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Quantifying Hair Motion

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Synopsis

A commercially-available instrument, previously intended to visualize and quantify hair shape and volume, has been modified to measure hair motion. Specifically, a transversal motor now induces a side-to-side oscillating tress stimulus, while a video camera records the outcome. Image analysis software allows for quantifying the amount of motion (i.e. the amplitude), the shape and volume of the hair during motion, and the homogeneity of the hair (i.e. bulk –vs- flyaways). Each of these parameters has considerable dependence on the frequency of oscillation and so evaluations are carried out by systematically varying this parameter. Preliminary validation experiments are documented which involved methodical variation of parameters that were presumed to be of importance. These included the size and shape of hair tresses, various hair treatments, and environmental conditions.

As a result of the sizable amount of data that results, graphical depictions provide the best means of representation. For example, amplitude –vs- frequency plots describe the extent of hair motion as a function of energy supplied to the system. Visually noticeable decreases in tress motion were observed after applying small quantities of silicone oil to the hair. This occurrence reduced the measured amplitude of tress motion, while also moving the maximum amplitude to high frequency. Accordingly, it is supposed that improved motion is attained by inducing a higher amplitude at a given frequency, and/or by attaining comparable amplitude under the application of a lower frequency.

INTRODUCTION

During virtually every TV commercial for hair care products, a model is shown whose hair moves in a beautiful, fluid, flowing manner. Clearly, this motion is a significant factor in the perception of attractive hair; yet, this topic has received relatively little attention in the scientific literature (1).

Even with primitive experimental set-ups, it is easily seen that different “hair types” do indeed move quite differently. Asian hair moves differently from Caucasian hair; straight hair moves differently from curly hair; virgin hair moves differently from chemically damaged hair. The issue becomes how to quantify this process and describe motion in terms of numbers. In this work, we report on modifications to a commercially available device (previously intended to quantify the shape of static hair tresses) to visualize and analyze hair motion.

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In validating any instrumental method, it is desirable to conceive of means for systematically manipulating the desired variable to ensure that predictable responses result from such logical changes. Thus, it is necessary to contemplate which physical properties of the hair might provide impact. Hair weight would seem a contributor—where higher weight may be a result of fiber thickness, length, and/or density on the scalp. Hair stiffness would seem a factor, as would curvature and interfiber friction. It is noteworthy that these exact same parameters have also been suggested to be key components of hair *body* and *volume* (2,3). Therefore, these attributes are seemingly related and it is hoped that learnings from studying hair motion may provide much needed insight into these two other ambiguous and poorly understood variables.

EQUIPMENT

BOLERO® by Bossa Nova Technologies (Culver City, CA) is a commercially available instrument that allows for visualization and quantification of the 3D shape and volume of hair tresses. A digital video camera is used to procure photographs of hair tresses under precise mounting and lighting conditions. The tresses are also automatically rotated to provide 360° visualization of hair shape. Another feature involves a back field illumination source which highlights and differentiates wispy, flyaway fibers from the tress bulk. Image analysis techniques subsequently allow for quantification of tress shape and volume, while also providing a means for evaluating relative proportions of these frizzy fibers (see Figure 1). Details of this device have been described elsewhere (4).

In the present work, this existing setup has been modified to visualize and analyze tress motion. The rotational mechanism of the original instrument was replaced by a transversal motor that induces a side-to-side oscillating tress stimulus. In the present form, frequencies in the range 0.5–2 Hz can be selected. Similarly, the camera was replaced by a digital

Figure 1. Image analysis for evaluating hair volume and flyaway using Bolero® from Bossa Nova Tech.

monochrome video camera that captures 70 frames per second with a resolution of 1,850 × 2,300 pixels and 8-bit digitalization. The videos are saved in AVI format, without any compression to retain all image information for subsequent processing. Modified software allows for the control of experimental setup, visualization of captured videos, and a variety of post-experiment imaging analyses. For example, experiments can be setup at a single specific frequency or automatically run across a range of values, and tress motion can be replayed in real time or slow motion.

At this early stage of the work, we have considered a variety of analyses to gather information on tress movement. Figure 2 shows the result of tress edge detection that allows for a skeleton of the swatch to be determined for each video frame. In this way, it is possible to derive measures for the volume and shape of the tress bulk during motion. Moreover, the *homogeneity* of the tresses can be assessed during motion by looking at relative levels of wispy flyaway fibers—as per the purpose of the initial device.

