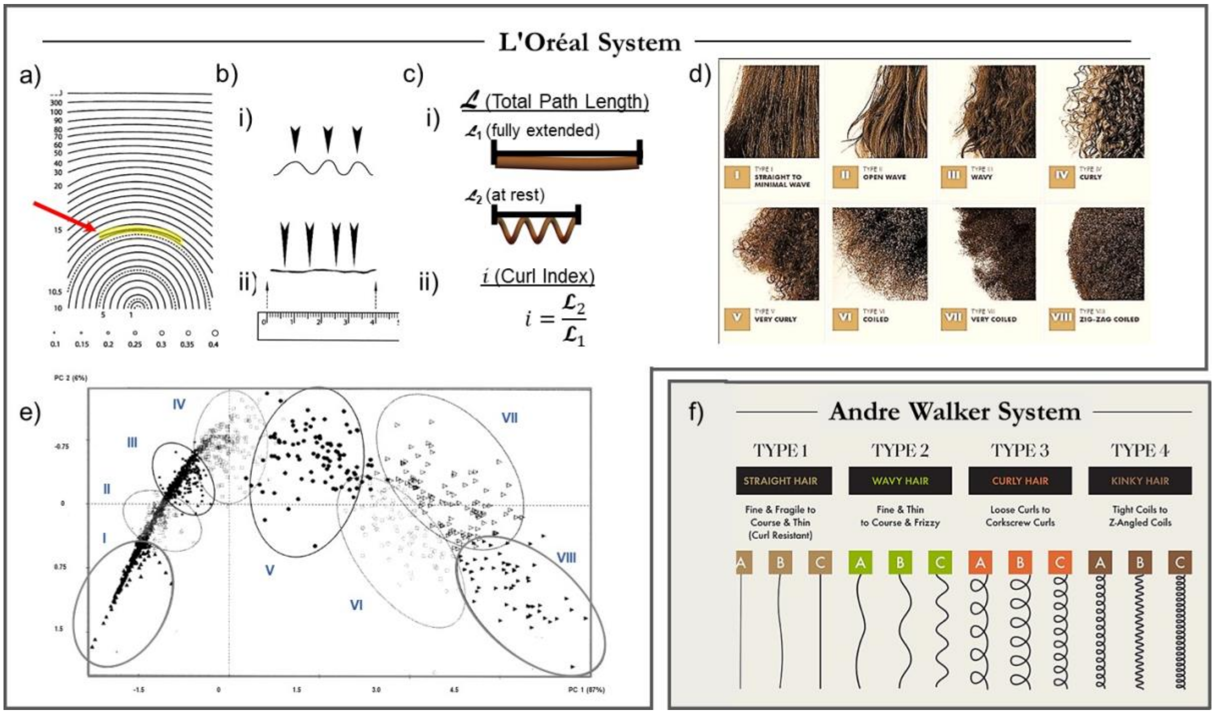


Figure 1. L'Oréal and Andre Walker Hair Classification Systems: (a-d) correspond to L'Oréal's naming scheme (I-VIII). (a) Template derived by Bailey & Schliebe used to measure curve diameter (*CD*).[15,16] The template is composed of concentric arcs ranging from miniscule to very large radii of curvature. 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. The principle component plot illustrates relation patterns between the parameters. (e) 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/coily hair morphologies. Subtypes a-c are defined according to increasing fiber diameter within each hair type and increasing coarseness, respectively.

recognized among the consumer products industry as the official standard for hair typing.[2] They used it to lead the effort towards developing natural hair products, specifically developed for each distinct hair type.

While L'Oréal's system is most 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.[3,14] Consumer confusion stems from believing that the outcome of using a particular product will provide the desired, visible results promised on each product label. If the expected outcome does not materialize, consumers are left feeling frustrated because the results didn't coincide with the marketed expectations.

