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Cross-Sectional Observational Skin Diagnostic Study to Characterize the Dermatological Status of Junior and Senior Subjects from Both Genders in the Central European Region.

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Abstract

Background/Objectives: This cross-sectional observational study addresses the limited population-specific reference data on skin physiology in the Central European region. It aims to characterize the dermatological status of healthy volunteers from different age groups and genders, assessing the variability and reliability of skin barrier and physiological parameters. The study seeks to provide reference data and evaluate inter-individual variability in relation to age, gender, and body region, contributing to a more comprehensive understanding of regional skin physiology.

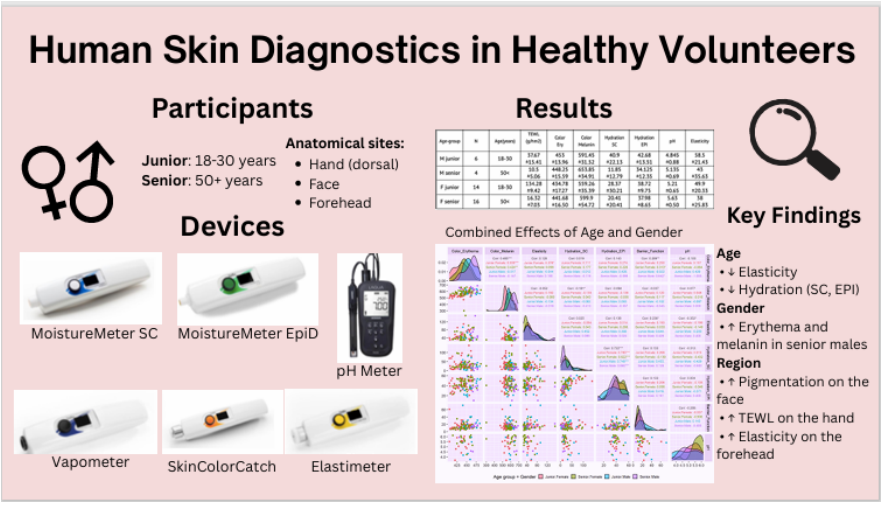
Methods: The study involved healthy volunteers from Pázmány Péter Catholic University and Semmelweis University in Budapest, Hungary, divided into junior (18-30 years) and senior (50+ years) groups of both genders. Skin elasticity, transepidermal water loss (TEWL), hydration (stratum corneum and epidermis), color (erythema and melanin), and pH were measured on the face, hand, and forehead using non-invasive biophysical instruments (Delfin Instruments). Statistical analysis was performed using R software, employing non-parametric methods such as Spearman correlation, Wilcoxon signed-rank tests, and Kruskal-Wallis tests.

Results: Aging was associated with decreases in elasticity and hydration across all anatomical sites. Anatomical region was the strongest contributor to variability, with each site exhibiting a distinct biophysical profile. Gender effects were observed, with males showing higher erythema and melanin values, particularly on the face and forehead, while females tended to have lower values.

Conclusions: This study establishes baseline reference values for skin physiological parameters in the Central European white population. The findings highlight the importance of considering age, gender, and anatomical region in dermatological research and clinical evaluations, supporting the development of tailored cosmetic and skincare strategies.

Keywords: Skin physiology; Central European white population; aging; gender; anatomical region; elasticity; hydration; TEWL; erythema; melanin; pH.

Graphical Abstract



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INTRODUCTION

Human skin serves as a complex, multifunctional organ acting as the primary barrier between the body and the external environment. Its physiological properties, such as elasticity, hydration, color, and pH, are crucial indicators of both dermatological health and systemic well-being. These parameters reflect the integrity of the skin barrier and are influenced by numerous intrinsic factors (e.g., age, gender, ethnicity, anatomical site) and extrinsic factors (e.g., environmental exposure, climate, and lifestyle) [1–3]. Quantitative, non-invasive skin biophysical measurements have therefore become essential tools in dermatological research, cosmetology, and clinical diagnostics, allowing objective evaluation 36 of skin condition under standardized conditions [4,5,30].

In recent years, technological advances have enabled high-precision, portable instruments to assess key skin properties such as transepidermal water loss (TEWL), elasticity, hydration at different epidermal depths, pigmentation, erythema, and surface pH. These devices, such as corneometers, elasticity meters, colorimeters, and pH meters, are widely used to characterize skin physiology, to monitor treatment outcomes, and to evaluate the effects of aging or cosmetic interventions [6–11]. Recent studies also emphasize the importance of environmental and lifestyle influences on skin barrier function and hydrationdynamics, supported by novel imaging and spectroscopic techniques such as terahertz sensing and nanoscale poroelasticity analyses [9,12].

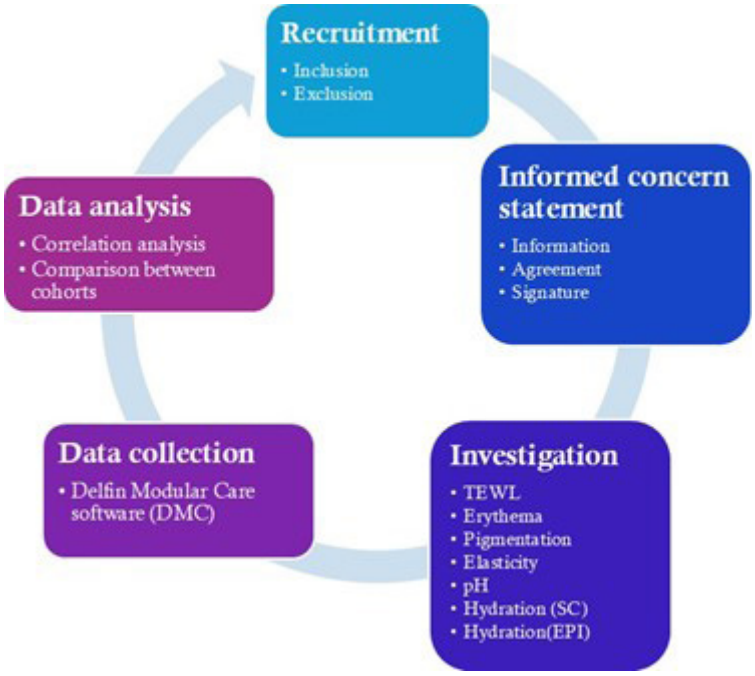
Despite these advances, population-specific reference data remain limited, particularly in the Central European region, where differences in genetic background, environmental conditions, and skincare practices may influence baseline skin characteristics [13–15]. Moreover, age- and gender-related variations in skin parameters have been extensively documented, but most studies have focused on Asian or Western European populations[16,17,29,31]. Few cross-sectional datasets are available that systematically compare young and elderly subjects of both genders across multiple anatomical regions under controlled environmental conditions. Establishing such baseline reference values is essential not only for understanding physiological skin aging but also for improving the design and interpretation of dermatological and cosmetic studies in diverse populations [18,32]. The present cross-sectional observational study was therefore designed to characterize the dermatological status of healthy volunteers from different age groups and both genders in the Central European region using a combination of validated, non-invasive biophysical instruments. We assessed the variability and reliability of skin barrier and physiological parameters, including elasticity, hydration, color, pH, and TEWL, at three anatomical sites (face, hand, and forehead). The aim of this study was to provide reference data and evaluate inter-individual variability in relation to age, gender, and body region, contributing to a more comprehensive understanding of regional skin physiology and its determinants.

MATERIALS AND METHODS

Study design

This study was conducted on the students and staff of Pázmány Péter Catholic University and Semmelweis University in Budapest, Hungary. The aim of the study was to investigate the reliability of measurements made on healthy skin using a skin elasticity meter, Vapometer, Moisture meter (SC and EPI), Color meter, pH meter (all from Delfin Instruments, Kupio, Finnland) in face, hand and forehead positions on all subjects, as well as the evaluation of its variability by age group, gender, and body regions and its absolute reliability. Therefore, this study is a cross-sectional observational study without any topical treatment. At each anatomical site, three consecutive measurements were taken to ensure reliability, and the mean value of these measurements was calculated for analysis. To eliminate potential bias, the tester was blinded to the results of previous measurements. The measurements were carried out in a controlled environment, maintaining a temperature of 23 ± 2°C and a relative humidity within the range of 50% to 60%, ensuring optimal conditions for accurate skin assessments.

Figure 1. Workflow of human skin diagnostic study in healthy volunteers.



Participants (volunteers)

From the beginning of September to the end of October 2025, a total of 40 healthy volunteers aged from 18 to 89 years with, comprised of 10 males and 30 females, were enrolled in the study. The volunteers were divided into four groups: the junior males, junior females (18-30 years), the senior males, senior females (50 years or older).

Recruitment

Participants were recruited from Pázmány Péter Catholic University, Faculty of Information Technology and Bionics and also from Semmelweis University, Budapest, Hungary by an invitation published in a circular email.

Inclusion criteria

Volunteer who met the following conditions was included in the study: a) healthy male or female aged 18–30 years or aged 50 years or older, d) volunteered to participate in and complete the study as required.

Exclusion criteria

Volunteer who met any of the following conditions was excluded from the study:

- subject who was lactating or pregnant,
- subject who used any makeup products on the face such as foundation, powder, concealer, etc. on the day of the test,
- subject who had dermatological disease on the studied anatomical regions,
- behaviors that could affect test results within 30 min before the test, such as drinking alcoholic or hot drinks or caffeinated products, eating spicy food, smoking, etc.,
- subject who has received facial treatments including botox and injection fillers in the last 4 months.

Variables

All instrumental assessments were conducted by trained personnel using standardized operating procedures specific to each device. Calibration was performed prior to each measurement session according to the manufacturer's instructions. Imaging conditions, including lighting, camera angle, and participant positioning, were standardized across all experiments. Measurements were taken in triplicate where applicable, and intra-operator consistency was ensured by assigning the same operator to each subject throughout the study. As each skin parameter was assessed using a single, validated instrument, interinstrument validation was not required.

Skin barrier function

The VapoMeter (Delfin) is equipped with a closed cylindrical chamber which contains sensors for relative humidity and temperature. A linear increase of relative humidity (RH%) appears in the chamber shortly after placing the device in contact with the skin. The TEWL is calculated from the increase in RH%. The chamber is passively ventilated between measurements. The measurement time is automatically controlled and the progress is shown on the display. The higher the TEWL, the shorter the measurement time. The VapoMeter has been calibrated with the standard and small adapters prior to experiments.

The diameter of the standard opening is 11 mm. A wireless connection to the computer was used when the receiver unit was connected to the PC, the Delfin Modular Core (DMC) software was running and the PC mode of the VapoMeter was ON.

Skin elasticity

The ElastiMeter (Delfin) utilizes an indenter which is briefly pressed on the skin. The skin resists the change in shape when an external force is applied and thus the skin's response under a short-term load indicates its instant elastic properties. Instant skin elasticity measurements give important information on the biophysical properties of the skin. The ElastiMeter gives information that can be used to assess elasticity changes related to skin aging, UV damage, hydration and seasonal variations of the skin. Effects of skin treatments and different skin care products on the skin can also be examined [6].

Skin Color Catch

White LEDs corresponding to daylight are arranged circularly inside the measurement chamber of the SkinColorCatch device (Delfin). When the SkinColorCatch is gently placed on the skin, the LEDs illuminate the skin at the angle of 45 degrees to minimize skin gloss. The light reflecting from the skin is detected with an RGB color sensor. The measured RGB and L*a*b* readings are corrected using a reference color matrix measured with a spectrophotometer. The Delfin Skin Color Catch Colorimeter device is placed perpendicularly and gently on the skin, a light-emitting diode (LED) white light source illuminates the skin, and the light reflected is detected with an RGB sensor, and several measurement values are displayed within seconds. Strict adherence to the manufacturer's guidelines is crucial for cleaning and disinfecting the device between patient uses. For example it involves cleaning the measurement head using soft paper tissue moistened with diluted ethanol between each application. Care must be taken during measurements, as these devices are sensitive to environmental changes and the degree of cutaneous pressure applied at the measurement site. Measurements should be obtained in an adequately lit room without direct and intense sunlight and with an ambient temperature ranging from 19°C to 25°C [1,27]. The measurement results are divided into two windows. The first page shows erythema (E) and melanin(M) what is proportional with the pigmentation degree indices, which vary between 0 and 999. The higher the reading, the more erythema/melanin in the skin. This view shows also CIE L*a*b* color space coordinates and the ITA degree which classifies the skin tone. The second page displays RGB (red, green, blue) coordinates (0 – 255) of the measured skin. In the current study only E and M indices were evaluated.

Erythema

Erythema index (EI) values were derived from reflected light intensity in the green and red spectral channels. This provides an objective measure of skin redness linked to vascular reactivity or irritation. The SkinColorCatch method has been validated for erythema quantification under controlled environmental conditions [19].

Pigmentation (melanin)

Pigmentation was quantified using the melanin index (MI), calculated from reflected light in the red and infrared ranges. The MI reflects epidermal melanin content and provides an objective parameter of pigmentation. The method has been validated in clinical trials for assessing pigmentary disorders [20].

Hydration SC

The skin is electrically a layered structure. The electrical properties of these layers are related to their water content. The probe head, the skin surface and the deeper skin layers form a structure, similar to an electrical capacitor. The measured capacitance is proportional to the water content of the surface layer of the skin. Higher measured value indicates higher moisture content of the stratum corneum. The measurement of skin hydration on the skin surface was performed using MoistureMeterSC (Delphin Technologies, Kuopio, Finland), which measures the water content in corneocytes in terms of electrical potential. Skin surface moisture is a function of two variables: moisture retained in the stratum corneum and the thickness of the dry layer of the stratum corneum. The MoistureMeterSC uses a precise electromagnetic field (1.25 MHz) to measure the skin's dielectric constant that accounts for both variables. The measurement principle is based on the resistance that the outer layer of the skin opposes the passage of electric current: a higher value indicates a greater moisture content in the stratum corneum Dzihovsky et al, 2025.