RESULTS

Initial experiments were performed using clean, straight tresses of healthy Caucasian hair. Tresses contained approximately 3 g of hair and measured 20 cm in length by about 1 cm in width. These tresses gave rise to a natural oscillating motion in their clean, untreated state; but the negative impact of fixative polymers (styling products) and relatively heavy coatings (oils) was visually evident in early “feel-out” experiments. The natural swinging motion of the hair tips was considerably dampened after oil treatment and essentially eliminated by the styling treatment. Thus, the amplitude of the swaying associated with the tress tips appeared an instinctive measure of this motion.

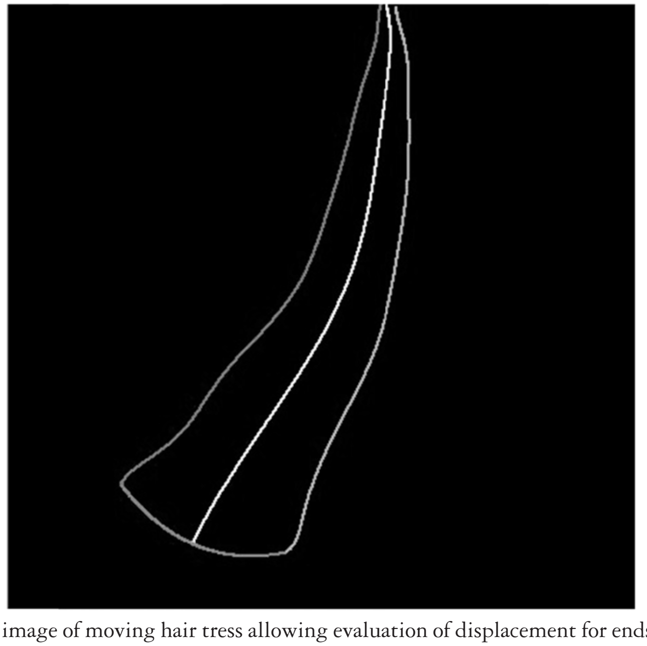

Figure 2. Skeletal image of moving hair tress allowing evaluation of displacement for ends relative to anchor point.

Figure 3 shows results for a straight Caucasian hair tress oscillating at a frequency of 1 Hz. The oscillating tress displaces from the center point by approximately ±20°—resulting in a total amplitude of motion of about 40°. For comparison purposes, an identical experiment using decidedly curly/frizzy hair resulted in an amplitude of 28°, whereas Caucasian hair treated with a hair spray essentially gave a value of zero. Thus, a direct correlation between the magnitude of the measured amplitudes and the perceived motions of these tresses might be presumed—however, considerably greater complexity exists.

The considerable influence of the oscillating frequency is another observation that arises from watching hair with natural and unnatural motion. In clean tresses, the nature of the motion varies significantly with changing frequency; however, this does not happen in hair treated with a hair spray. As possibly anticipated, application of progressively higher frequencies of motion initially produces higher amplitudes in clean tresses—but only up to a point. Eventually, application of still higher frequencies ultimately produces a decrease in this parameter—presumably as hair motion in one direction is stifled by the tress now being pulled in the opposite direction, before motion has finished in the original direction.

Figure 4 shows examples of amplitude versus frequency curves for the aforementioned Caucasian, frizzy, and hair spray–treated hair. As already noted, the independence of the hair spray–treated hair on frequency is considered an aspect of unnatural motion. This graph illustrates how conclusions based on a single frequency can be misleading. That is, experiments at 1 Hz showed straight Caucasian hair producing a higher amplitude of motion than frizzy hair; however, this trend is seen to reverse at higher frequencies. A value for the maximum attainable amplitude (A_{max}) for any particular test sample and the frequency at which it occurs (f_{max}), potentially become useful characterization parameters.