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.[11,15] 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.[14,16] Developing more inclusive and robust hair classification system has been challenging because curly human hair fibers display a vast range of variable phenotypic characteristics. Each phenotypic variable displays unique material properties, which thus produce different observable and desirable outcomes.[2,16]

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 all holistic properties of curly hair.[14,16] The same research group proposed a modified version of L'Oréal's hair-typing system, which classified hair only according to curve diameter (*CD*) (Fig 1a).[17,18] Same as L'Oréal, *CD* accurately classified 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 named as such 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 simplified version captures straight, wavy, curly, coily, 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.

This research aims to use quantitative methods to identify new geometric parameters and material properties that will account for more phenotypic differences in curly, coily, and kinky hair. These new parameters were used to propose the beginnings of a new classification system, based on quantitative measurements. This research will provide more information on the kinds of ingredients in personal care products that will resonate best with these curl patterns to maximize desired appearance and overall hair health. It also aims to correlate these new parameters with the mechanical properties displayed by curly, coily, and kinky hair fibers. In this work, geometric properties including ellipticity (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), and conclusions were to explain how hair geometry and morphology impact hair fiber mechanics. This research is performed primarily by Chemistry & Biochemistry undergraduate student researchers attending Spelman College, a small liberal arts Black 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, coily, and kinky hair that is being researched upon.

2. METHODS

Hair samples were collected from individual volunteers, and 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, 6cm or longer, so that multiple experiments could be conducted on each sample. Once received, hair samples were prepared for experimentation by administering a controlled washing and drying procedure, identical to L'Oréal's sample preparation process.[8] Samples were soaked in reverse osmosis water for twenty minutes then placed onto a drying rack set up that allowed curls to naturally form as the hair strands dried. Hair strands were set out to dry on the benchtop for at least twelve hours before any experimentation was carried out (SUPP-2).

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, 3D modeling software. Photogrammetry was the technique employed to image individual hair fibers in three-dimensions. The purpose was to capture each sample's full geometric shape in 3D, thus providing more structural information than 2D images. 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 helps to increase accuracy when measuring total path length ($\boldsymbol{\mathcal{L}}$), as indicated by the red dotted line extending down the length of the hair fiber shaft (Fig. 2b). $\boldsymbol{\mathcal{L}}$ was one of the parameters originally measured by L'Oréal.[8] 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

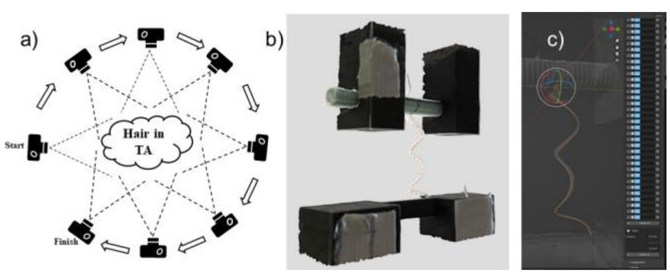


Figure 2. Photogrammetry. (a) Experimental design for capturing data for 3D rendering of hair fibers. (b) 3D render of a curly hair fiber mounted to the Texture Analyzer (TA).The fiber was imaged at zero displacement. (c) Fiber length measured in Blender (3D-modeling software) by tracing the path along the length the rendered 3D curve. Curve length of pictured fiber, 37.519 ± 0.454 mm. SUPP V1 is the 3D render of the curly fiber at different angles, visualized in Sketchfab.

axes from the cross section of each hair strand. ***e*** was measured from images of samples collected via SEM. The sample preparation process used to collect SEM images of hair fiber cross sections is explained in the Supplementary Information. Other newly identified geometric parameters, such as contour length (L), number of contours, and pitch (ρ) 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) and a dynamic mechanical analyzer (DMA). Stress-strain curves were developed from force-displacement measurements collected from each hair strand in the TA. Hair strains were loaded between the grips by gently 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 6cm, 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. Each experiment concluded at the point for fracture for each hair fiber (SUPP V-1).