Hydration EpiD

The instrument consists of an electronic control unit and an integrated probe to measure the dielectric constant of the measurement site. The device generates a high-frequency electromagnetic (EM) wave of 265 MHz and sends it into the coaxial probe and the skin down to 0,5 mm's depth. The reflected EM wave is registered. This wave contains information of the water content of the measured tissue (skin). The MoistureMeterEpiD measures the tissue dielectric constant (TDC), which is a dimensionless physical quantity. It is known that tissue water has a high dielectric constant value and fat and tissue macromolecules, especially proteins, have a very low dielectric constant. The MoistureMeterEpiD converts automatically the measured TDC value into percentage water content (PWC) of the measurement site and displays the PWC (%). A higher PWC indicates higher water content. The percentage water content value is calculated using the formula:

$$\mathrm{PWC} = \left(\mathrm{TDC} - \frac{1}{77.5}\right) \times 100\%$$

where TDC is the measured tissue dielectric constant. The PWC value is an accurate objective indicator of tissue water when following subject's tissue water changes on a single

site over time or detecting site-to-site differences. Epidermal hydration was assessed using the MoistureMeterEpiD (Delfin Technologies, Kuopio, Finland), based on highfrequency (265 MHz) electromagnetic wave reflection. The device measures the tissue dielectric constant (TDC) up to 0.5 mm depth, which correlates with local water content.

Measurements were performed after a 10-minute rest period on clean, hair-free skin, with the probe gently placed perpendicular to the surface. The MoistureMeterEpiD has been validated for clinical use in quantifying epidermal hydration [21–23].

pH

Human skin is covered with an acid mantle making it slightly acidic: pH 4.8 to 6.0. The apparent pH value of skin can be measured by applying 1 or 2 drops of ditilled or MilliQ water or physiological saline and placing a 6261-10C flat glass pH electrode or 0040-10D ISFET pH electrode on the moistened surface. The results may vary for test sites within an individual and between individuals. In this study LAQUA skin pH elctrodes were used (Horiba UK Limited). Skin surface pH was measured using the LAQUA PH220 pH meter (HORIBA Instruments) equipped with a flat-surface electrode designed for dermal measurements. Calibration was performed prior to each session using standard buffer solutions (pH 4.0, 7.0, and 10.0). Measurements were taken after a 15-minute acclimatization period under stable room temperature and humidity. Skin pH serves as an indicator of acid mantle integrity and barrier function, typically ranging between 4.8 and 6.0. The LAQUA PH220 has been validated for dermatological applications [24].

Statistical analysis

Statistical analysis was performed using 'R' software (version 4.3.0, [28]). Before conducting the correlation analysis, the normality of the data was assessed using the Shapiro-Wilk test, which indicated that not all data categories did follow normal distribution ($p< 0.05$). Therefore, non-parametric statistical methods were employed for further analysis. Spearman correlation analysis was used to assess the correlation between different physiological indicators as well as between physiological data and age, as Spearman correlation does not require the assumption of normality and is less sensitive to outliers. Wilcoxon signed-rank tests were used to compare the physiological indicators in the two age and gender groups($p<0.05$) for the entire dataset and for separate anatomical regions.

Kruskal-Wallis test was applied for comparisons of the physiological indicators among different groups specified by age and gender for the entire dataset and for the separate anatomical regions ($p<0.05$). These test were followed by Mann-Whitney U post-hoctests with Bonferroni corrections to control for multiple comparisons (adjusted p-value threshold=0.0083). Friedman tests were performed to study the relationships between the indicators at different anatomical regions of the same participants ($p<0.05$). Wilcoxon signed ranks with Bonferroni corrections were applied as post hoc tests in these case (adjusted p-value threshold=0.0167).

ETHICS

This study complied with the principles of the Declaration of Helsinki, and the experimental protocol was reviewed and approved by the Human Trial Ethics Committee of Hungary, National Center For Public Health And Pharmacy, Department of Clinical Research (NNGYK/19704-9/2025). Before the formal study, written informed consent was obtained from each volunteer.

RESULTS

Population Socio-Demographics

Table 1. Comparison of physiological parameters of the different age groups.

Agegroup	Anatomical region	Erythema	Melanin	Elasticity	Hydration SC	Hydration EpiD	Barrier function	pH
Junior Female (14pts)	Face	422.857±16.42	870.5±1253.75	48.286±25.14	35.82±37.12	36.62±10.63	10.278±3.56	-
	Forehead	448.64±11.43	543.4±39.46	67.14±23.9	47.44±32.35	50.43±6.9	16.69±5.9	-
	Hand	434.785±13.46	559.26±33.78	49.92±13.18	28.37±15.96	38.72±4.5	135.285±422.35	5.21±0.65
Junior Male (6pts)	Face	449.83±5.77	577.27±28.56	51.5±20.5	15.97±13.82	24.57±6.1	14.43±4.2	-
	Forehead	475.5±7.3	581.67±35.73	-	36.23±19.54	50.1±7.4	19.85±7.6	-
	Hand	453±10.3	591.45±34	58.5±22.8	40.92±25.88	42.68±10.76	37.67±19.45	4.845±0.88
Senior Female (16pts)	Face	443.125±17.95	583.1375±20.88	49.83±24.5	25.2±12.23	41.46±7.9	8.8±3.175	-
	Forehead	449.2±16.4	578.5±29.2	62.2±35.6	41.6±28.4	50.4±6.75	23.23±36.2	-
	Hand	441.6875±15.12	599.9±88.5	38±14.2	20.41±9.3	37.98±6.15	16.32±7.5	5.634±0.5
Senior Male (4pts)	Face	465.5±11.6	641.1±36.86	65±20.95	11.575±10.1	30.65±14.52	13.125±4.24	-
	Forehead	468.25±11.26	598.5±25.88	79.67±61.1	28±15.5	47.7±10.11	19±3.98	-
	Hand	448.25±17.8	653.85±14.18	43±15.25	11.85±4.59	34.125±5.44	10.5±3.1	5.135±0.69

The units of the parameters are provided by the instrument manufacturer. (mean±SD).*$p<0.05$.

Physiological parameters

Figure 2 presents the distribution of TEWL values, reflecting skin barrier integrity, across junior and senior male and female participants. Panel A shows aggregated data from all anatomical sites combined, while Panels B–D display the hand, face, and forehead separately. TEWL values demonstrate region-specific variability, with the hand exhibiting higher water loss compared to the face and forehead. Subtle agerelated differences are observed, with seniors showing slightly higher TEWL in some regions, suggesting mild barrier impairment. Gender differences appear modest overall, though slightly elevated TEWL is noted in males in certain regions. In the case of barrier function, a significant difference was observed in the pooled data (p =0.004), mainly between older women and young men (p = 0.00048), in favor of the former. A similar trend can be observed on the palms (p = 0.0052). According to the literature, up to the age of 50, men have lower transepidermal water loss (TEWL) than women of the same age, regardless of body regions, but with advancing age, the gender differences gradually equalize [16]. These results indicate that barrier function shows age- and gender-related differences. Lower TEWL values in young men indicate better barrier integrity, while higher values in older women can be partly explained by adaptive, ifestyle or skin care factors. The decrease in gender differences with age suggests that the skin's regenerative capacity and lipid profile change in a similar way in both sexes [16]. These results highlight that barrier function is influenced by anatomical location, with secondary contributions from age and gender.

Figure 2. Comparison of age groups and genders for the barrier function (TEWL in g/m²/h) of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead. Adjusted p-value threshold=0.0083 for pairwise comparisons. N = 14 junior female, 6 junior male, 16 senior female, 4 senior male.

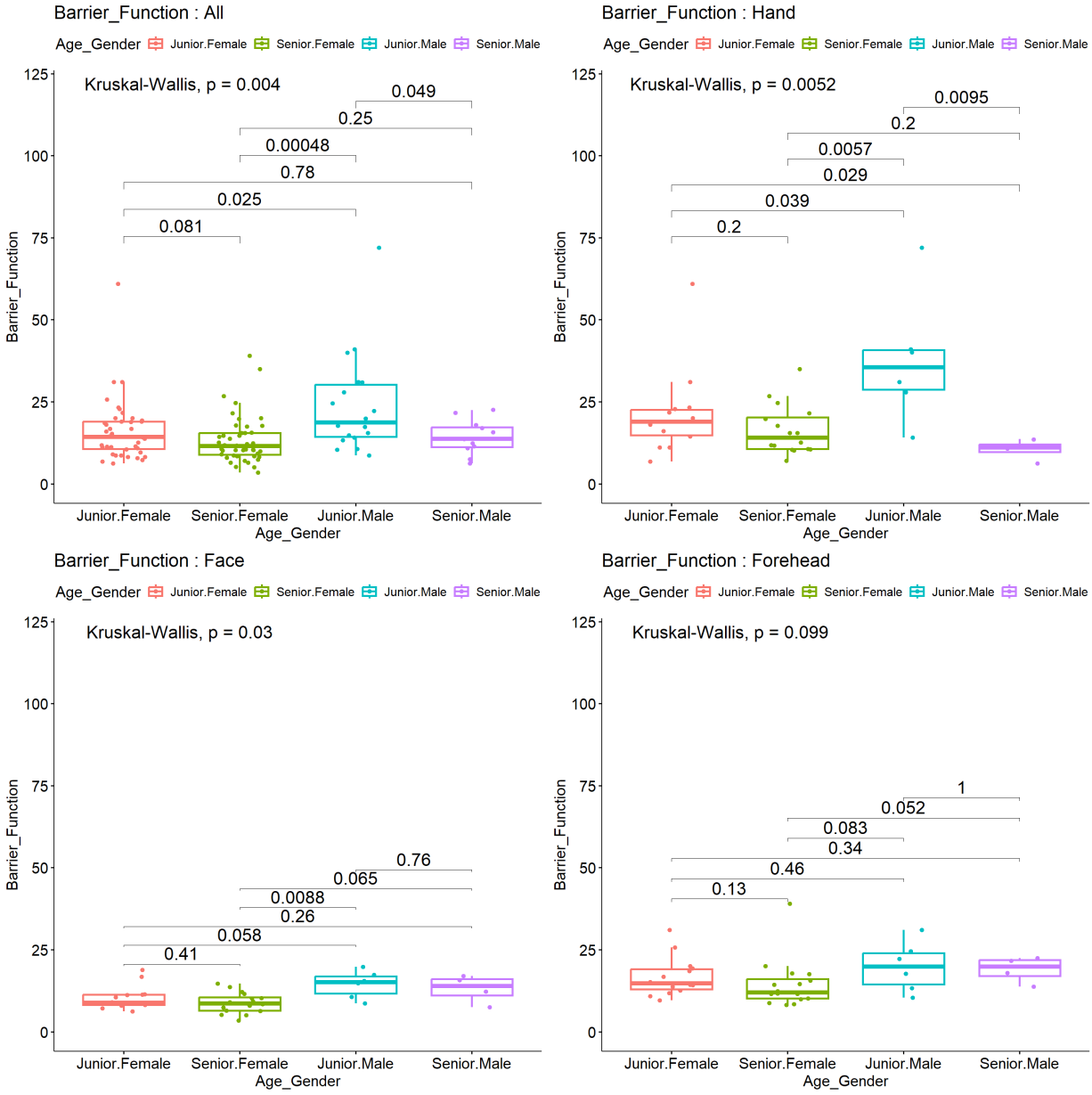
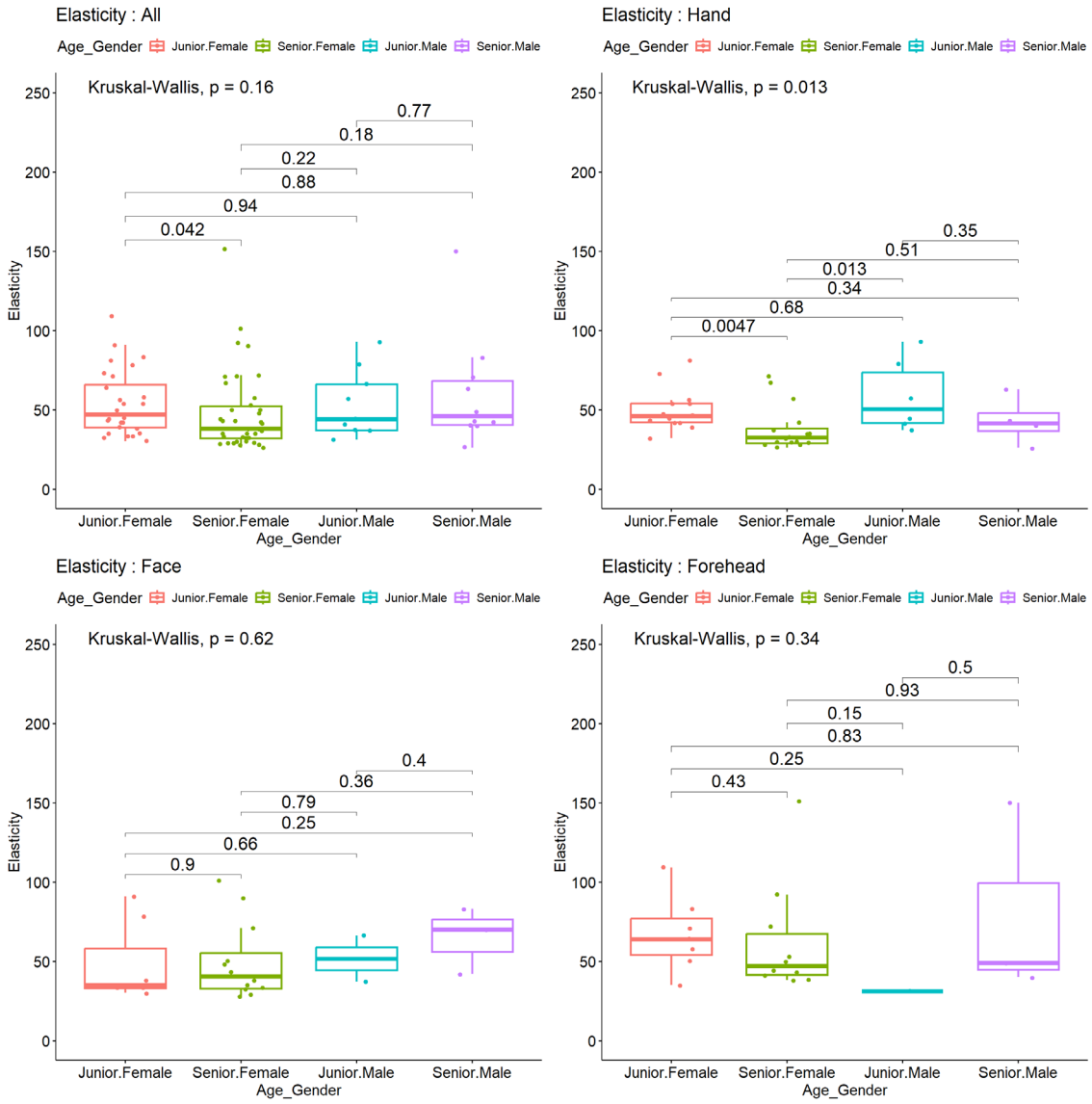


Figure 3 illustrates age- and gender-related differences in skin mechanical properties measured by the ElastiMeter. Aggregated values (Panel A) and region-specific plots (Panels B–D) are presented. Senior groups consistently display reduced elastic response across all regions, whereas gender-related differences are smaller. These patterns underscore that skin elasticity is strongly shaped by chronological aging and only modestly modulated by gender or anatomical site. When examining skin elasticity, contrary to expectations, no significant difference was found between the groups in any body region ($p>0.01$ in all cases). Based on previous literature, it could have been assumed that skin elasticity decreases significantly in the senior age group, since the amount of collagen and elastin fibers and their structural integrity gradually deteriorate with age. As a result, the fibers in the dermis fragment, the elastic network loosens, and the mechanical resistance of the skin weakens, which is clinically manifested as a decrease in elasticity, the appearance of fine wrinkles and sagging [25]. Taking these into account, it could have been expected that a greater difference would appear in the elasticity parameters between the younger and older groups. However, this did not appear to be statistically significant in our study, which can be explained by the combined effect of several factors. The low number of elements and the technical limitations of the ElastiMeter device may have limited the reliability of the data: namely on the face and forehead, the measuring head did not always ensure adequate contact with the skin urface, thus several measurements were excluded. In the case of facial skin, slight muscle tension (inflating the face) was required for accurate measurement, while on the forehead only the upper, perpendicular measurement points gave stable results.