HAIR TRESS EFFECTS

In most *in vitro* hair testing experiments, the nature of the results can be greatly influenced by the properties of the hair itself and the size/shape of tresses. For example, when performing extremely popular instrumental combing experiments, it is desirable to initially

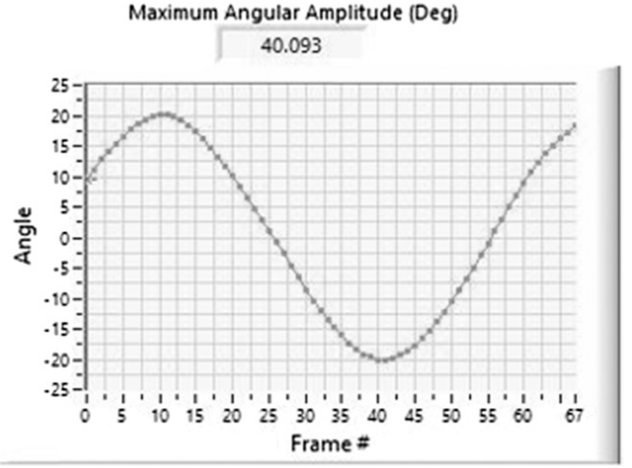

Figure 3. Motion amplitude for a Caucasian hair tress under the application of a 1-Hz oscillating frequency.

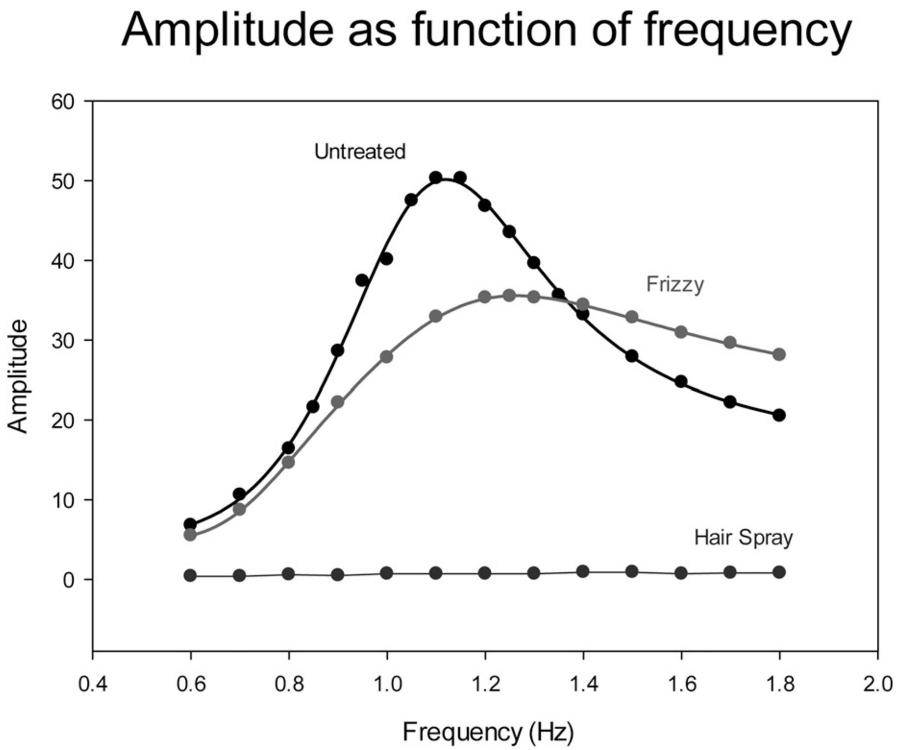

Figure 4. Effect of hair type and treatment on amplitude versus frequency plots.

generate relatively high combing forces such that the lubricating benefits of products can more effectively be demonstrated. This can be attained by using somewhat thicker/denser tresses or, more economically, by chemically damaging the hair. Likewise, looking for shine benefits using very straight, heavily pigmented Asian hair would yield minimal sensitivity because of the already highly shiny innate state of the hair. For these reasons, it was considered prudent to look for contributions from the size, shape and nature of hair tresses on motion. In these experiments, longer 25 cm tresses of Asian hair were used that measured 7 g in weight.

Instinctively, longer hair might be anticipated to yield more motion—but again, amplitude versus frequency curves suggest a more complex story. Figure 5 shows the effect of tress length on such experiments. Note: all experiments were performed on the same tresses, wherein the length was controlled by the use of a plastic cable tie. That is, the tie could initially be placed around the top of a tress—and then progressively slid downward to yield systematically shorter tress lengths.

