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Morphological Changes of Human Hair Related to "Graying"

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Synopsis

The appearance of hair is a crucial factor of human well-being. Besides hair color and shine, the dynamic movement characteristics have a great impact on a youthful look, which is desirable at all ages. However, the hair follicle is subject to biochemical changes which tend to become obvious in the mid-30s by the appearance of the first nonpigmented "gray" hairs. Especially, these fibers seem to be unruly, hereby influencing the hair collective. In this investigation, the complex dynamic movement of swinging hair is modeled by an *in vitro* method. Using pigmented and nonpigmented hair strands, the results are related to the morphological and mechanical changes associated with the process of ageing. Furthermore, the *in vitro* method is extended toward a real life setting by monitoring the movement of women's ponytails with different fractions of gray hair, while walking on a treadmill. The dynamic movement of hair is a complex phenomenon, which can be affected by several factors: the internal structure, thickness and waviness of single hair fibers, the fiber–fiber interactions, and the shape and volume of hair collectives. As these properties change with age, they are expected to lead to differences in the dynamic hair movement. Using the *in vitro* method, the dynamic hair movement of pigmented and nonpigmented hair strands is quantified. A harmonic bending oscillation of a hair collective is induced by rotational excitation at the upper strand end, which allows the analysis of the driven as well as the free oscillation mode. The maximum swing height of the hair collective, characterized by the parameter "relative amplitude," is measured during the driven oscillation and correlates with the deflection of the hair collective. Compared with pigmented hair, the relative amplitude is significantly lower for nonpigmented hair strands. This indicates a stronger damping, i.e., energy loss, for the nonpigmented hair strands, which relates to higher waviness and larger hair collective volume. In addition, the larger diameter of the nonpigmented hair fibers leads to a higher contribution of these fibers to the collective's bending stiffness. Furthermore, the natural frequency during the free oscillation stage of the measurement is significantly lower for partly nonpigmented hair strands. The damping of hair collectives expressed by the logarithmic decrement is, in turn, significantly higher for nonpigmented hair strands. This is attributed to increased fiber–fiber interactions and higher frictional forces within the strand and to increased air resistance. With the laboratory test (*in vitro* method), the oscillation of different hair qualities using hair strands with defined weights and lengths can be analyzed, providing the practical and theoretical concepts to determine the hair movement in a realistic setting. This enables the measurement of the ponytail movement for women walking on a treadmill. Like the *in vitro* method, the *in vivo* method allows the analysis of the driven and the free oscillation mode. It is shown that the results of both methods demonstrate a high degree of correspondence. Ponytails with ≥5% nonpigmented hair fibers have a significantly lower relative amplitude and a significantly higher damping performance in comparison with ponytails with no or less than 5% nonpigmented hair

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fibers. This highlights the importance of even small fractions of "gray" hair for the dynamic movement and, as such, the appearance and perception of hair collectives.

INTRODUCTION

Ageing of the hair follicle leads to various morphological changes of the fiber. Robbins et al. (1) have shown that the fiber diameter increases up to an age of approx. 45 years and decreases afterward. The hair density (number of hairs/area of skin surface) increases after age 30 and hair thinning becomes increasingly more noticeable in the mid-40s to the late 50s (1). In addition, hair curliness and stiffness increase with age, whereas hair luster decreases (2). Furthermore, there is wide-spread anecdotal evidence that nonpigmented hairs strongly influence the physical behavior of a hair collective, especially the hair movement.

Only few studies have been published dealing with the quantification of hair collective movement. Hindley et al. (3) measured the movement of a hair tress that is attached to a sliding bar and moves horizontally backward and forward at a set speed.

Focht et al. (4,5) described the stimulation of a bending oscillation of a roundly bundled hair strand by a rotation axis and developed the concepts to analyze the movement characteristics of pigmented and bleached hair. Other recent investigations (6) have shown that natural gray hair moves significantly different in comparison with pigmented hair and that already small admixtures of "gray" hair can lead to significant performance changes of a hair collective.

THEORETICAL CONCEPTS OF THE HAIR MOVEMENT

For the analysis of hair movement, the model of a harmonic oscillator can be used (7,8). An oscillator is characterized by a periodic motion where the motion is repeated at regular intervals of time. A simple harmonic motion is described by a sine or cosine oscillation curve. Figure 1 shows a harmonic motion with the function:

$$x(t) = A \sin(\omega t), \tag{1}$$

where A is the magnitude or amplitude with the units of x. The circular frequency ω is expressed in radians per second. T is the time period in seconds of one complete cycle (e.g., the time interval that a hair collective needs for one complete swing) of the signal $x(t)$.