Figure 3. Comparison of age groups and genders for the elasticity (in %) of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead. Adjusted p-value thresh- old=0.0083 for pairwise comparisons. N (hand) = 14 junior female, 6 junior male, 16 senior female, 4 senior male, N (face) = 7 junior female, 2 junior male, 12 senior female, 3 senior male, N (forehead) = 7 junior female, 1 junior male, 9 senior female, 3 senior male.



The erythema index (EI), reflecting cutaneous redness due to vascular reactivity or superficial irritation, is compared across groups. **Figure 4**. Panel A shows pooled data from all anatomical locations. Region-specific analyses reveal that the face and forehead exhibit higher EI compared to the hand, likely due to increased vascular density and environmental exposure. Erythema values in the pooled analysis were significantly different between groups (Kruskal–Wallis p = 2.1e–06). Based on pairwise analyses, the largest differences were observed between young women and older men (p = 1.6e–05), with the latter group having the highest erythema values. Men had higher skin redness than women in all age groups. There was no significant difference between values measured on the dorsal surface of the hand (p = 0.093), while there were significant differences on both the face (p = 0.00084) and forehead (p = 0.0014). Young women showed the lowest erythema values. The age and gender differences measured in the present study are consistent with an in vivo study of 442 women by Machková et al. (2018), in which erythema values increased gradually with age up to 50 years and then decreased in older age. According to the authors, this change can be explained by age-related changes in microcirculation and remodeling of the dermal vascular network. The increase in redness until middle age may be partly due to the effect of increased UV exposure, while its subsequent decrease may be related to a decline in vascular activity and lower blood volume due to a thinner dermal layer [26]. A similar pattern can be observed in our results: higher erythema values in older men may be a consequence of age-related inflammatory predisposition, while lower values in women may partly be a consequence of skin protection habits (e.g. sun protection, use of cosmetics) and different hormonal background [26].

Figure 4. Comparison of age groups and genders for the erythema index (RGB in %) of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead. Adjusted p-value threshold=0.0083 for pairwise comparisons. N=14 junior female, 6 junior male, 16 senior female, 4 senior male.

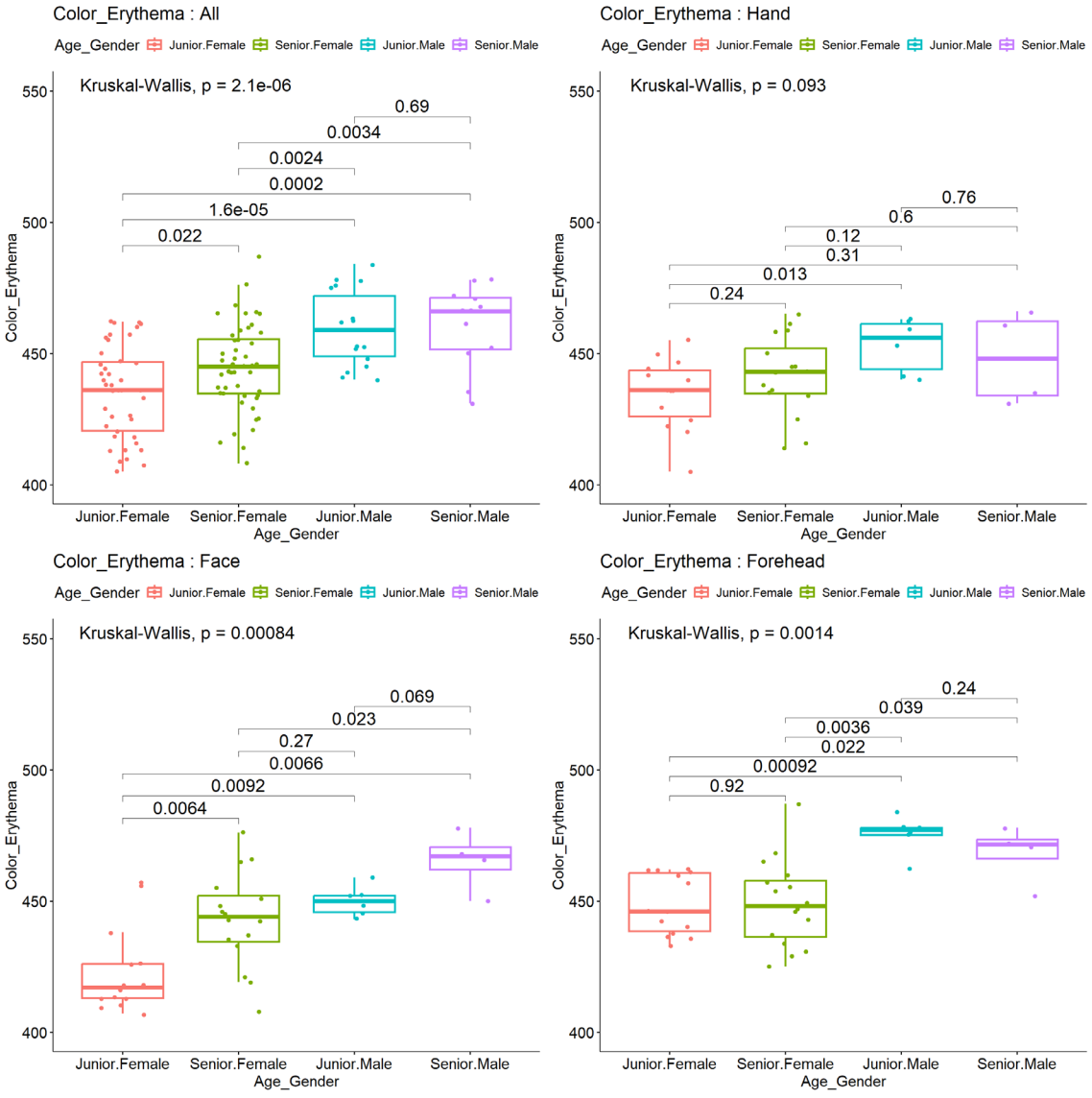
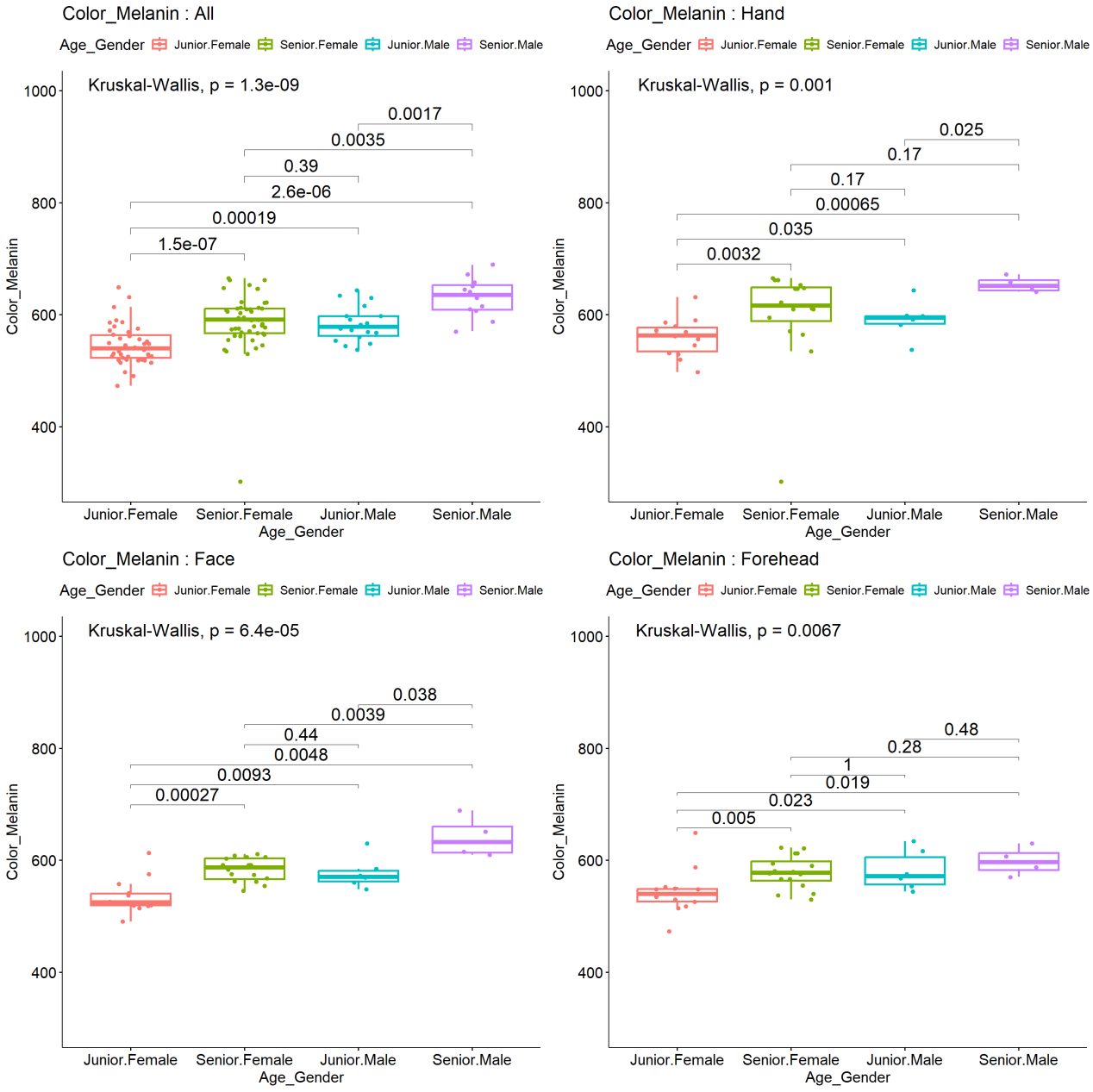


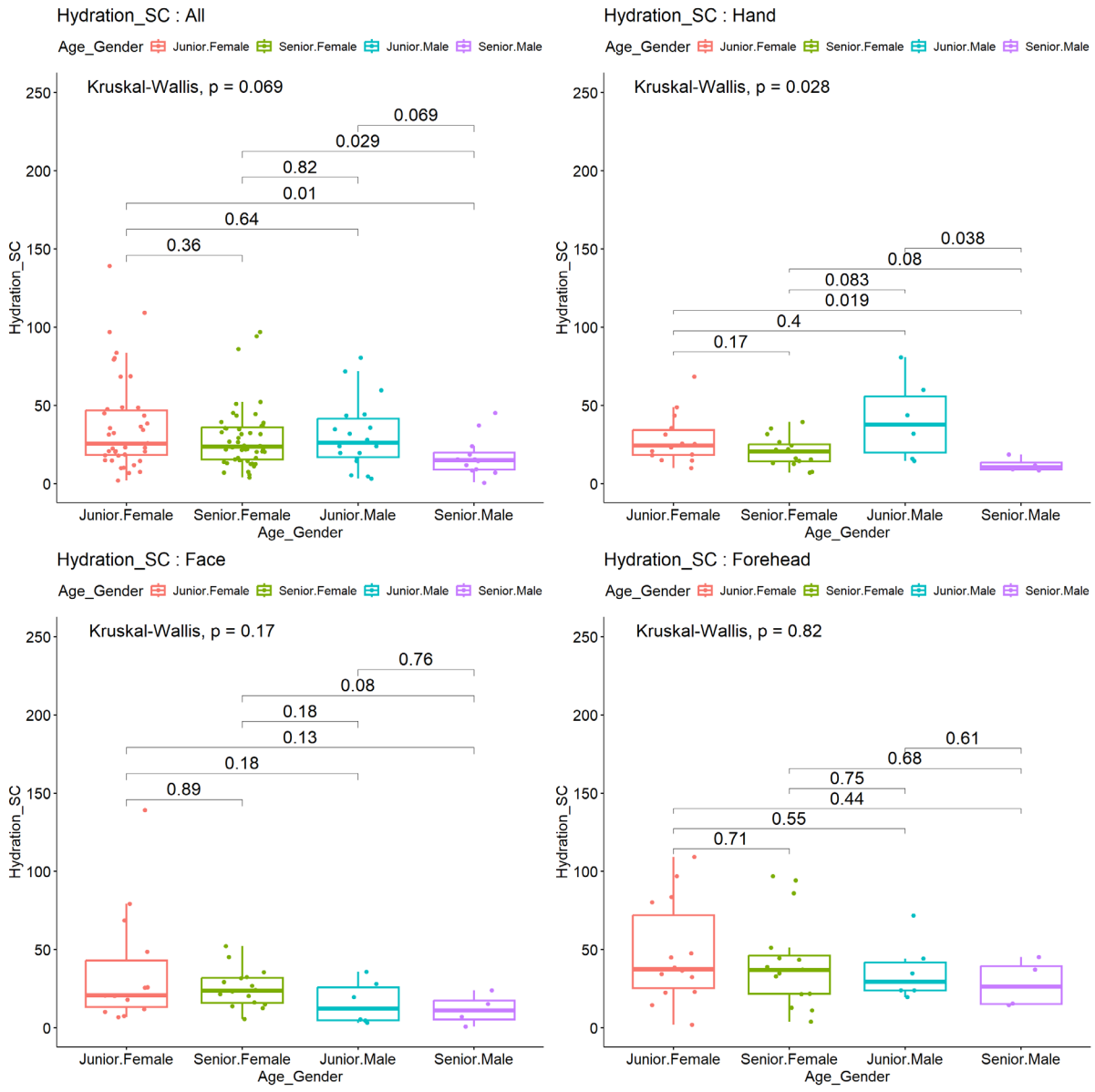
Figure 5 compares melanin index (MI) values, a measure of pigmentation intensity. Aggregated data (Panel A) and site-specific plots (Panels B–D) show robust regional dif- ferences, with the face demonstrating higher melanin levels due to chronic UV exposure. Gender differences are also notable, with males generally exhibiting slightly higher pigmentation. Age effects appear region-dependent: seniors display increased pigmentation on sun-exposed regions but not on the hand. As for the statistics, melanin levels differed significantly between the groups (Kruskal–Wallis p =1.3e–09). The largest difference was observed between young women and older men (p= 2.6e–06). Older men had the highest skin pigmentation, while young women had the lowest. When examined by body region, significant differences were also found on the hands (p = 0.001), face (p = 6.4e–05), and forehead (p = 0.0067), with higher pigment content in the older groups in each case. In line with the trend described by Machková et al. (2018), melanin levels increase with age, especially in the 30–50 age group, and then stagnate or slightly decrease after age 50. The authors explained this in part by the effect of chronic UV exposure [26]. The higher melanin values in older men in the present study are likely to be related to higher sun exposure and gender differences in skin protection habits. The lower pigment content in young women, on the other hand, may indicate a more conscious use of sun protection and that the hormonal effects of estrogen may also play a role in reducing melanin production [26]. The results reflect the interplay of anatomical location, gender-related pigmentation patterns, and cumulative photodamage.