In general, reducing the tress length leads to amplitude versus frequency curves shifting upward and to the right (higher A_{max} and f_{max}). That is, higher amplitudes of motion can be attained but higher frequencies are required to produce this occurrence. Again the shape of these curves illustrates the danger of making conclusions from experiments at a single frequency. For example, from Figure 5, experiments at 1 Hz would suggest progressively higher motion (amplitudes) with increasing hair length, whereas testing the exact same tresses at higher frequencies (≥1.6 Hz) yields the reverse conclusion. Meanwhile,

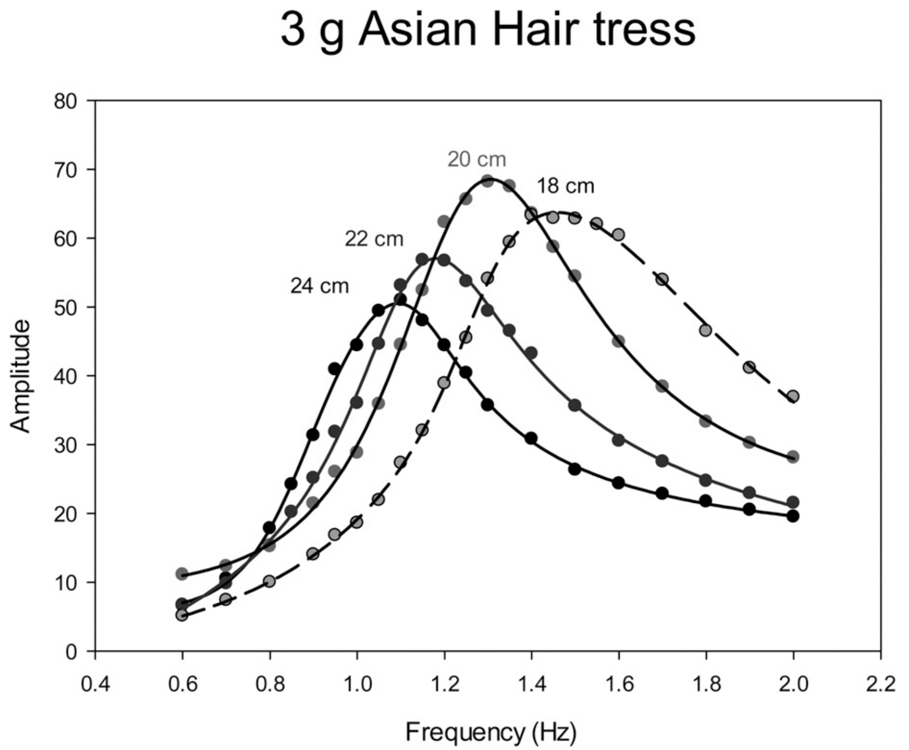

Figure 5. Effect of hair length on the shape of amplitude versus frequency plots.

experiments at 1.2 Hz would produce the puzzling conclusion of the longest and shortest tresses giving comparable results, whereas high values result for intermediate lengths.

Frequency and energy are directly related (more energy is required to attain higher frequencies) and so a means of conceptualizing results in Figure 5 is to suggest that although higher amplitudes can be achieved in shorter tresses, more energy is needed to attain this state. This produces an alternate way for thinking about results in Figure 5. Namely, rather than considering what amplitude results from application of a given frequency—one can evaluate the frequency (energy) necessary to move the hair at a given amplitude. By means of illustration, Table I shows the frequency necessary to achieve a 40° amplitude of motion in tresses of differing length. It is evident that this amplitude can be obtained via two

Table I
Frequency Required to Attain a 40° Amplitude of Motion in Hair of Different Lengths

Tress length (cm)	Frequency to attain 40° amplitude (low side) (Hz)	Frequency to attain 40° amplitude (high side) (Hz)
24	0.95	1.25
22	1.02	1.42
20	1.07	1.67
18	1.21	1.92

Frequencies listed in the table are calculated from best fitting curves (as shown in Figure 5) as obtained using Table Curve 2D® V5.0 by SYSTAT (San Jose, CA).

different conditions—i.e., the low and high frequency sides of the inflection point. Both are shown in Table I—with both yielding comparable rankings of the different tresses, namely, higher frequency/energy is necessary to produce comparable motion in progressively shorter hair.

Similar experiments were performed to investigate the effect of hair weight. In these experiments, first two and then three tresses were affixed together in a back-to-back manner—again using plastic cable ties. Results showed a notable increase in amplitude when doubling up the hair—with a further slight increase from use of triple tresses. It is concluded that heavy, short tresses produce the highest amplitudes of oscillation—and would therefore have the least sensitivity in experiments intending to find means of increasing hair motion. Therefore, all further experiments have been performed on 24-cm single tresses.