3. GEOMETRIC FEATURES

Hair Structure & Composition

Hair is composed of three main components – medulla, cortex, and cuticle (Figure 3d).[1] 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.[19] The cortex surrounds the medulla and is the structure that provides the bulk of geometric structure, morphological shape, mechanical strength, and elasticity for hair fibers.[9] The cortex is composed of cortical anisotropic cells among a matrix of keratinized amorphous proteins. Each cortical cell is macrofibril composite of aggregated alpha-helical microfibrils. These macrofibrils originate from aggregated bundles of alpha-helical microfibrils. The inner-structure of microfibrils is made of keratin proteins, arranged in tight aggregated bundles of alpha-helical keratein fiber intermediate filaments that have been aggregated and arranged into micro- alpha-helices.[19] Human hair contains three types of cortical cells – paracortical, mesocortical, and orthocortical – each differing slightly in shape.[9,20] Wool contains additional types of cortical cells.[20,21] According to Wortmann *et. al.*, the structural arrangement of each type of cortical cell directly correlates to overall hair fiber shape, which originates from di-sulfide bond chemical crosslinking pattern along the hair shaft between cortical cells and keratinous amorphous matrix proteins and the long-range order displayed by the packing resulted from the crosslinked structures.[20] Wortmann and coworkers suggest that lateral phase segregation between the three cortical cells is one of the main factors that dictate curl formation in hair, thus indicating that homogeneous cortical cell arrangements achieve wavy and straight phenotypes.[9,20]

The external protective outer layer of hair is called the cuticle.[1] Its main function is to protect the cortex from outside physical and chemical stresses and maintain a homeostatic environment within the hair shaft. 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.[9,20] 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 open and close reversibly in response to the hair fiber's chemical environment. Hair porosity is defined as the extent of reversible sheath cell opening and closing, which occurs in response to chemical stimuli. Thus, the cuticle is the structure that behaves similarly to an environmentally stimulated hydrogel and is responsible for maintaining hydration across each hair fiber.

Diameter & Cross-Sectional Ellipticity

The dermatology and anthropology fields are the two major groups that publish on hair science in the academic literature. Cosmetic science would fall under the umbrella of dermatology and forensic science would fall under anthropology. The key variables most often reported are fiber geometry (length, diameter, ellipticity, and degree of curl), emergence angle from the scalp, and fiber-to-fiber interactions.[22] Most studies have broadly reported that curlier hair had shorter lengths, lower hair density, and slower growth rates.[23] As for the other geometrical parameters, L'Oreal has used diameter (*d*) as a geometric descriptor to infer coarseness and thus "texture", "handle", and "feel".[24] *d* has also been used to draw conclusions on fiber growth rate, trends in hair fiber density, to evaluate the scalp health.[23,25,26] Hair fiber diameter (*d*) was measured from hair samples donated by volunteers. The average *d* from those samples are reported in Figure 3.[23] The results don't indicate much difference between the *d* of 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 of a hair fiber to its tip, and the diameter of hair fibers can also vary across each person's scalp.[25,27,28] Importantly, *d* does not capture the ellipticity (***e***) of a hair fiber.[29] ***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).[25,28] ***e*** is a normalized value, and has been used to examine structural differences along the hair shaft in curly hair.[28,30] To the best of our knowledge, the literature has yet to report comparative studies on hair fiber ellipticity (***e***) and diameter across the different phenotypes. There was one study that compared medulla ellipticity across several of the L'Oréal phenotypes. They reported similar trends in medulla ellipticity as this research reports for the full fiber cross section.[31] The studies that have been conducted and reported ***e*** as a geometrical descriptor were mostly conducted on "Caucasian" hair samples, in the context of mitigating adult male hair loss.[24,28,32–36] Although one study conducted on "Caucasian" females reported an 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.[28] According to data collected in this research, ***e*** increases as extent of curliness increases. These results are in agreement with what has been reported in the literature.[27,37]