The reciprocal value of the time period T in seconds is the frequency f (Hz) of the hair movement [equation (2)]:

$$f = \frac{1}{T}. \tag{2}$$

For the analysis of the hair movement, two types of oscillations are used: Forced (or driven) and free oscillation. In a driven oscillation, a continuing periodic excitation is applied to the system. In this setting, the amplitude A or "swing height" of the collectives can be analyzed.

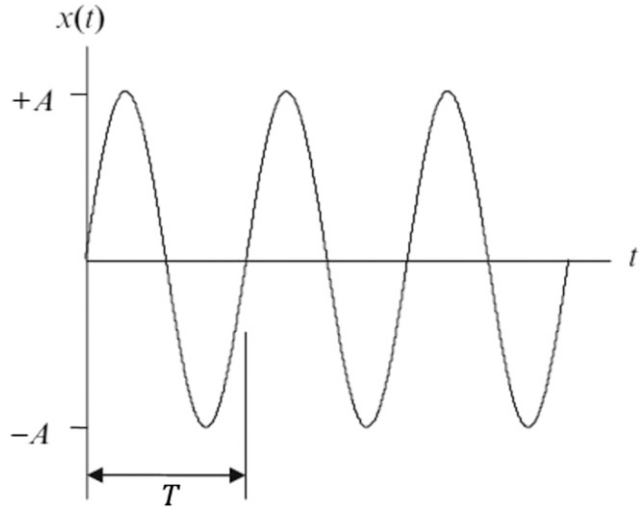

Figure 1. The sine function is an example of harmonic motion (7).

When the driving motion stops, the hair oscillates freely. During this stage, oscillation proceeds at its natural frequency f_0 and is damped (8). Energy is stored as potential energy E_{pot} and is transformed into kinetic energy E_{kin}, while dissipating through air and internal friction.

Damped harmonic oscillation can be described as an exponentially decaying, periodic response, characterized by the logarithmic decrement Λ. The logarithmic decrement Λ is given by the natural logarithm of the ratio of the amplitudes A of two successive peaks at time t in the same direction (9):

$$\Lambda = \ln \frac{A(t_n)}{A(t_{n+1})}. \tag{3}$$

MATERIALS

HAIR STRANDS

For the determination of the fiber diameter, waviness and Youngs' modulus and for the analysis of the *in vitro* hair movement, pigmented (color 7/0—medium brown) and non-pigmented hair strands (Caucasian hair) from Kerling International Haarfabrik GmbH (Backnang, Germany) are used. The *in vitro* analysis of the hair movement is performed on pigmented and nonpigmented, roundly bundled hair strands with a defined length (18.0 ± 0.1 cm) and weight (4.00 ± 0.02 g).

STANDARD HAIR STRAND CLEANSING AND DRYING

The hair strands are washed under tap water ($\dot{V}$ = 100 ± 20 ml/s; T = 33 ± 2°C) for 2 min to remove coarse contaminants. Then, an aqueous solution (pH 5.5) of 12.5% (w/v)

sodium laureth sulfate is applied to hair (0.5 ml/1 g). The fibers are rubbed against each other (shampooing) for 2 min. Afterward, the strand is rinsed under tap water for another 2 min. The processes of shampooing and rinsing are repeated once more. Finally, the hair strand is combed up to 15× by hand.

After washing and combing, the hair strand is dried under standardized conditions (T = 21 ± 0.4°C; relative humidity = 50% ± 3%) in a hanging position for 24 h. After 1 h, the strand is combed up to 15× by hand again. The weight of the dry hair strand is measured under standardized conditions after drying.

VOLUNTEERS FOR THE *IN VIVO* METHOD

The *in vivo* analysis comprises 41 Caucasian women, aged 9–67 years, with a ponytail length from 9 up to 54 cm and individual hair condition (independent hair cleansing and treatment ≤24 h before measurement, no styling products allowed). The amount of nonpigmented hair fibers is determined for each volunteer and taken into account for the quantification of the ponytail movement. Twenty-nine women have an amount of nonpigmented hair fibers <5% (9–35 years) and 12 women an amount of nonpigmented hair fibers ≥5% (27–67 years).