Figure 5. Comparison of age groups and genders for the pigmentation (melanin content in %) of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead. . Adjusted p-value threshold=0.0083 for pairwise comparisons. N=14junior female, 6 junior male, 16 senior female, 4 senior male.



The surface hydration levels assessed via MoistureMeterSC are presented in **Figure 6**. When combined, pooled (Panel A), the data show an age-related decrease in SC hydration, with senior groups displaying noticeably lower values. Region-specific plots illustrate that the face and forehead have higher surface hydration than the hand, consistent with their thinner, more sebaceous skin. Gender differences are minimal. However, no significant differences were found in stratum corneum and epidermis hydration in most body regions, except for the face, where older women had higher values than young men (p = 0.0013). In contrast, the literature suggests that older age groups generally have lower hydration values, as lipids and natural moisturizing factors decrease with age and the stratum corneum thins [25]. The higher hydration values measured on the face in older women are likely partly explained by the more regular use of moisturizing cosmetics, which may contribute to maintaining the skin's water-binding capacity. However, a large-sample study found that young men typically have higher stratum corneum hydration than women, but while women's hydration values remain stable or increase slightly with age, men's gradually decrease from the age of 40 [16]. Our results therefore partly reflect the nonlinear age-related dependence of hydration parameters. While no significant differences were observed in most body regions, the higher hydration values of older women on the facial skin suggest that the skin's water-retaining capacity may change around the menopause (50 years). This observation is in line with the tendency described in the literature that physiological characteristics of the skin, including hydration, do not develop linearly but are linked to age transitions (e.g., hormonal changes) [16]. These results confirm that SC hydration declines with age and varies substantially by anatomical region.

Figure 6. Comparison of age groups and genders for the skin surface hydration (water content of the corneocytes at the Stratum Corneum) of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead. Adjusted p-value threshold=0.0083 for pairwise comparisons. N=14junior female, 6 junior male, 16 senior female, 4 senior male.



Deep epidermal hydration, measured by the Moisture Meter EpiD, is compared across groups in **Figure 7**. Panels A–D show that viable epidermal hydration also decreases with age, though the magnitude is smaller than in the SC. The forehead consistently shows the highest hydration values, reflecting its thinner epidermis and higher sebaceous gland activity. Gender differences remain small. These findings indicate that aging affects both superficial and deeper layers of the epidermis, though regional differences are more dominant.

Figure 7. Comparison of age groups and genders for the hydration of the viable epidermis of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead. Adjusted p-value threshold=0.0083 for pairwise comparisons. N=14junior female, 6 junior male, 16 senior female, 4 senior male.

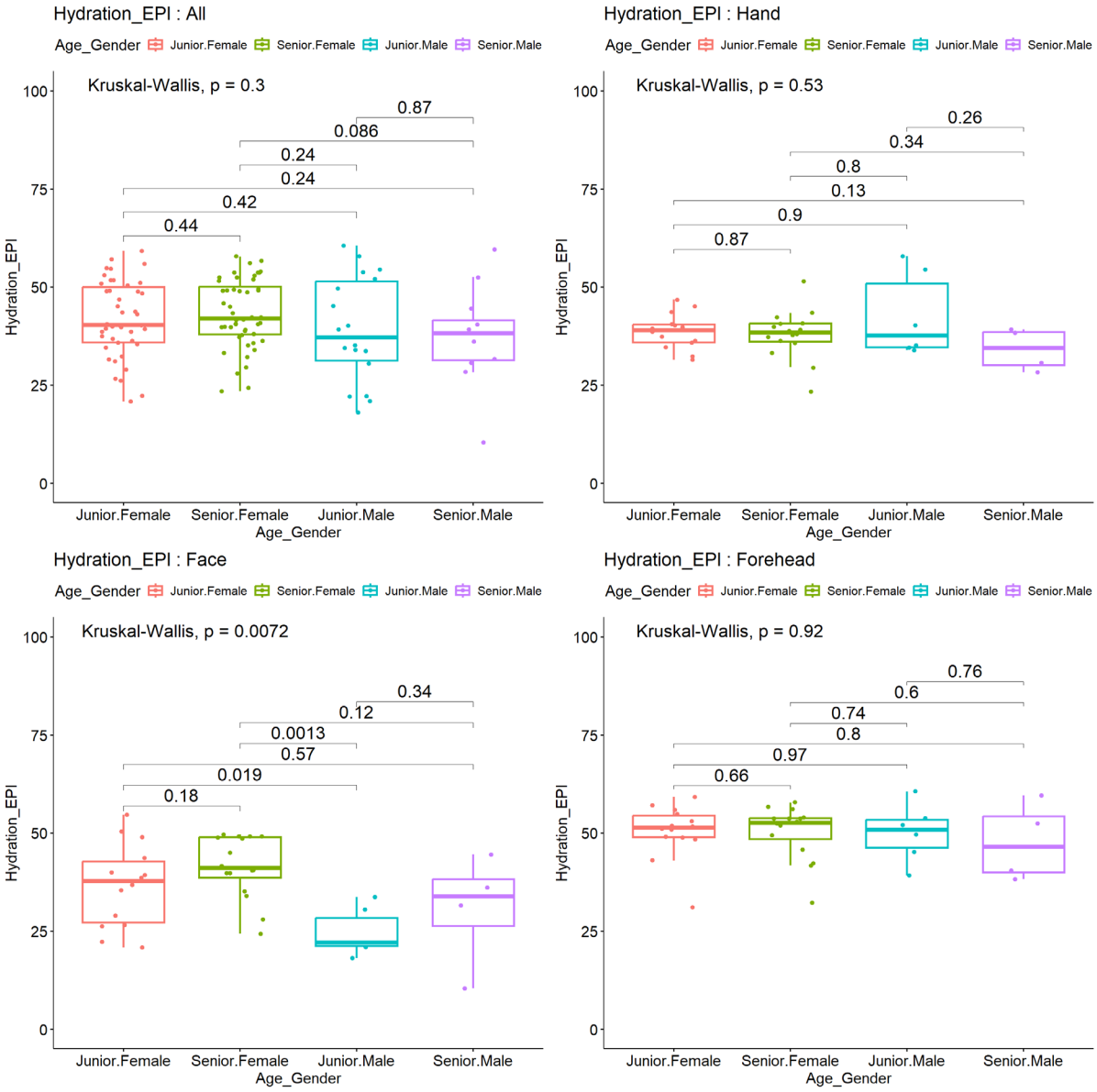
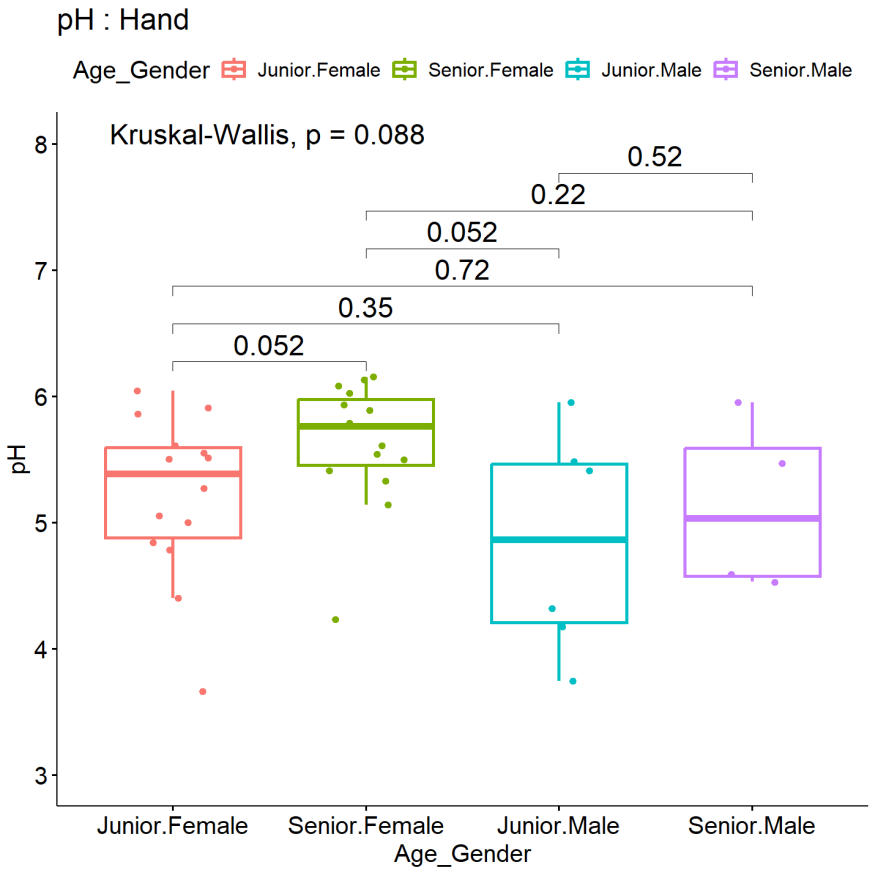


Figure 8 displays skin surface pH values measured on the hand, the only location evaluated for this parameter where there was no significant difference between the groups (p = 0.088). All values fall within the expected physiological acidic range (4.8–6.0). Senior groups show slightly higher pH values compared to juniors, consistent with age-related shifts in acid mantle integrity. Gender differences are minimal. According to a recent study that measured 300 healthy women and men aged 20–74 years, the pH of men's skin was always below 5, while that of women was usually above 5 [16]. Compared with our own results, our measurements partially confirm the literature trend: although there was no significant difference at the group level, the average pH of men was lower and that of women was higher, which supports the fact that skin pH may differ between the genders [16]. This is an important aspect in the development of skin care and preventive strategies. These data reinforce that hand skin pH is relatively stable, with only modest variation associated with aging.

Differences in the skin parameters between all female and all male participants can be found on supplementary figures S1, S3, S5, S7, S9, S11 and S13. Differences in the skin parameters between all senior and all junior participants are shown on supplementary figures S2, S4, S6, S8, S10, S12 and S14. Differences of the skin parameters measured on multiple anatomical regions were also compared with controlling for the participants (supplementary Figure S15).