PRODUCT AND INGREDIENT EFFECTS

Silicone oil was applied to tresses at the lowest dosage considered possible. This was accomplished by touching a finger to the surface of the oil—such that only the smallest amount was retained. This minute dosage was then massaged thoroughly through the tress to ensure uniform application. Later, after initial testing, a second dosage was similarly applied.

Amplitude versus frequency curves for untreated hair and these two silicone treatments are shown in Figure 6. Results show the treated hair giving rise to notably lower amplitudes of motions, although higher frequencies (energy) are also needed to attain a given

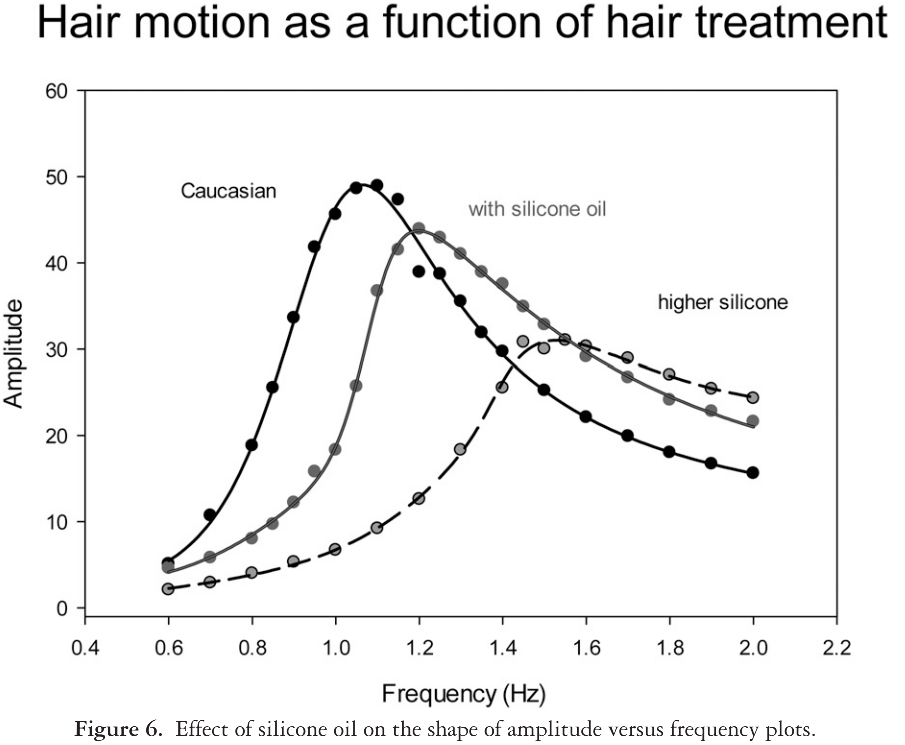

Figure 6. Effect of silicone oil on the shape of amplitude versus frequency plots.

amplitude. Visually, these treated tresses exhibit considerably less motion. Therefore, lower amplitudes at higher frequencies is surmised to be an indication of diminished motion. Conversely, higher amplitudes in combination with lower frequency/energy would seemingly equate to improved motion.

Silicones are widely thought of as lubricants and so ability to reduce interfiber friction might have been speculated to enhance motion. This said, silicones are lubricants under high shear conditions. Here, fibers rubbing against each other presumably constitutes low shear conditions—where the presence of silicone oil possibly produces a degree of interfiber cohesion. The increased weight of the silicone on the hair may also be a negative contributor.

Commercial hair conditioner. The lubricating ability of typical commercial conditioner products is well recognized. To that end, amplitude versus frequency curves for conditioner-treated hair shift slightly to the left (lower frequency), although also decreasing slightly in amplitude. Per the previous argument, this might be interpreted as slightly less overall motion but being attained under the application of less energy input.

Heat straightening. Heat straightening appears to improve hair motion. Despite the known damaging effects of these treatments—short-term benefits involve a highly aligned, straight conformation that seemingly possesses visibly enhanced movement properties. In this instance, amplitude versus frequency curves became taller, slightly broader but without any notable shifting of the peak on the frequency axis. This is interpreted as enhanced motion without meaningfully more energy input.