METHODS

HAIR THICKNESS MEASUREMENT

The fiber diameter of the hair strands is measured using a Laser Scan Micrometer LSM 6000 (Mitutoyo, Kanagawa, Japan). A hundred single hair fibers are used per sample. The laser scan micrometer takes profile width measurements as the fiber is rotated through 360°. The circle equivalent fiber diameter d is calculated by the cross-sectional area A of hair as follows:

$$d = 2 \cdot \sqrt[2]{\frac{A}{\pi}}. \tag{4}$$

QUANTIFICATION OF WAVINESS

The waviness of 50 pigmented and nonpigmented hair fibers of the hair strands are measured in a climate chamber (Binder KFB 720; Binder GmbH, Tuttlingen, Germany) at 21.0 ± 0.4°C and 50% ± 3% relative humidity in a hanging position. The percentage reduction of the fiber length due to waviness is detected via laser (Dot laser LFD650-0.4-12, Picotronic GmbH, Koblenz, Germany) at the tip of the fiber and serves as a measure for waviness.

DETERMINATION OF THE YOUNGS' MODULUS

The Youngs' modulus of the hair strands is analyzed by tensile strength measurements using the Stress-Strain-System MTT 686 with control unit UV 1000 (Dia-Stron Ltd.,

Andover SP10 5NY, UK). At a relative humidity of 55%, 100 pigmented and nonpigmented hair fibers were stretched at a constant speed rate of 10 mm/min up to the breaking point. The Youngs' modulus is determined in the Hookean region between 0.3% and 1.2% strain.

OSCILLATION OF HAIR STRANDS–*IN VITRO*

A new measurement method has been developed by the University of Manchester (UK) and Henkel AG & Co. KGaA (Hamburg, Germany) to analyze the movement characteristics of human hair (4,5). A round hair strand is placed vertically into a sample holder that is connected at the top to a rotation axis. The latter enables impartment of a defined driving frequency (0–5 Hz) and a defined rotational angle (0–160°) by an electronic motor (V1.0, voltage: 220 V, power: 0.1 kW). The swinging movement of the strand is recorded by a high-speed camera (VW-9000; Keyence Corp., Osaka, Japan) at 1,000 frames per second.

Before measurement, the hair strand is combed up to 5× by hand, discharged (Static Line LC, HAUG GmbH & Co. KG, Leinfelden-Echterdingen, Germany) and attached to the sample holder. Ten driven oscillations with an angle of 60° and a frequency of 1.40 Hz are imposed. With these parameters, a harmonic-driven oscillation and a subsequent harmonic-free oscillation can be established. The video recording starts with the rotation of the axis and stops after the free oscillation when no further movement of the strand can be subjectively noticed.

To account for the 3D shape of the hair strand, it is recorded in four defined lateral orientations. The measurement of the hair movement takes place at 24 ± 3°C and 40% ± 10% relative humidity.

OSCILLATION OF PONYTAILS—*IN VIVO*

To differentiate between various hair movements in a realistic setting, the *in vitro* approach was modified to assess the motion of ponytails of female volunteers while walking on a treadmill (Paragon 308, Drive motor 2.5 CHP Digital System, 150 × 50-cm running area, Horizon Fitness, Taichung, Taiwan).

To enable a stable hair movement, the women's hair is tied up in a ponytail (middle center of the back of the head) and the women are instructed to walk (not run) on the treadmill.

To generate a comparable walking frequency, the driven oscillation or "walking swing" is measured at a specified velocity v that depends on the leg length L (pelvic bone to ankle) of the woman:

$$\mathrm{v}\left[\frac{m}{s}\right]=2.0\left[\frac{1}{s}\right]\cdot L[m]. \tag{5}$$

The ponytail is combed up to 5× by hand and after a warm-up (walking for 1 min with an individual velocity and 2 min with at the specified velocity on the treadmill), the hair movement is recorded for 24 s with a high-speed camera from the back (VW-9000; Keyence Corp., Osaka, Japan).

Besides the driven oscillation, the free oscillation performance of each ponytail is also determined by dropping the ponytail from a 90° angle. The motion is recorded until the resting position is reached.