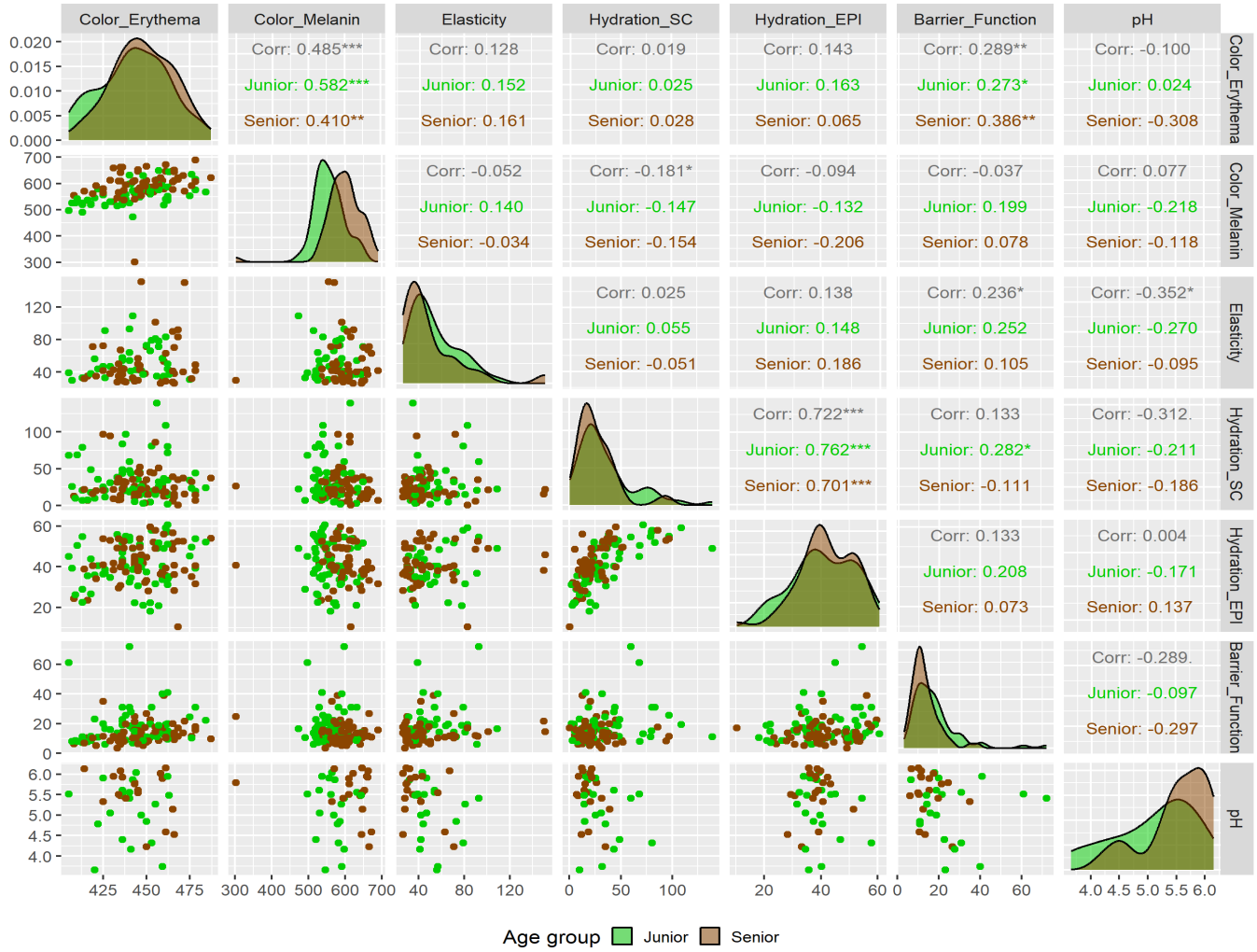
Figure 8. Comparison of age groups and genders for the skin surface pH values on the hand skin. Adjusted p-value threshold=0.0083 for pairwise comparisons. N=14junior female, 6 junior male, 16 senior female, 4 senior male.



Effect of age

Figure 9 displays correlation coefficients quantifying the relationship between age and all measured skin parameters. Strong negative correlations are observed for elasticity, SC hydration, and EPI hydration, confirming their decline with age. Erythema and melanin show moderate associations, reflecting cumulative vascular and pigmentary changes. TEWL and pH exhibit weaker correlations, indicating that barrier function and acid mantlestability are less directly influenced by chronological age. Significant coefficients are marked with asterisks based on statistical significance thresholds.

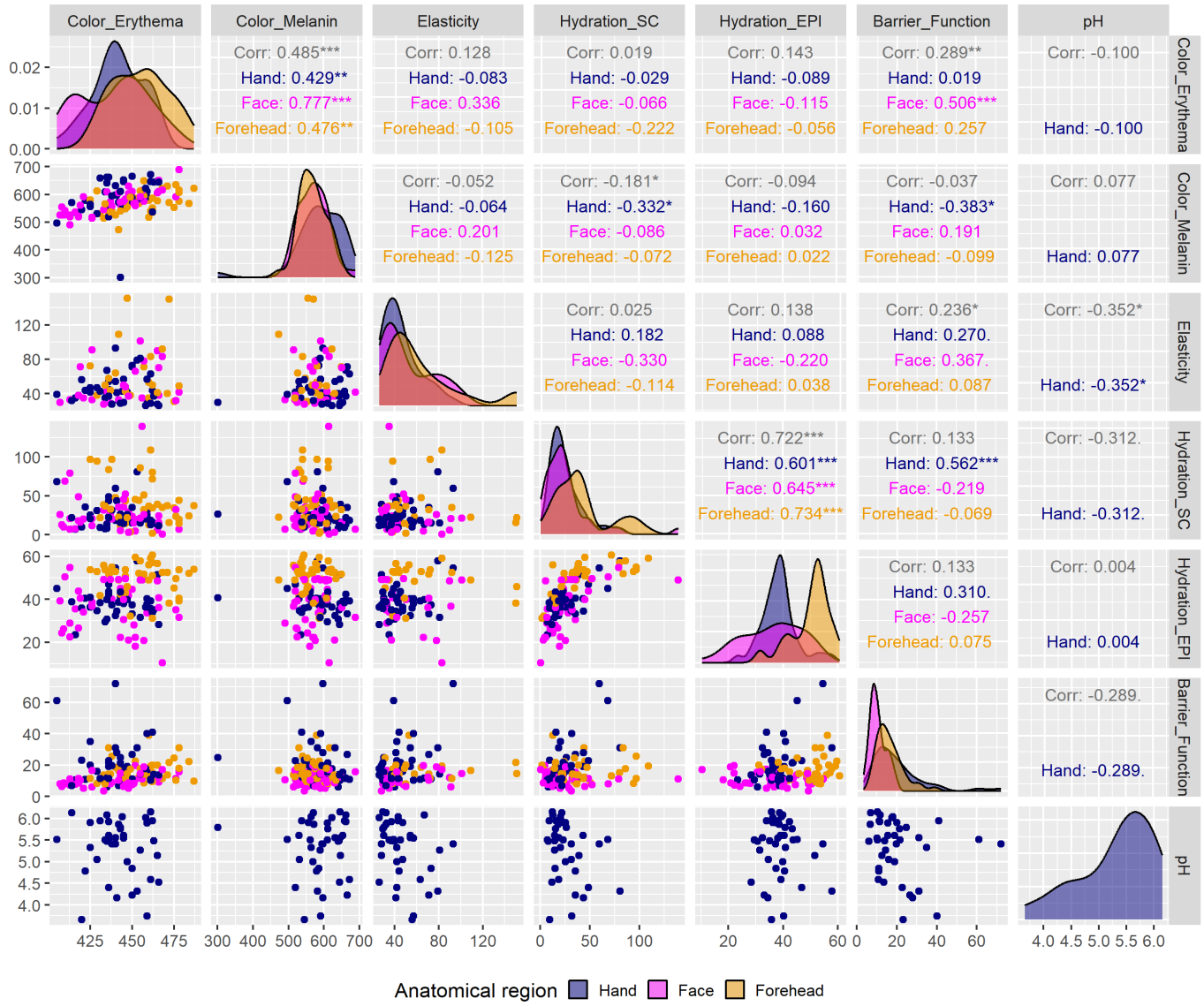
Figure 9. Correlation analysis for the effect of aging (junior vs senior) on different skin parameters (color-erythema, color-melanin, elasticity, skin surface hydration, skin deep layer hydration, barrier function and pH. All measured data points are presented. Green: juniors, Brown: seniors. The correlation coefficients were calculated. *: coefficient significant at 5% level, **: coefficient significant at 1% level, ***: coefficient significant at 0.1% level, n_{junior} = 60, n_{senior} = 60.



Effect of anatomical region

Figure 10 illustrates how skin properties cluster according to anatomical site (hand, face, forehead). Hydration metrics and elasticity correlate strongly with region, highlighting major physiological differences between glabrous and facial skin. TEWL, pigmentation, and erythema also demonstrate region-specific patterns. These results underscore the necessity of anatomical standardization in dermatological studies.

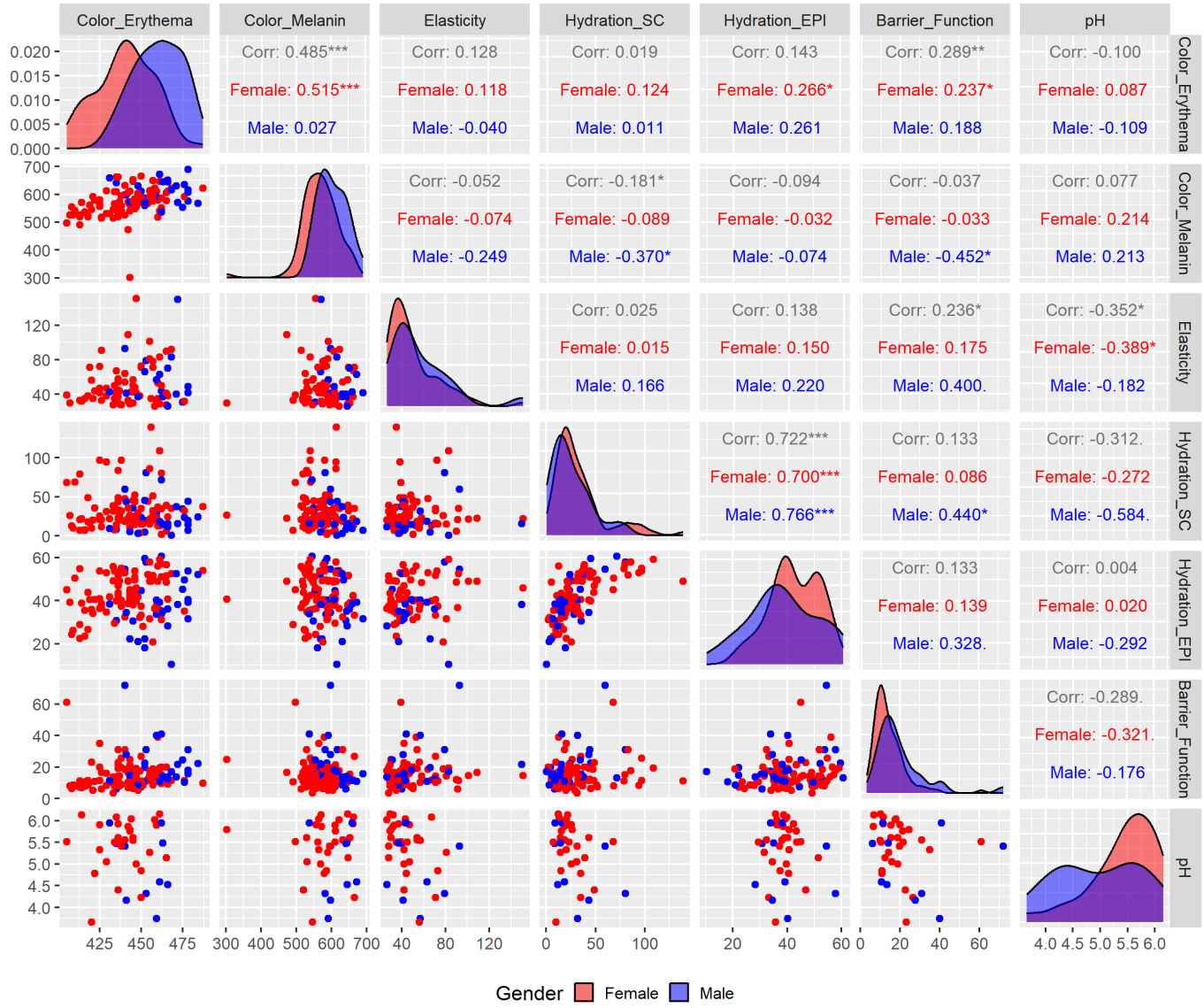
Figure 10. Correlation analysis for the effect of the tested anatomical regions (hand vs face vs forehead) on different skin parameters (color-erythema, color-melanin, elasticity, skin surface hydration, skin deep layer hydration, barrier function and pH. All measured data points are presented. Blue: hand, Pink: face, Yellow: forehead. The correlation coefficients were calculated. *: coefficient significant at 5% level, **: coefficient significant at 1% level, ***: coefficient significant at 0.1% level, n_{hand} = 40, n_{face} = 40, $n_{forehead}$ = 40.



Effect of gender

The associations between biological sex and each measured skin parameter are assessed in **Figure 11**. Pigmentation shows the strongest gender-linked variation, followed by erythema. Hydration and elasticity show weaker correlations, while TEWL and pH demonstrate minimal gender dependency. These findings indicate that gender influences colorimetric skin traits more strongly than mechanical or barrier parameters.

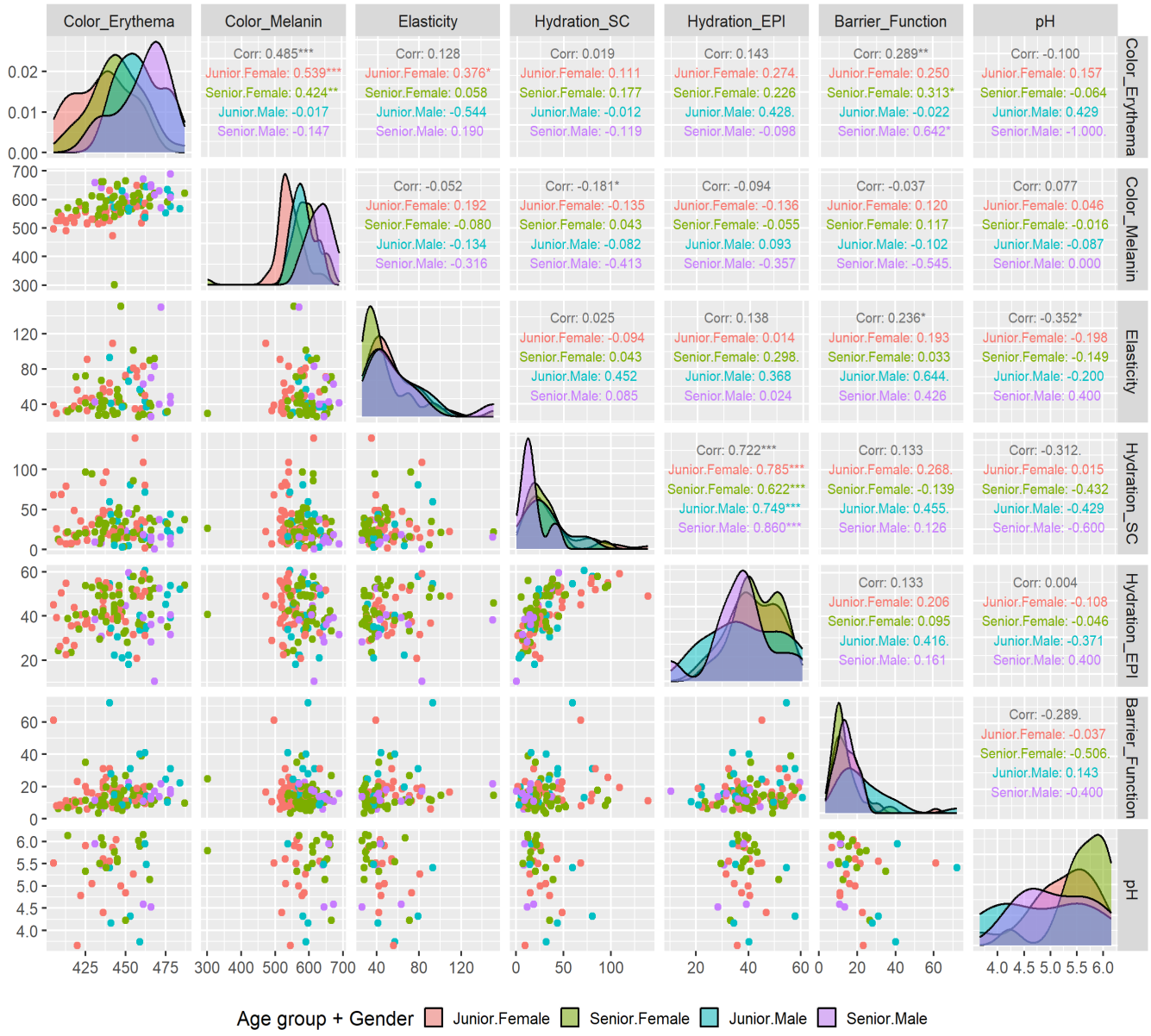
Figure 11. Correlation analysis for the effect of gender (female vs male) on different skin parameters (color-erythema, color-melanin, elasticity, skin surface hydration, skin deep layer hydration, barrier function and pH. All measured data points are presented. Red: females, Violet: males. The correlation coefficients were calculated. *: coefficient significant at 5% level, **: coefficient significant at 1% level, ***: coefficient significant at 0.1% level, n_{female} = 80, n_{male} = 40.