In contemplating the differing ways in which amplitude versus frequency curves can be altered by these treatments, it is perhaps useful to again think about the way the previously mentioned fundamental fiber properties are affected. For simplification, we consider hair weight, hair stiffness, and fiber–fiber interactions.

The application of silicones adds weight to the hair, seemingly provides interfiber cohesion but presumably does not change fiber stiffness. Commercial conditioner deposits (i.e., quats and fatty alcohols) might add lesser weight and provide interfiber lubrication, while also having no effect on fiber stiffness. Meanwhile, heat straightening would decrease fiber weight via water removal, with fibers becoming stiffer concomitantly, whereas improved alignment and de-swelling result in lesser interfiber friction. It is evident that each of these hair treatments impacts fundamental properties in different manners and so amplitude versus frequency curves might also be anticipated to change in different ways.

HUMIDITY EFFECTS

To this end, relative humidity might be expected to have considerable effect on hair motion. Hair adsorbs progressively higher levels of moisture with increasing relative humidity (5)—and, therefore, becomes heavier. Moreover, water is a plasticizer for hair and so fibers also become progressively less stiff. Furthermore, elevated water content leads to a degree of radial swelling within fibers, which raises overall tress volume and likely induces some increased friction.

Figure 7 shows amplitude versus frequency curves for the same hair equilibrated at first low humidity and then high. Although notable differences arise, interpretation is not

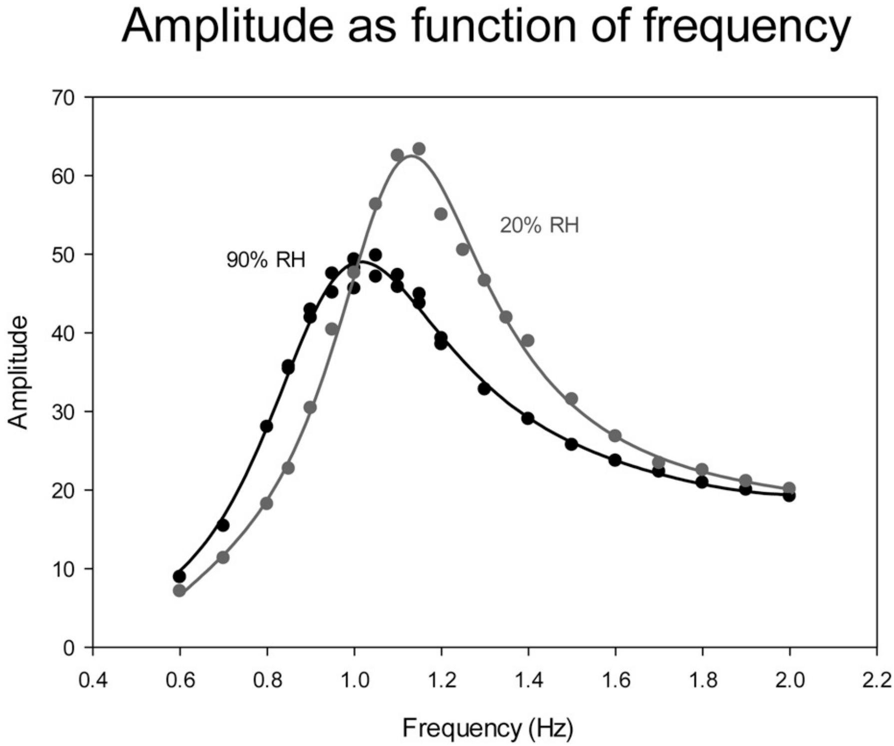

Figure 7. Amplitude versus frequency curves for common hair at low and high humidity.

straightforward. As per previous arguments, the increased maximum amplitude of motion at low humidity might be suggested as an indication of enhanced motion. Or, conversely, the ability to generate a given amplitude of motion using lesser frequency (energy) at high humidity might similarly be noted.

REPRODUCIBILITY

Any testing of hair fibers and/or hair tresses is subject to issues relating to the high variability of the substrate. It is therefore necessary to run a sufficient number of replicate samples to afford an ability to perform suitable statistical analyses. Figure 8 shows a graph containing amplitude versus frequency curves for five experiments on the exact same hair tress. The hair was initially subjected to motion testing at progressively higher frequencies. The tress was then carefully removed from the instrument, remounted and run three times more in the exact same manner. The dotted line shows a best-fitting curve through these very tight data points. However, before one final replicate experiment, the hair tress was given a somewhat vigorous shake. Figure 8 also shows how a very different shaped curve arises after this shaking.