QUANTIFICATION OF HAIR MOVEMENT

The analysis of the movement characteristics is based on single frames of the video recording (VW-9000 Motion Analyser; Keyence Corp.). The length l of the hair strand/ponytail is measured in the resting position at $t = 0$ s, and the position of the hair tips in the resting position is also used as a baseline.

During the driven and free oscillation, the amplitude A is tracked and the corresponding time t of the hair tips is determined in the area of the maximum swing height (Figure 2). The distance between the maximum of the tracking point and the baseline is defined as the maximum displacement. In addition, for the determination of the amplitude of the ponytail, the movement of the head is taken into account.

During the driven oscillation, six amplitudes are determined (*in vitro* method: amplitudes number 6–11; *in vivo* method: constant swing height shown by an automatically generated motion curve). The ratio of the amplitude A and the length of the hair collective l is defined as the relative amplitude A_{rel}:

$$A_{rel} = \frac{A}{l}. \tag{6}$$

The free oscillation is recorded when the excitation stops (*in vitro*) or by dropping the ponytail from a 90° angle (*in vivo*). During the free oscillation, the first six amplitudes are determined. The natural frequency f_0 [equation (2)] and the logarithmic decrement Λ [equation (3)] of the strand is calculated with the corresponding times.

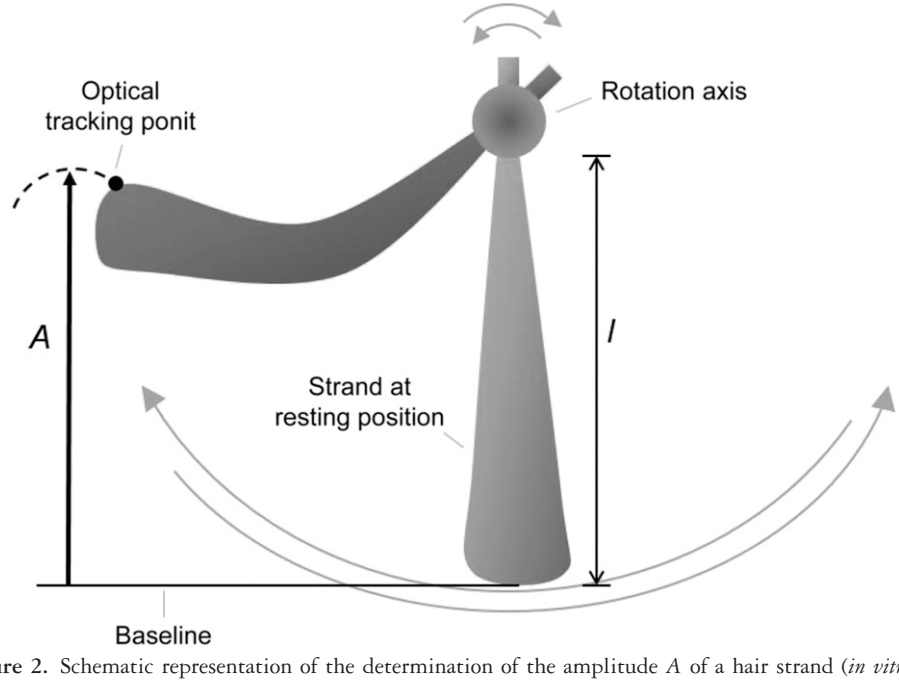

Figure 2. Schematic representation of the determination of the amplitude A of a hair strand (*in vitro*) by means of tracking the left hair tips and measuring the length l of the strand at the resting position. The gray arrows represent the motion of the rotation axis and the hair strand.

RESULTS AND DISCUSSION

CHARACTERIZATION OF PIGMENTED AND NONPIGMENTED HAIR FIBERS

The movement characteristics of human hair depend, aside from the shape of the hair collective, greatly on fiber–fiber interactions and the properties of the single hair fibers. Therefore, the fiber diameter, waviness, and Youngs' modulus of pigmented and nonpigmented hair fibers of the hair strands (Kerling International Haarfabrik GmbH) are analyzed.

Nonpigmented hair fibers have a significantly higher equivalent fiber diameter ($p \leq 0.001$) in comparison with pigmented hairs as shown in Figure 3.

Furthermore, nonpigmented hair fibers are significantly ($p \leq 0.001$) wavier in comparison with pigmented hair as shown in Figure 4. The parameter to determine the waviness of single hair fibers is the decrease of the fiber length (%).