Combined effects of age and gender

This multidimensional comparison across four subgroups (junior female, senior female, junior male, senior male) demonstrates how age and gender interact to shape skin physiology (Figure 12). The clearest separations are seen for elasticity and hydration, where age is the dominant factor. Pigmentation and erythema show combined age–gender effects. TEWL and pH show the least separation. This figure illustrates the multifactorial determinants of skin biophysical characteristics.

Figure 12. Correlation analysis for the effect of gender and age (junior female vs senior female vs junior male vs senior male) on different skin parameters (color-erythema, color-melanin, elasticity, skin surface hydration, skin deep layer hydration, barrier function and pH. All measured data points are presented. Orange: junior females, Green: senior females, Turkiz: junior males, Violet: senior males. The correlation coefficients were calculated. *: coefficient significant at 5% level, **: coefficient significant at 1% level, ***: coefficient significant at 0.1% level, n_j female = 42, n_s female = 48, n_j male = 18, n_s male = 12.



DISCUSSION

This cross-sectional observational study provides a comprehensive evaluation of key physiological skin parameters, including barrier function, elasticity, hydration at multiple depths, pigmentation, erythema, and pH, in healthy junior and senior individuals of both genders within the Central European region. By assessing three anatomical sites (hand, face, forehead) under strictly controlled environmental conditions and applying validated measurement techniques, the study establishes region-specific and age-specific reference characteristics and highlights the factors that most strongly influence skin physiology.

Aging emerged as a major determinant of several skin parameters. The most pronounced age-related changes were observed in elasticity and hydration. Elasticity declined across all anatomical sites in senior participants, consistent with well-documented reductions in collagen density, elastin integrity, and extracellular matrix remodeling during intrinsic aging. Both stratum corneum and epidermal hydration also decreased significantly with age, reflecting alterations in lipid composition, natural moisturizing factor (NMF) levels, and epidermal renewal rates. Interestingly, TEWL showed only mild agerelated differences,

suggesting that while hydration diminishes with age, barrier integrity, measured by water loss, remains relatively preserved in healthy older adults.

Anatomical region was the strongest overall contributor to variability, as confirmed by correlation analyses. Each region exhibited a distinct biophysical profile (**Table 2**).

Table 2. Biophysical characteristics of different anatomical regions.

Anatomical region	Biophysical profile
Forehead	Displayed the highest hydration and elasticity.
Face	Showed elevated pigmentation and erythema, reflecting UV exposure and vascular density.
Hand	Exhibited lower elasticity and hydration, and higher TEWL (impaired barrier function), consistent with its thicker stratum corneum and reduced sebaceous gland density.

These findings underscore the necessity of region-matched comparisons in dermatological research and support prior reports that anatomical variability exceeds inter-individual variability for many parameters.

Gender effects were present but generally smaller than age or regional effects. Females showed slightly higher erythema values and lower melanin indices in several regions, consistent with known differences in vascular reactivity and pigmentation biology. Mechanical and barrier parameters showed minimal gender differences, suggesting that structural skin properties are less sexually dimorphic in this Central European cohort.

Importantly, the combined analysis of age and gender (Figure 12) demonstrated that age exerts a stronger influence than gender on most parameters, particularly hydration and elasticity, while pigmentation reflects a more balanced contribution of both factors. These multidimensional comparisons highlight the complex interplay between intrinsic and extrinsic determinants of skin physiology.

Strengths of this work include the use of multiple validated devices across standardized environmental conditions, triplicate measurements per site, and blinded operation to minimize measurement bias. Nonetheless, limitations must be acknowledged. The sample size in some subgroups (particularly male seniors) was limited, which reduces statistical power to detect small effects and may have influenced variance estimates. The crosssectional design prevents causal inference about longitudinal aging trajectories. Participant recruitment from academic institutions may introduce selection bias limiting generalizability to the broader Central European population. Finally, behavioral and lifetime UV-exposure histories were not quantified in detail and could confound pigmentation and erythema results.

Overall, the study contributes valuable population-specific reference data for Central European white population, a region where comprehensive skin biophysical datasets are scarce. By documenting inter-individual, inter-regional, and demographic variability, the findings support improved study design, personalized dermatological assessment, and more accurate interpretation of cosmetic or therapeutic interventions.

CONCLUSIONS

This study systematically evaluated multiple skin physiological parameters in healthy junior and senior male and female participants across three anatomical regions under controlled conditions. Aging was associated with marked declines in elasticity and hydration, while barrier function (TEWL) and pH showed relatively minor changes. Anatomical region exerted the strongest influence on all measured parameters, highlighting the importance of site-specific analysis. Gender affected pigmentation and erythema more prominently than mechanical or barrier-related traits. Together, these data establish baseline reference values for the Central European white population and provide insight into the multifactorial determinants of skin physiology. These findings may inform future dermatological research, guide clinical evaluation, and support the development of tailored cosmetic and skincare strategies.

Author Contributions

Conceptualization: FE, KL; Data curation: LM, Á-HM, EP, JJ; Formal analysis: JJ; Investigation: LM, EP; Methodology: LM, FE; Supervision: FE, KL; Validation: LM Visualization: JJ; Writing – FE, JJ, LM; Writing – review & editing: FE, KL.

Institutional Review Board Statement

The study was approved by the Human Trial Ethics Committee of Hungary (NNGYK/19704-9/2025).

Informed Consent Statement

Informed consent was obtained from all the subjects involved in the study. Written informed consent was obtained from the patients to publish this paper.

Data Availability Statement

The data presented in this study are available from the corresponding author on reasonable request.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Figure S1. Comparison of gender groups for the erythema index (RGB) of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead.

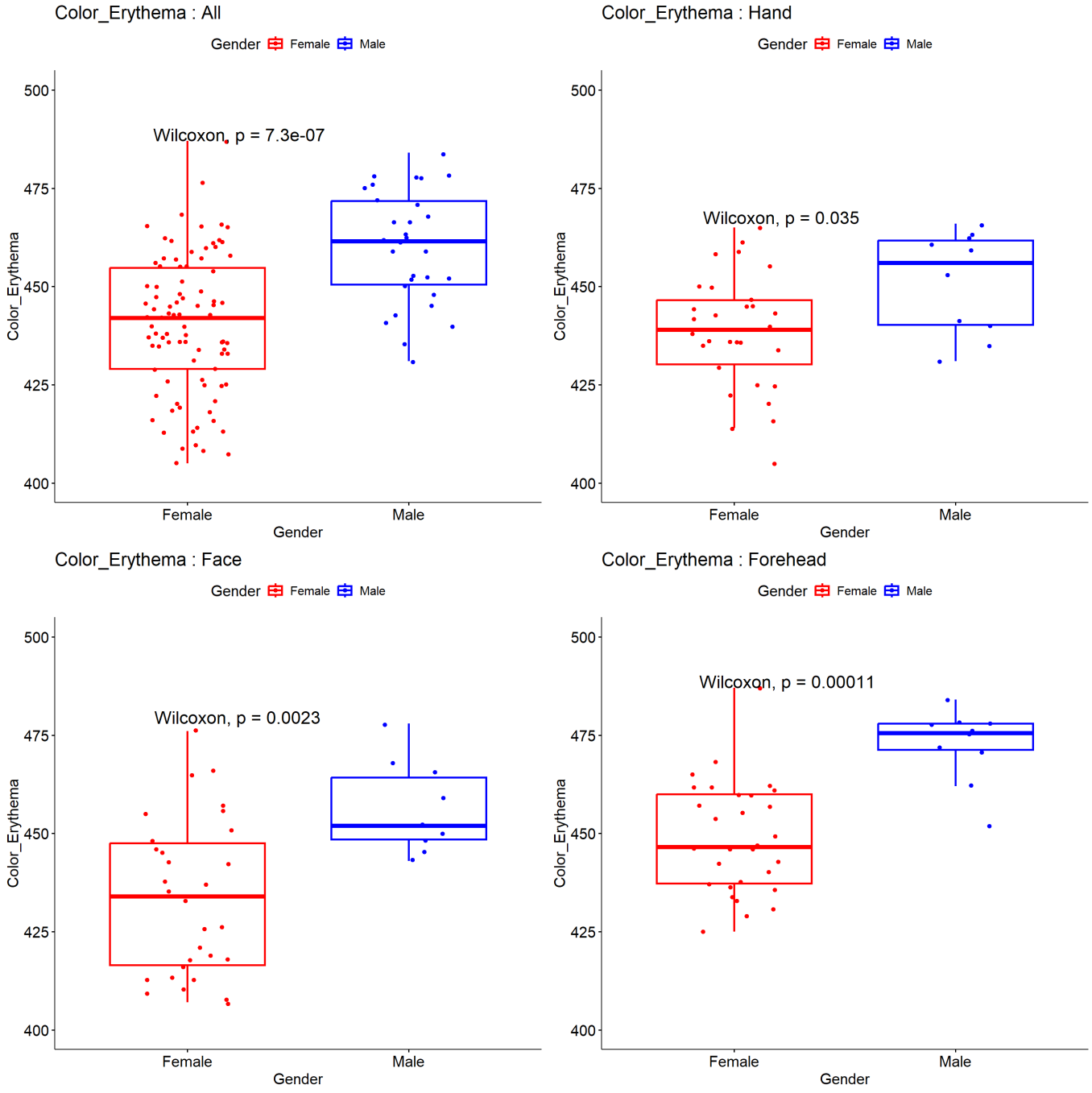


Figure S2. Comparison of age groups for the erythema index (RGB) of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead.

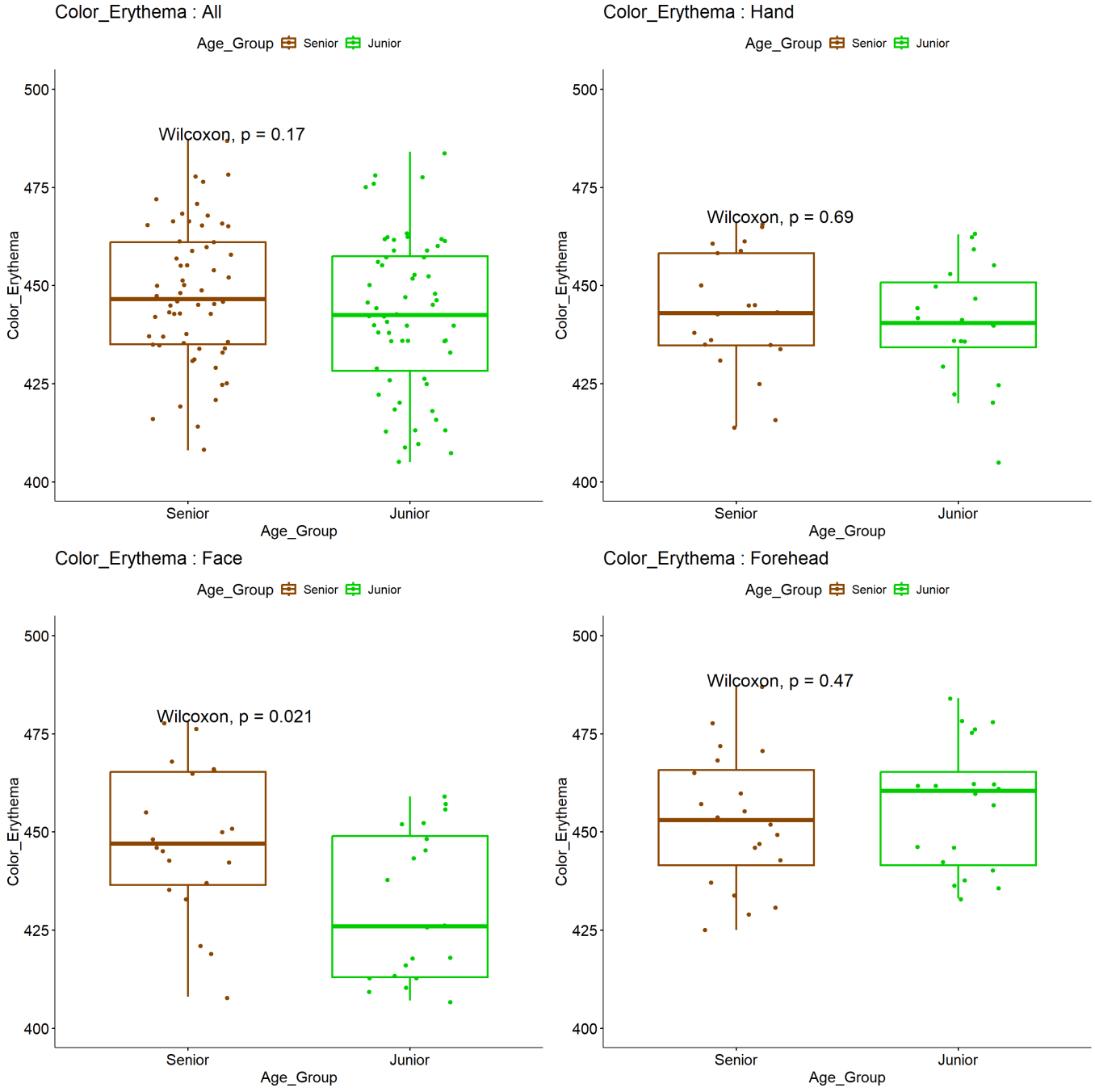


Figure S3. Comparison of gender groups for the pigmentation (melanin content) of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead.