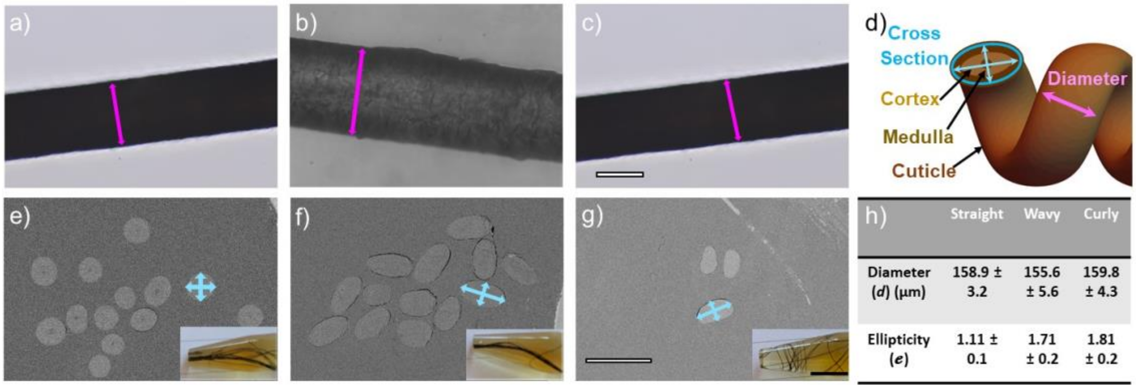
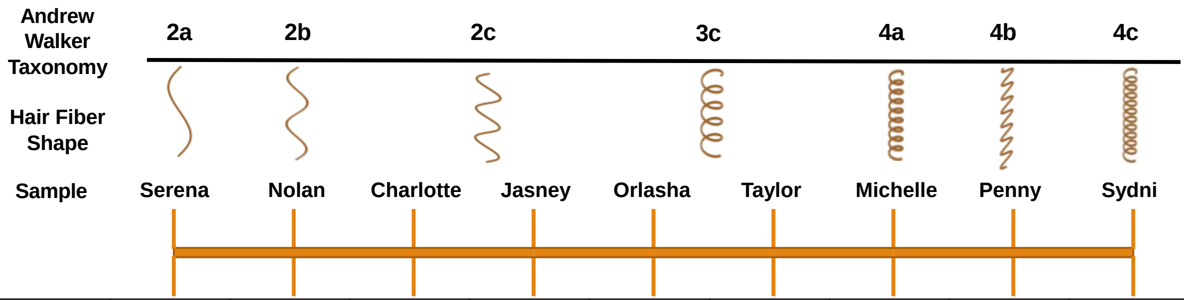


Figure 3. Hair Fiber Ellipticity & Hair Diameter Measurements. Bright-field optical microscopy and SEM images of hair fibers. (a-c) Average diameter (*d*) was measured from 3-5 strands of each hair sample, along multiple points along the length of each fiber. The samples shown are (a) straight, (b) wavy, 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 (***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.

New Geometric Parameters for New Classification System

Several of the other geometrical parameters have been reported in the literature, and several comparative studies across phenotypes have been conducted. 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.[3824] "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.[9,20] The shape of the follicle dictates the shape of the cross-section of each hair fiber (ellipticity, ***e***).[3] 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.[9,20] 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



	Serena	Nolan	Charlotte	Jasney	Orlasha	Taylor	Michelle	Penny	Sydni
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 coily (4a-c) hair. Measurements reported are the average taken from measurements collected off 12-15 strands from each sample of cleaned, dried hair fibers.

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, kinky, and coily, hair because straight and wavy hair exist in 2-dimensions, while the other phenotypes exist in 3-dimensions.

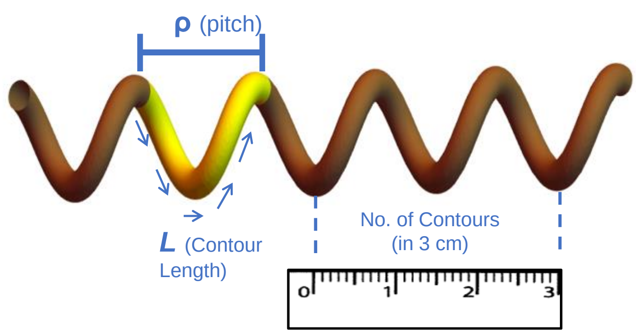


Figure 4. Contour Length, Number of Contours, & Pitch Geometric Parameters, Summarized in Table 1. The three key parameters measured, reported in Table 1 are *L*, *No. of Contours*,& *ρ*. Contour Length (*L*) – length in centimeters along one contour of a wavy, curly, or coily hair fiber. Number of Contours 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/coily hair. These new parameters were used to develop a quantitative taxonomy and was compared to Andre Walker's system and one of the new parameters reported in this work.