The Youngs' modulus is a material-dependent parameter that is measured in the linear elastic region during the deformation of the hair fiber. The modulus for nonpigmented hair (2.44 ± 0.28 GPa) is not significantly ($p = 0.088$) different in comparison with pigmented hair (2.51 ± 0.31 GPa).

DYNAMIC HAIR MOVEMENT OF STRANDS—RESULTS OF THE *IN VITR0* METHOD

Pigmented and nonpigmented hair fibers differ in their morphological and mechanical properties. It can be assumed that the movement characteristics change by ageing as well.

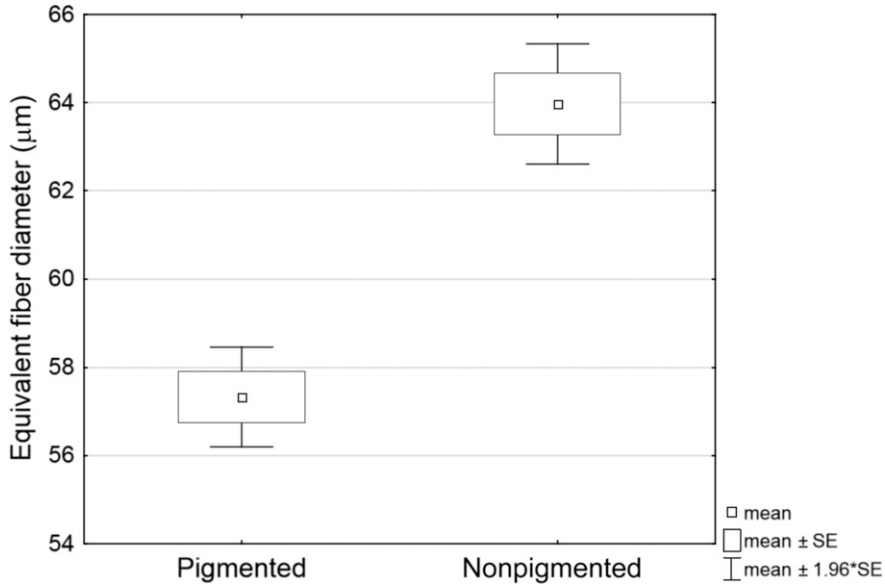

Figure 3. Box and whisker plot of the equivalent diameter of pigmented and nonpigmented hair fibers ($n = 100$). SE: standard error.

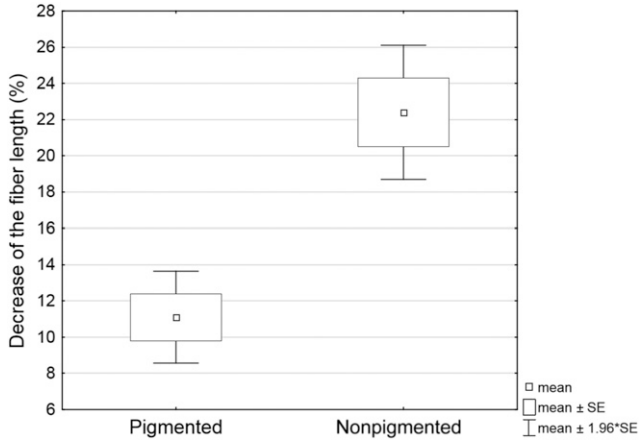

Figure 4. Decrease in the fiber length due to the fiber waviness of pigmented and nonpigmented hair ($n = 50$). SE: standard error.

Therefore, pigmented and nonpigmented human hair strands are investigated *in vitro* by means of driven and free oscillation.

During the driven oscillation, the relative amplitude A_{rel}, also called as "swing height," is determined. A_{rel} for a nonpigmented hair strand is significantly lower in comparison with pigmented hair ($p \leq 0.001$) as shown in Figure 5. This can be explained by higher bending stiffness and lower deflection of the nonpigmented hair strand during motion.

During the free oscillation, the natural frequency f_0 and the logarithmic decrement Λ are determined. f_0 is significantly lower ($p = 0.017$) for nonpigmented hair in comparison with pigmented hair (Figure 6).

The energy loss in a hair strand, given by the logarithmic decrement Λ, is significantly higher ($p \leq 0.001$) for nonpigmented hair in comparison with pigmented hair as shown in Figure 7.