Here again a parallel is drawn to the related attributes of hair body and volume where sizable changes in this property can be induced by manipulation after the treatment process. For example, static air drying of hair will produce very different volume and body characteristic in comparison with the same hair dried with some degree of agitation. In short, this manipulation can have an overriding impact on the desired property which exceeds

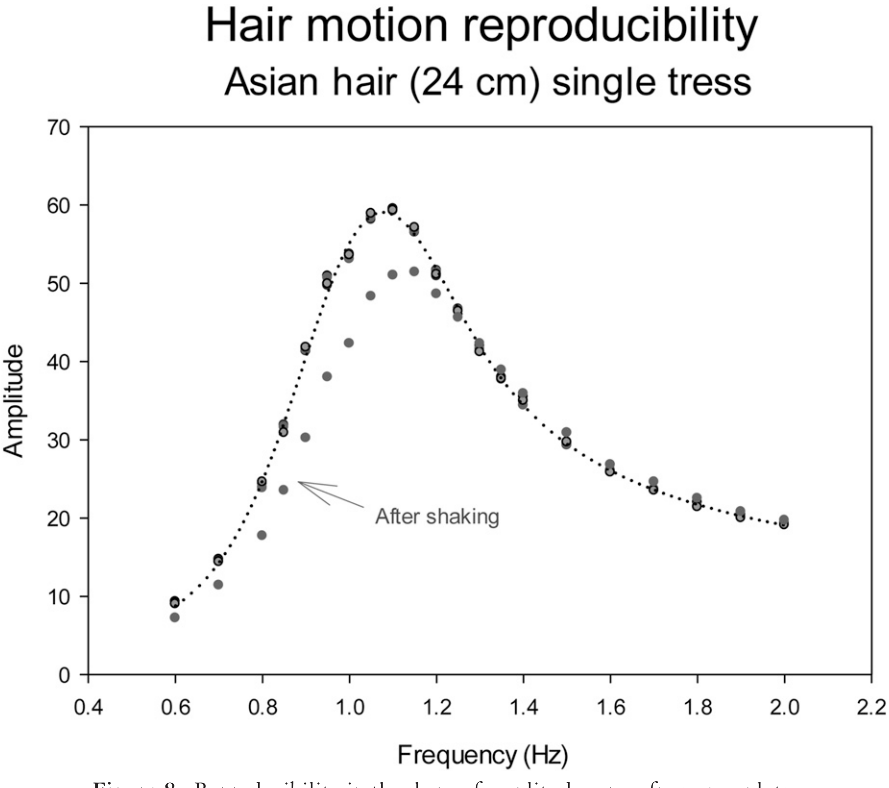

Figure 8. Reproducibility in the shape of amplitude versus frequency plots.

that of any product/treatment. For this reason a meticulous tress treatment and drying process is necessary in this work.

TRESS SHAPE DURING MOTION

The various aforementioned treatments and conditions can also affect the shape of the hair during motion. For example, in the previously described experiment involving the influence of relative humidity (see Figure 7), hair equilibrated at high humidity appeared decidedly more "puffed up" in comparison with the low humidity state. As a further example, heat straightening greatly decreases the technical volume of the hair because of the extremely straight and highly aligned nature of the fibers.

Such measurements represent the fundamental objective of the original BOLERO instrument, although here analyses can be further performed frame by frame on videos of moving hair (see Figure 9). As described earlier, the software is able to calculate an overall tress volume—however, via the backlighting approach, this total volume can be deconvoluted into a bulk volume and a volume of wispy flyaway fibers. Thus, all of these parameters can be tracked during the oscillating motion.