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 (SUPP-2). 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 an indication that the results from the current study coincide the curl pattern categories and subcategories included in his hair typing system. Importantly, Figure 5 also illustrates similar trends between the quantitative measurements obtained using image 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 with a ruler, without using any analytical techniques. These results will be verified after testing more hair samples in the future.

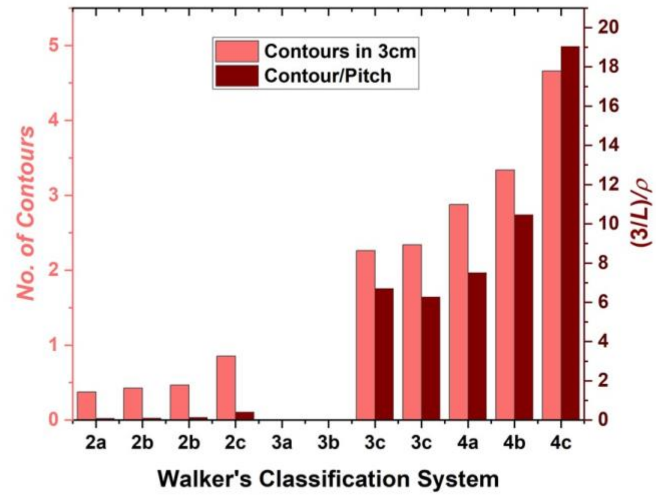


Figure 5. Comparison between Number of Contours and Contour Length to Pitch Ratio. Graphical representation of new parameters, *No. of Contours* & (*3*/*L*)/ρ, taken from Table 1, were identified in this work and compared against Andre Walker's hair-typing system. (Left) *No. of Contours* represents 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 coily 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 types of 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.

4. MECHANICAL PROPERITES

The literature has consistently report straight and wavy hair as being stronger than curly, coily, and kinky hair.[39–41] The mechanical properties measured in these studies reported that Young’s modulus (E), tensile strength (σ) and fracture point decrease with increasing degree of curliness, while friction coefficient increases with degree of curliness. Thus, hair breakage and damage from mechanical manipulation has been widely reported and commonly experienced by people with curly, coily, and kinky hair. These conclusions remain true for hair fibers that are dry, wet, or coated with products.[39,42–45] It is for these reasons that the cosmetic industry has done a lot of research and development to create products that will strengthen and fortify the natural structure of curly hair.[2,4] The results in the current study display similar trends to previous studies. The current study also examines a few other mechanical parameters, which are unique to curly, coily, 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 (σ_u) and elastic tensile strength (σ_ε). σ_u is analogous to the decrimping force measured in wool.[21] 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 σ_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).[46]

The results in the current study coincide well with Colete *et. al.* and depict several notable differences