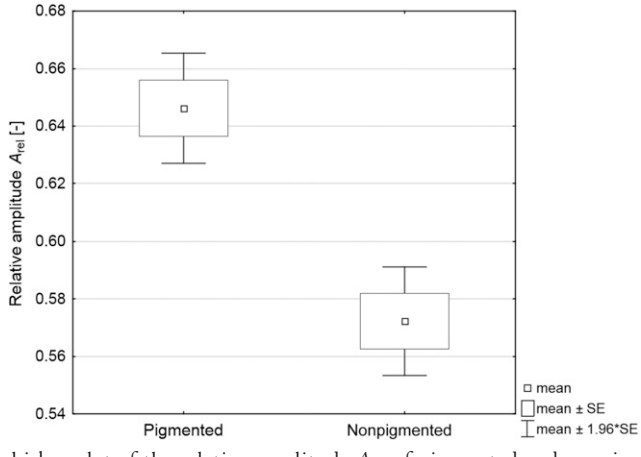

Figure 5. Box & whisker plot of the relative amplitude A_{rel} of pigmented and nonpigmented hair ($n = 3$). SE: standard error.

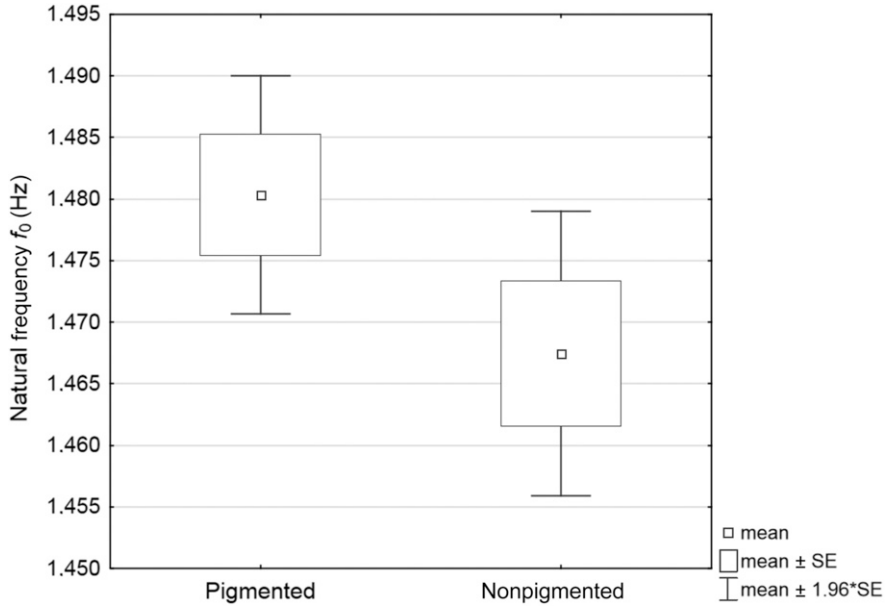

Figure 6. Box & whisker plot of the natural frequency f_0 of pigmented and nonpigmented hair ($n = 3$). SE: standard error.

The increased logarithmic decrement of the nonpigmented hair strands is attributed to higher friction forces between the single hair fibers and increased air resistance due to a higher collective volume.