Again, there is complexity to this process. The moving hair experiences differing degrees of momentum as it traverses the oscillating pathway. For example, the first image in Figure 8 (frame #0) shows hair concave to the left-hand apex of motion as it moves to the right. The reverse scenario would occur soon after frame #20 as hair returns from the

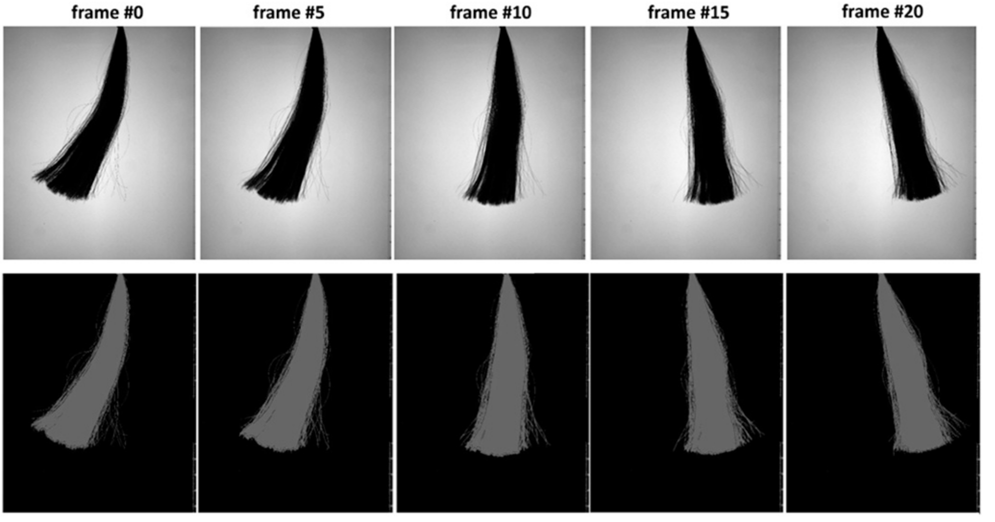

Figure 9. Analyzing hair shape and flyaway during motion.

right-hand apex. Thus, tress shape, volume, and the homogeneity can vary during this motion. Furthermore, frequency also has a major impact on the momentum magnitude.

SUMMARY/CONCLUSIONS

Earlier it was noted that relatively little work has been performed in the area of hair motion. Our foundational work perhaps sheds light on this deficiency by highlighting the complexity of the topic. Existing commercial equipment has been modified to provide a means of controlling hair motion, for video capture and manipulation, and to provide subsequent image analysis capability. However, even with this powerful device, the complexity of the task in hand is still formidable.

Using this equipment, we have performed systematic experiments to primarily study the amplitude of hair tress movement when oscillated in a side-to-side motion. Sizable changes in this property can occur as a function of hair treatments, experimental test conditions and considerations related the size and shape of the hair tresses being used. The nature of this motion is strongly dependent on the oscillating frequency—although the manner of this frequency response varies with the aforementioned considerations. Therefore, experiments performed at different single frequencies are very likely to produce different ranking of samples. Accordingly, we advocate the generation of amplitude versus frequency curves—which involve progressively and systematically increasing the oscillating frequency.

The relationship between frequency and energy allows for conceptualization of hair movement in terms of the amount of motion attained as a function of energy input to the system. For example, visibly diminished motion as a result of silicone oil treatment is accompanied by both a reduction in the motion amplitude and an increase in the frequency necessary to produce this motion (i.e., lesser motion, even though additional energy is being supplied to the system). Conversely, it can be suggested that improved movement might involve enhanced motion for a given energy input, and/or comparable motion for less energy input.

A further important factor appears to be the shape of the hair during motion. For example, clean, healthy hair tresses tend to rhythmically "pulse" during the sinusoidal motion—with the extent being dependent on factors such as hair shape, tress conformation, frequency, etc.

The goal of this work was to establish a method for numerically describing hair motion—and our approach yields a myriad of such numbers. We recognize that the nature of hair motion is highly frequency dependent and so comparisons necessitate systematic experiments performed across a range of conditions. For each of these conditions, it is then possible to quantify an amplitude of motion and values describing the hair shape of moving hair. Thus, we quickly end up with a sizable amount of data—which seemingly provides the most insight when compared holistically.

It appears reasonable to suppose that motion is dictated by a variety of single fiber properties—for example, weight, stiffness, and interfiber friction. Therefore, validation-type experiments have used treatments that influence such properties. However, specific treatments tend to not alter just one property. For example, surface lubrication might be attained in combination with increased hair weight; fiber stiffness might increase in combination with lesser friction. This severely complicates attempts to understand the effect of any single variable on the shape of our amplitude versus frequency curves.

Our work continues in an attempt to best elucidate which of these now measurable properties best equates to visual observation.

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