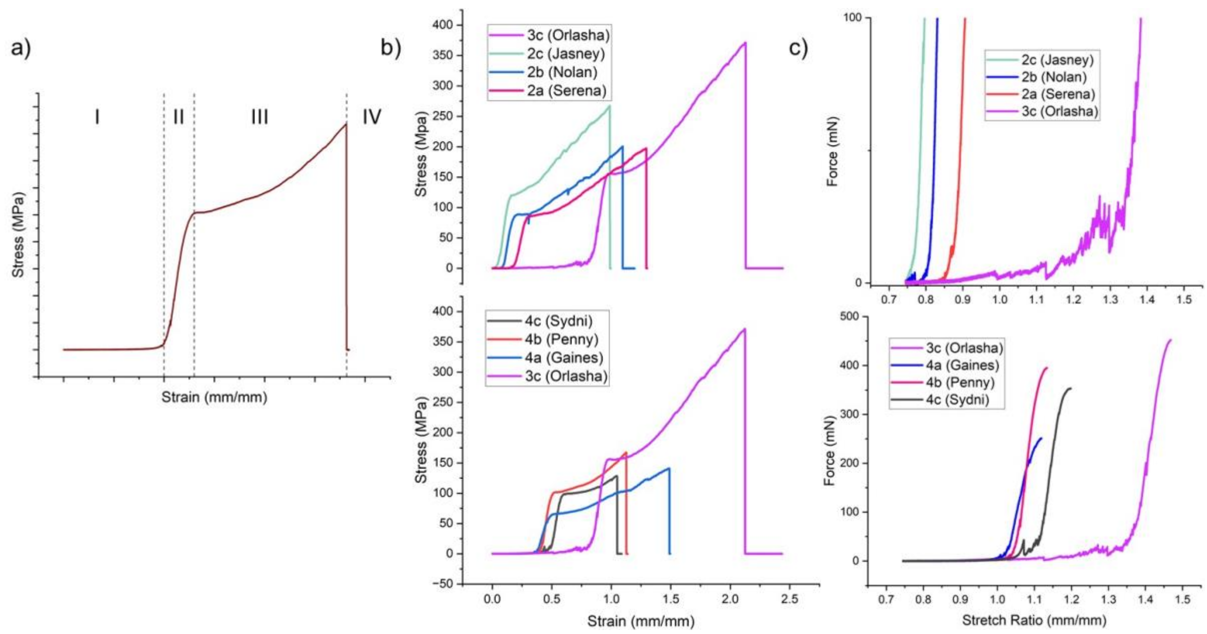


Figure 6. Mechanical Properties. (a) Example stress-strain graph for a curly, coily, or kinky hair fibers. I –Toe Region, the tensile force (σ_u) required to uncurl the natural curve morphology of a curly, coily, and kinky hair fibers. The toe region is virtually absent for straight and wavy hair samples (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 (σ_{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-coily 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-coily hair against a curly 3c sample.

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 (σ_u). Region II is the elastic region where elastic modulus (E) is determined. Regions II – IV are the regions captured in a typical stress-strain curve for a fiber. DMA can measure mechanical behavior at higher resolution and was used to collect on samples to measure force-displacement response with increased precision. The stress-strain behavior of wavy, curly, and coily 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-coily samples (bottom – 4a-c). Sample 3c shows evidence of the widest Toe Region (Region I) and thus the largest σ_u. Past studies have demonstrated a correlation between *CD* and with Young's modulus.[42] 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.

$$\frac{\varepsilon_0+\Delta\varepsilon}{\mathcal{L}} \tag{I}$$

ε_0 is initial displacement (mm), i.e. the displacement recorded at time = 0 seconds. $\Delta\varepsilon$ is displacement (mm), and $\mathcal{L}$ is total path length (mm). The stretch ratio depicts the extent of stretching that each hair fiber endures during the course of a tensile test. Figure 6c compares the extent of hair fiber stretching between the curly 3c sample, wavy hair (2a-c), and kinky-coily hair (4a-c). Stretch Ratio is 1.0 when ε_0 equals $\mathcal{L}$, which is depicts the mechanical behavior of a straight hair fiber. Wavy hair samples depicted stretch ratios < 1.0, which generally indicate $\mathcal{L} > \varepsilon_0$. Each of the kinky-coily hair samples consistently reported $\mathcal{L} < \varepsilon_0$, which captures some of extent of initial curliness for each of the hair samples.

5. SUMMARY AND OUTLOOK

The present study reported several distinguishing geometric and mechanical features of curly, coily, and kinky hair. The present study was performed on hair samples from several volunteers displaying observable differences hair phenotypic. 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 or declaring a new hair-typing system, the initial proof-of-concept reported here must be tested among larger sample sizes from larger populations of people. 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 normal individuals without a microscope or image processing software handy. 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. This research used 3 cm as the unperturbed length. 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).[47] 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 of many interacting strands in the simulation of entire heads of hair.[48–50] 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. 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, coily, and kinky hair in particular.

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