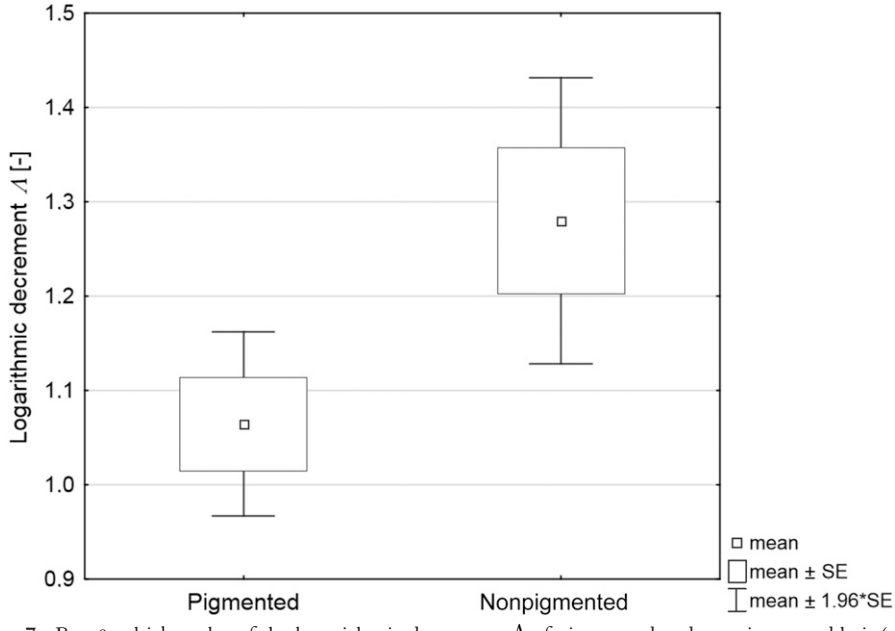

Figure 7. Box & whisker plot of the logarithmic decrement Λ of pigmented and nonpigmented hair ($n = 3$). SE: standard error.

DYNAMIC HAIR MOVEMENT OF PONYTAILS—RESULTS OF THE *IN VIVO* METHOD

The relative amplitude A_{rel} (swing height) of ponytails that contain ≥5% nonpigmented hair fibers is significantly lower ($p \leq 0.001$) in comparison with pigmented ponytails (<5% nonpigmented hair fibers) as shown in Figure 8.

The lower swing height of "gray ponytails" relates to the increasing fiber curvature and bending stiffness with increasing age of unpigmented hairs (1,2).

Free oscillation is analyzed by dropping the ponytail from a 90° angle until the resting position is reached. Logarithmic decrement Λ is significantly higher ($p \leq 0.001$) for "gray ponytails" (≥5% nonpigmented hair fibers) in comparison with pigmented ponytails as shown in Figure 9.

This can be explained by increased fiber–fiber interactions within the ponytail and increased frictional forces due to an increased fiber curvature (1,2).

SUMMARY AND CONCLUSIONS

Ageing of the hair follicle leads to various morphological and mechanical changes of the fibers. The nonpigmented hair fibers used in this study are significantly thicker, significantly wavier, and have a slightly, but not significantly, lower Youngs' modulus in comparison with the used pigmented hair.

The new *in vitro* method allows the quantification of the hair movement of hair strands. Thereby, nonpigmented hairs have a significantly lower relative amplitude in comparison with pigmented hair. The natural frequency is significantly lower and the damping significantly higher for nonpigmented hair in comparison with pigmented hair.

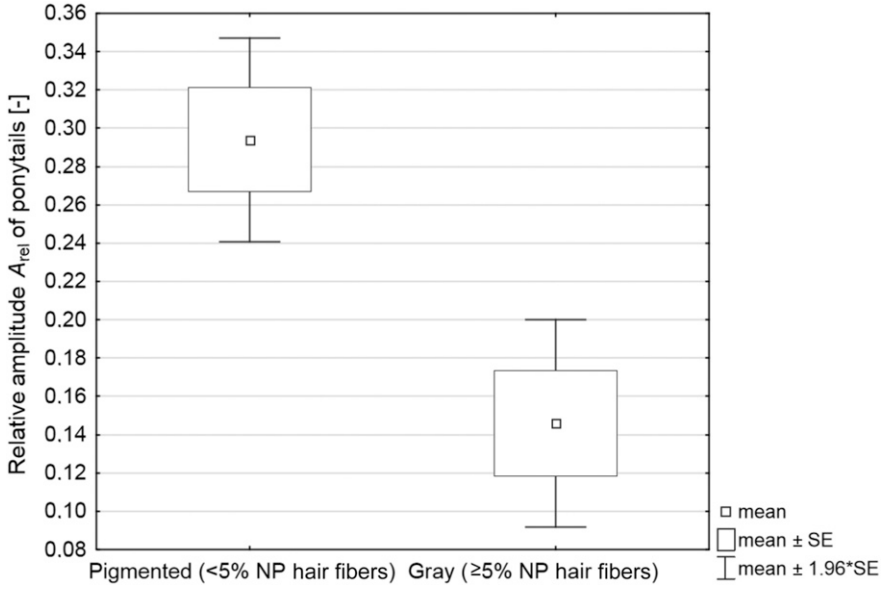

Figure 8. Box & whisker plot of the relative amplitude *A* of pigmented and "gray" ponytails ($n = 39$). NP: nonpigmented, SE: standard error.