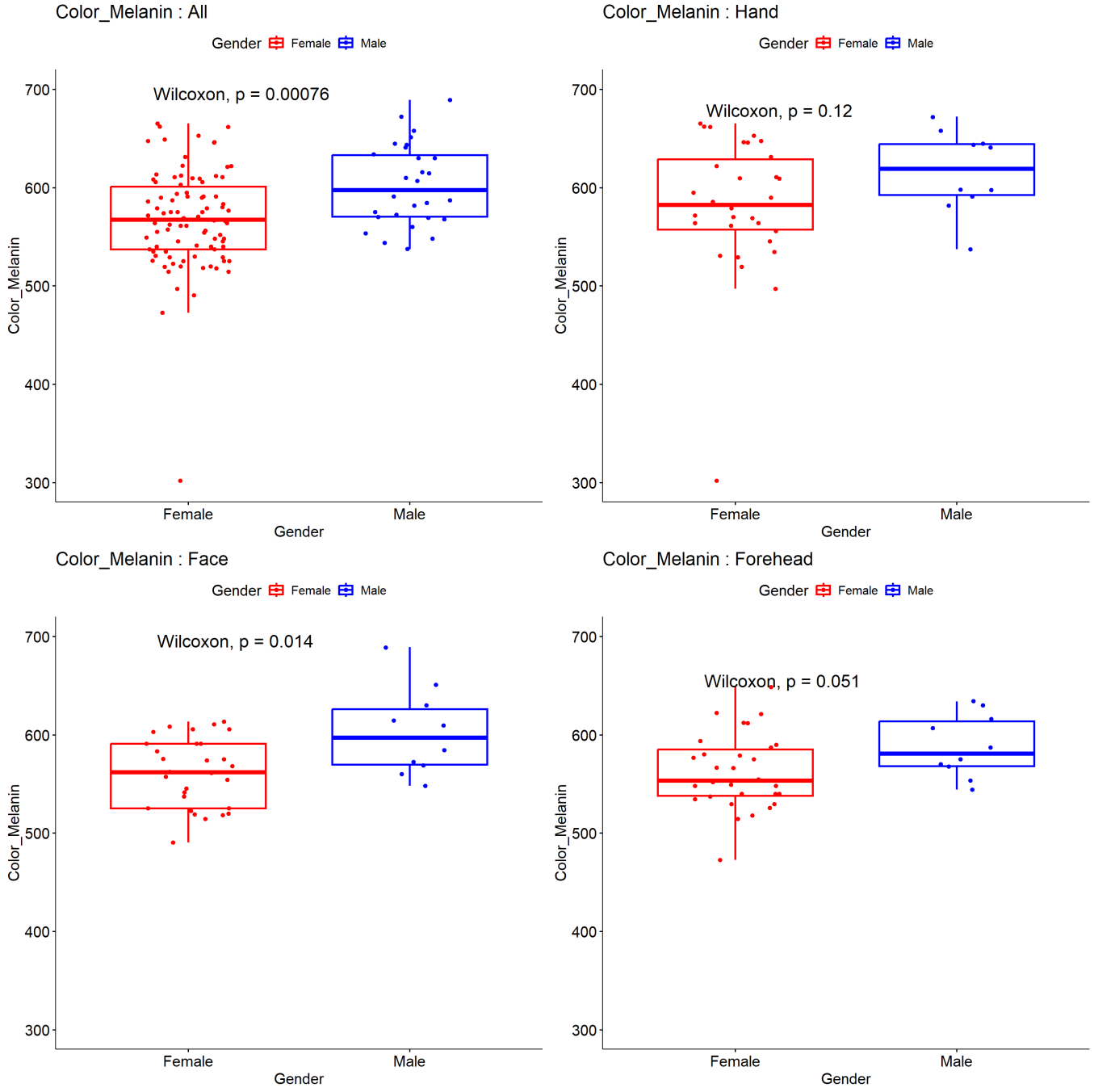


Figure S4. Comparison of age groups for the pigmentation (melanin content) of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead.

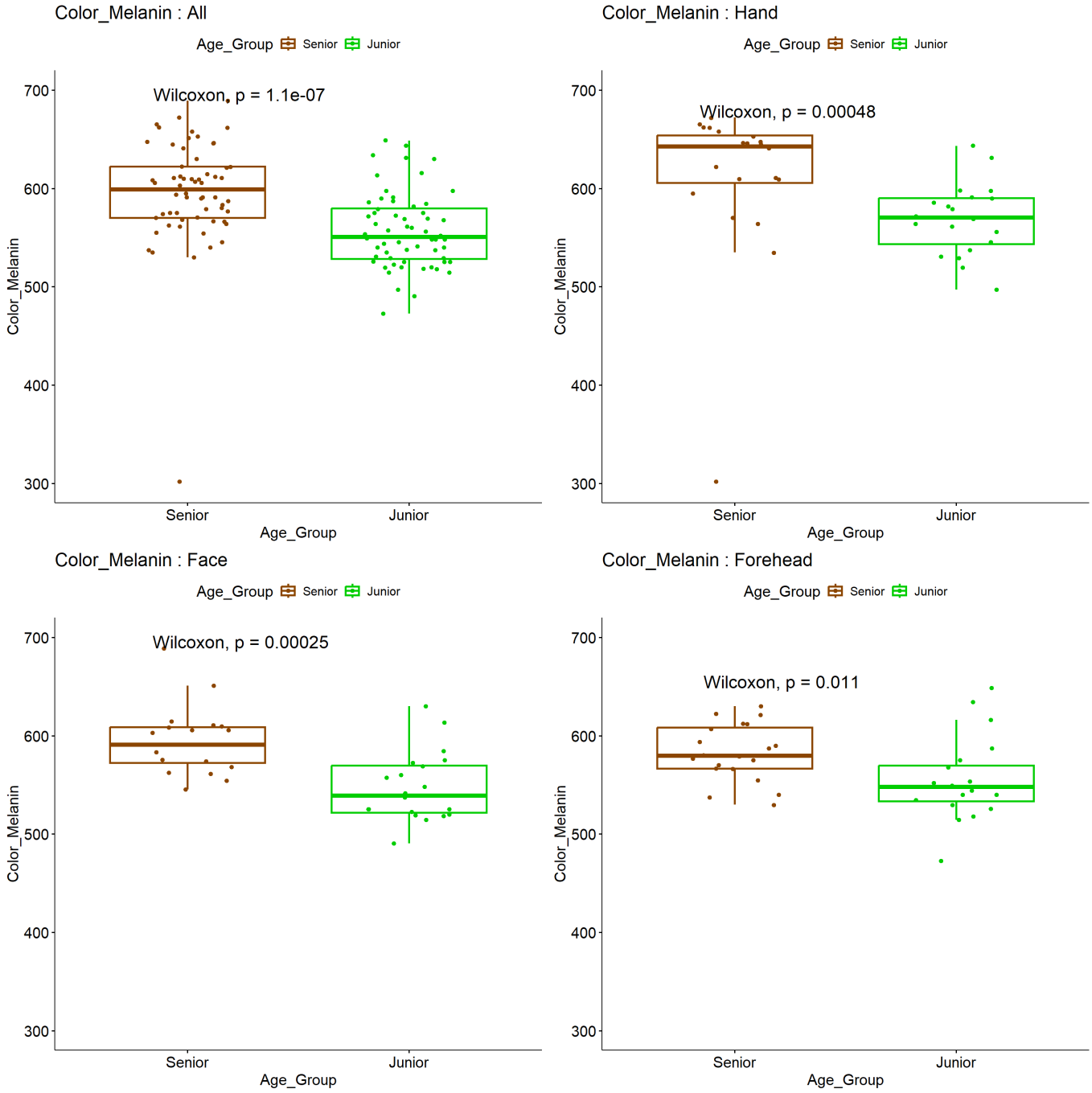


Figure S5. Comparison of gender groups for the elasticity of the skin on different anatomical regions. A: all regions together, B: hand (nf=30; nm=10), C: face (nf=19; nm=5), D: forehead (nf=17; nm=4).

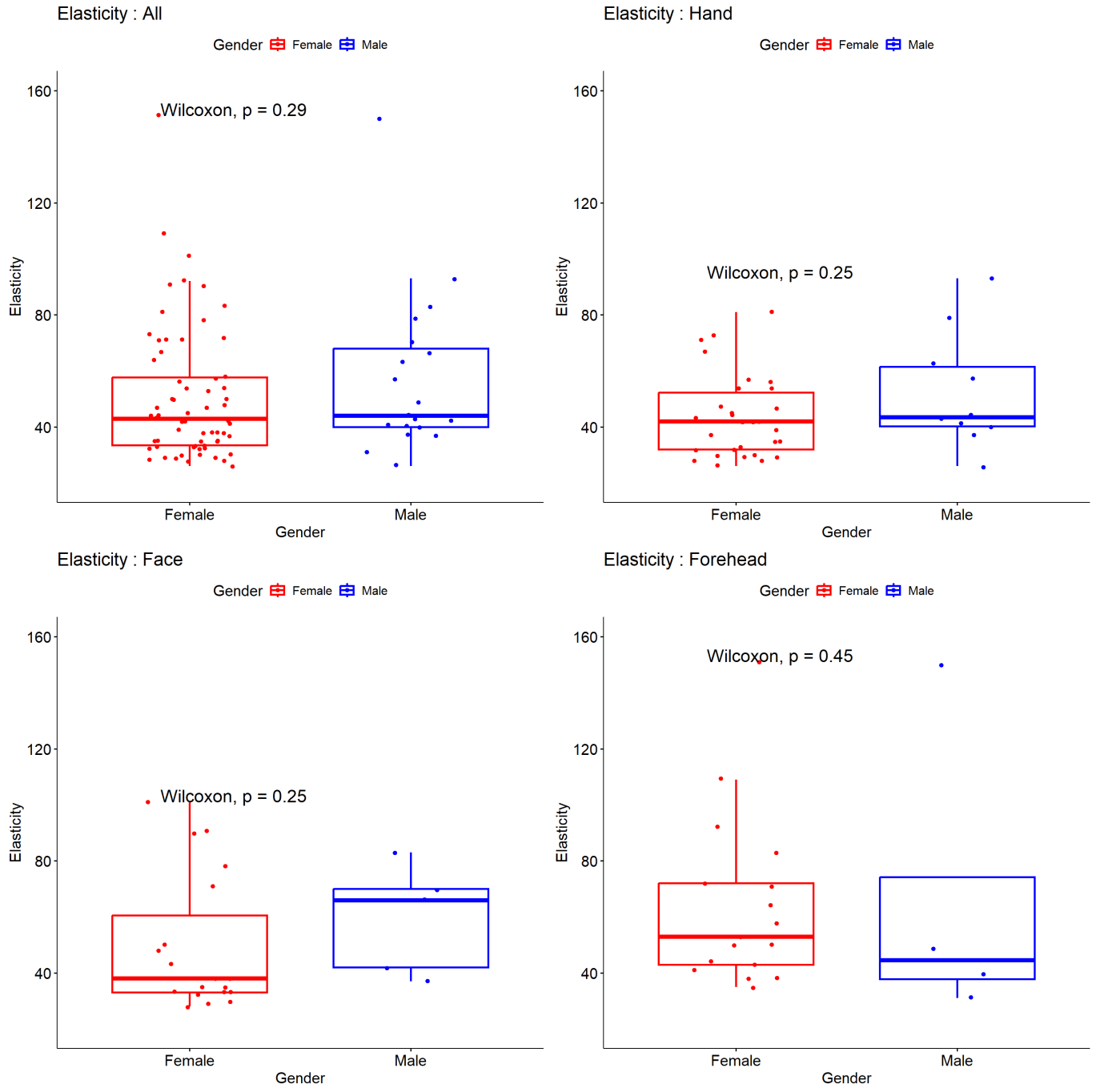


Figure S6. Comparison of age groups for the elasticity of the skin on different anatomical regions. A: all regions together, B: hand (nj=20; ns=20), C: face (nj=9; ns=15), D: forehead (nj=8; ns=13).