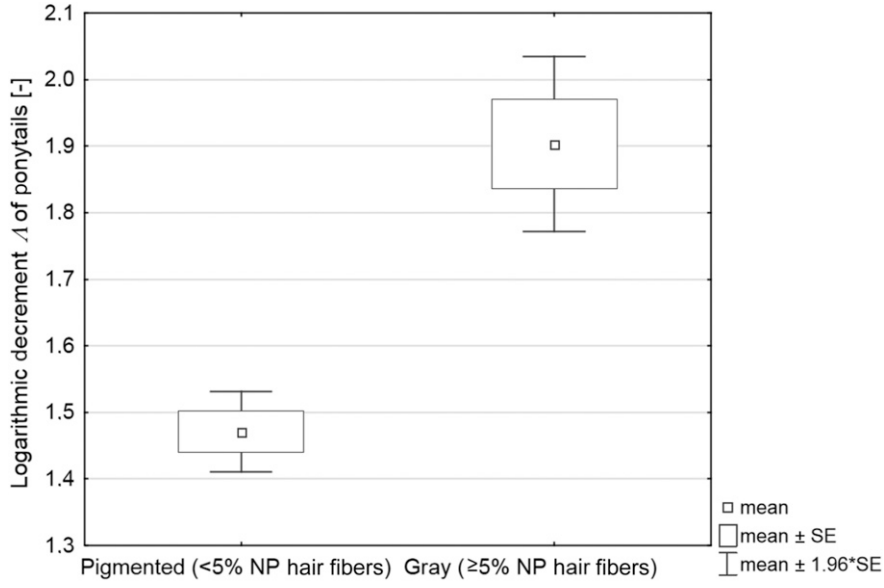

Figure 9. Box & whisker plot of the logarithmic decrement Λ pigmented and "gray" ponytails ($n = 41$). NP: nonpigmented, SE: standard error.

Furthermore, the *in vitro* method was successfully transferred into a real-life setting by analyzing the movement of women's ponytails while walking on a treadmill (*in vivo* method). The results of both the *in vitro* and the *in vivo* methods show a consistent relationship. Compared with pigmented hair, the "swing height" of ponytails with ≥5% nonpigmented hair fibers decreases like the relative amplitude of the nonpigmented hair strands and the damping of both hair collectives (ponytails with ≥5% and nonpigmented hair strands) increases.

The results of *in vitro* and *in vivo* measurements well reflect the perception of women with the appearance of "gray" hairs.

ACKNOWLEDGMENTS

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REFERENCES

(1) C. Robbins, P. Mirmirani, A. G. Messenger, M. P. Birch, R. S. Youngquist, M. Tamura, T. Filloon, F. Luo, and R. L. Dawson, Jr., What women want—quantifying the perception of hair amount: an analysis of hair diameter and density changes with age in caucasian women, *Br. J. Dermatol.*, **167**, 324–332 (2012).

(2) S. Nagase, Y. Kajiura, A. Mamada, H. Abe, S. Shibuichi, N. Satoh, T. Itou, Y. Shinohara, and Y. Amemiya, Changes in structure and geometric properties of human hair by aging, *J. Cosmet. Sci.*, **60**(6), 637–648 (2009).

(3) M. C. Hindley, M. Yap, and H. Ugail, Measurement of hair dynamics via video image analysis, IFSCC Conference, November 2, 2011, Bangkok, Thailand.

(4) N. Focht, Influence of chemical hair treatments on the structure and the mechanical properties of human hair, Ph.D. Thesis, University of Manchester, UK, 2016.
(5) E. Schulze zur Wiesche, N. Focht, and F. J. Wortmann, The swinging behaviour of human hair: a novel method to quantify hair collective movements, IFSCC Conference, September 22, 2015, Zurich, Switzerland.
(6) L. Bechthold, Investigation on the dynamic movement characteristics of pigmented and natural grey hair, Master's Thesis, University of Hamburg, Germany, 2015.
(7) T. L. Schmitz and K. S. Smith, Mechanical Vibrations: Modeling and Measurement (Springer, New York, NY, 2011), pp. 1–24.
(8) G. Takács and B. Rohal'-Ilkiv, Model Predictive Vibration Control (Springer, London, 2012), pp. 25–64.
(9) K. Magnus, K. Popp, and W. Sextro, Schwingungen: Physikalische Grundlagen und Mathematische Behandlung von Schwingungen (Springer, Wiesbaden, 2013), pp. 18–61.