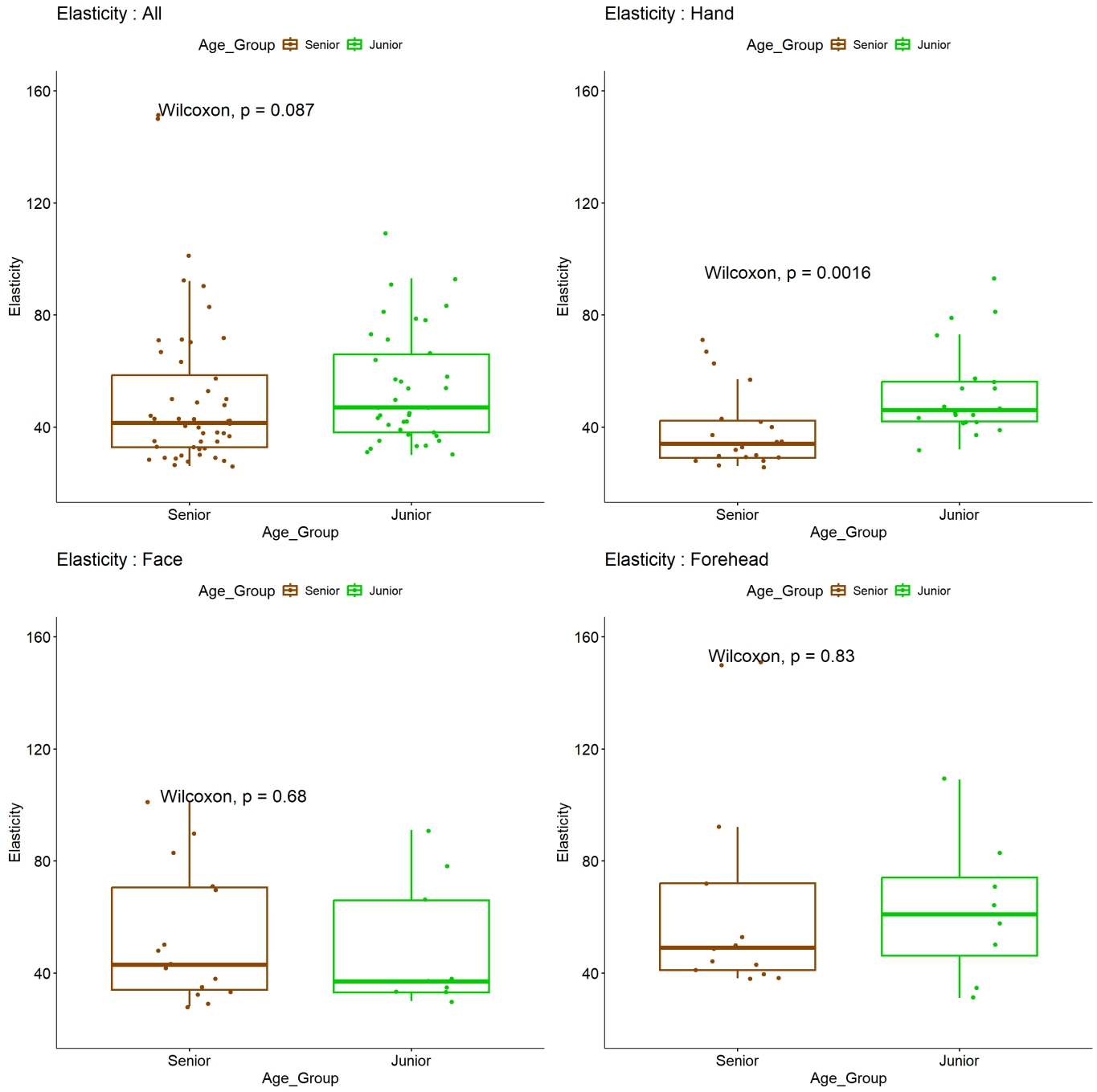


Figure S7. Comparison of gender groups for the skin surface hydration (water content of the corneocytes at the Stratum Corneum) of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead.

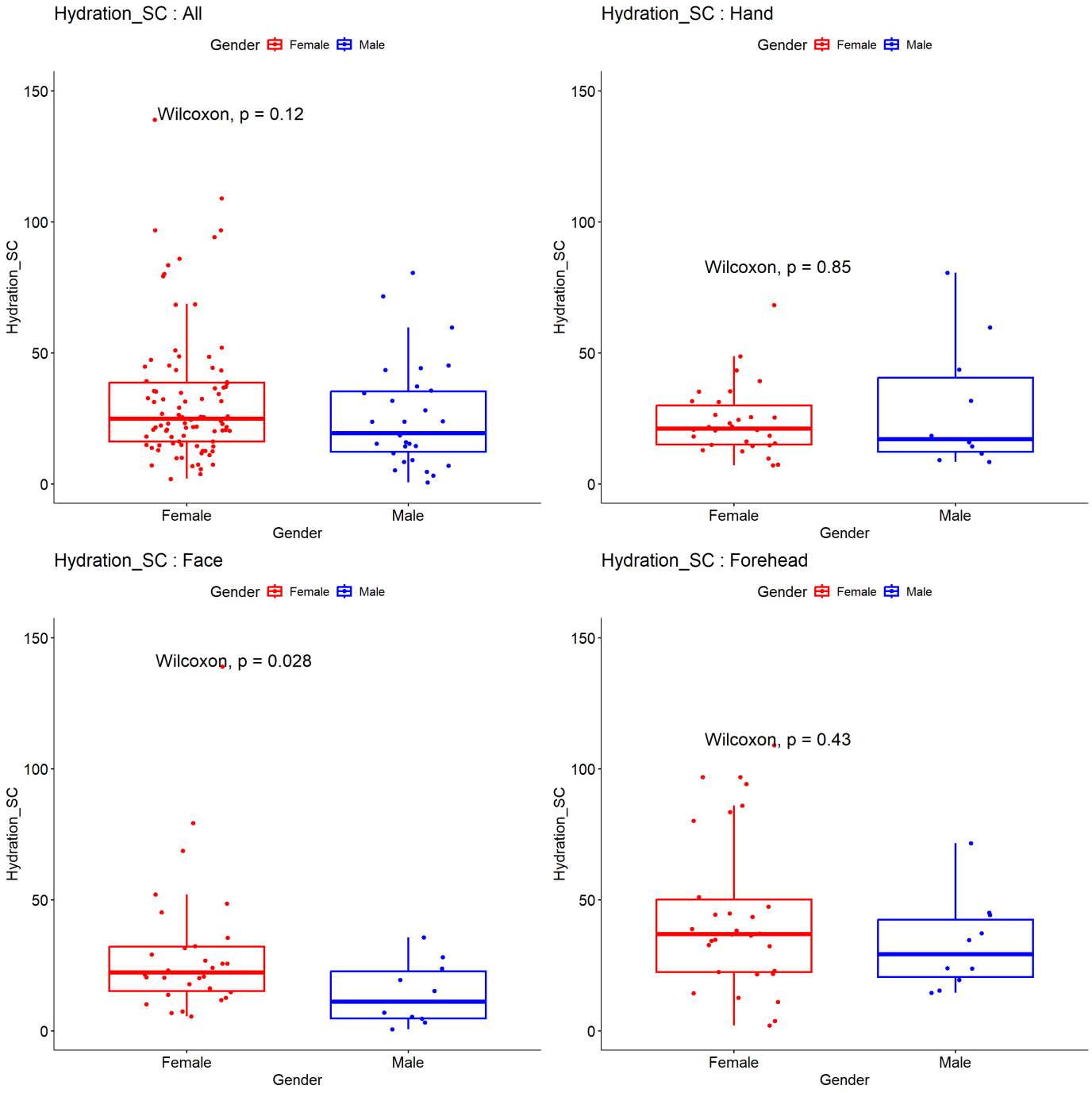


Figure S8. Comparison of age groups for the skin surface hydration (water content of the corneocytes at the Stratum Corneum) of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead.

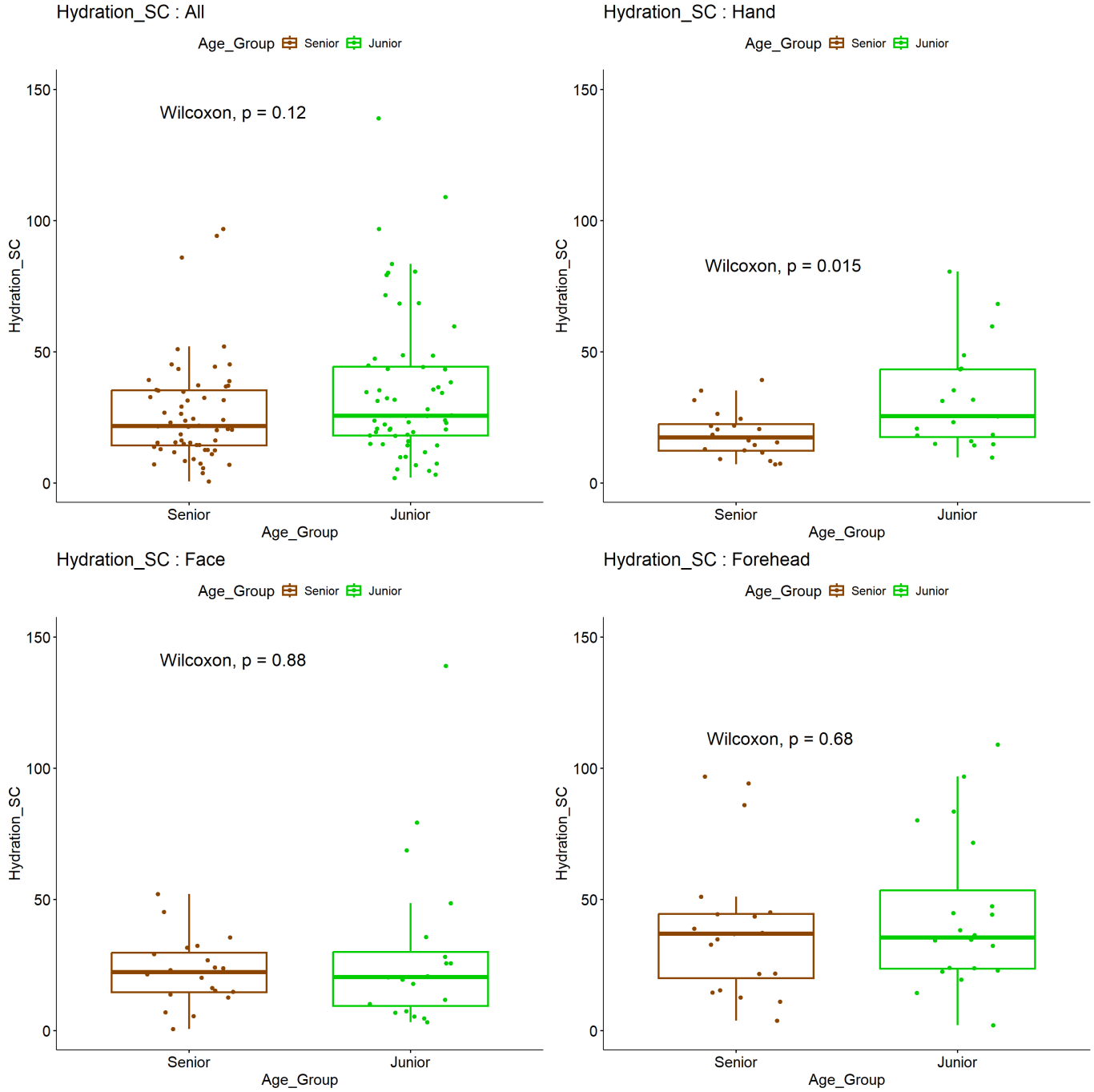


Figure S9. Comparison of gender groups for the hydration of the viable epidermis of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead.

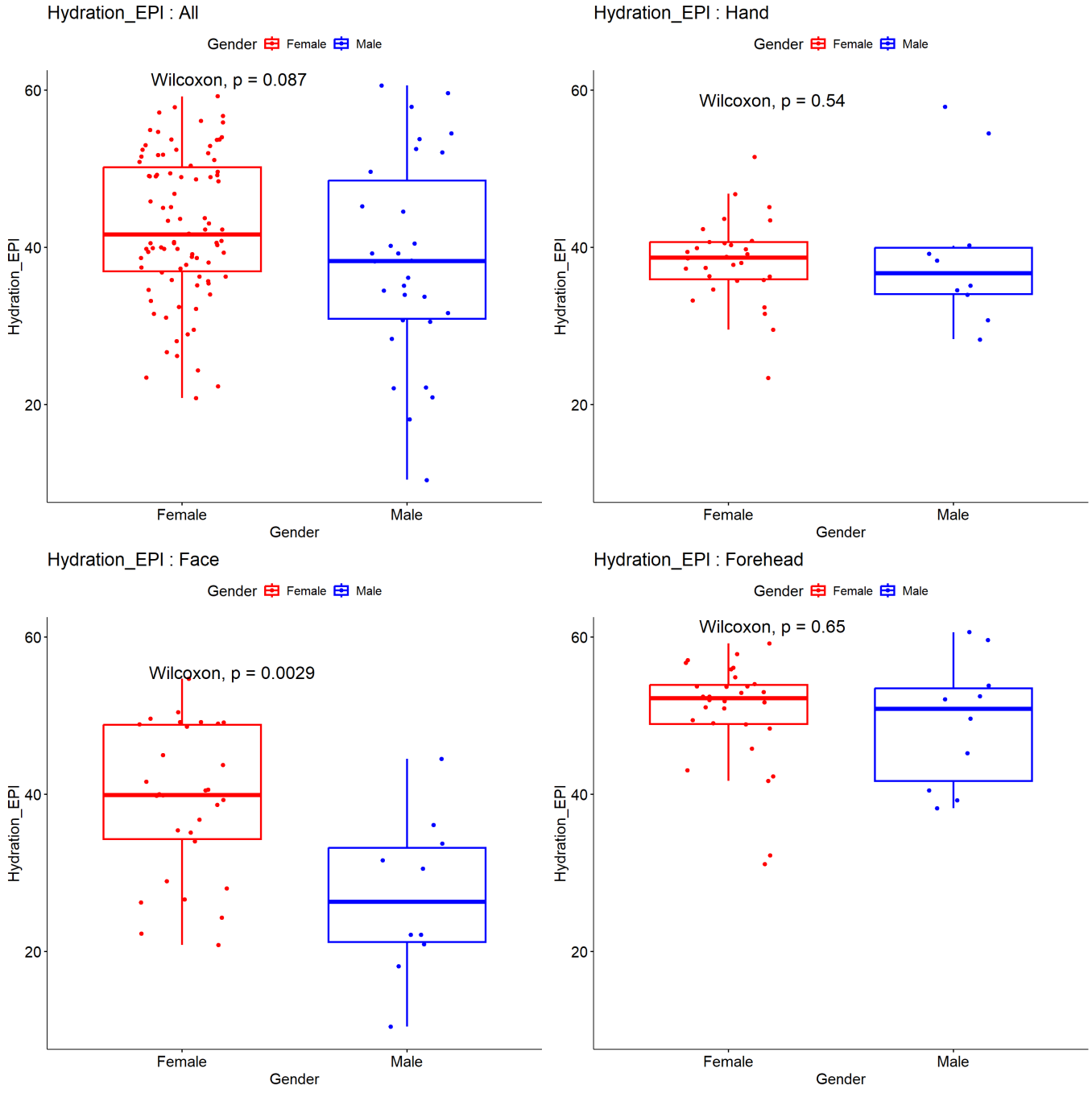


Figure S10. Comparison of age groups for the hydration of the viable epidermis of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead.

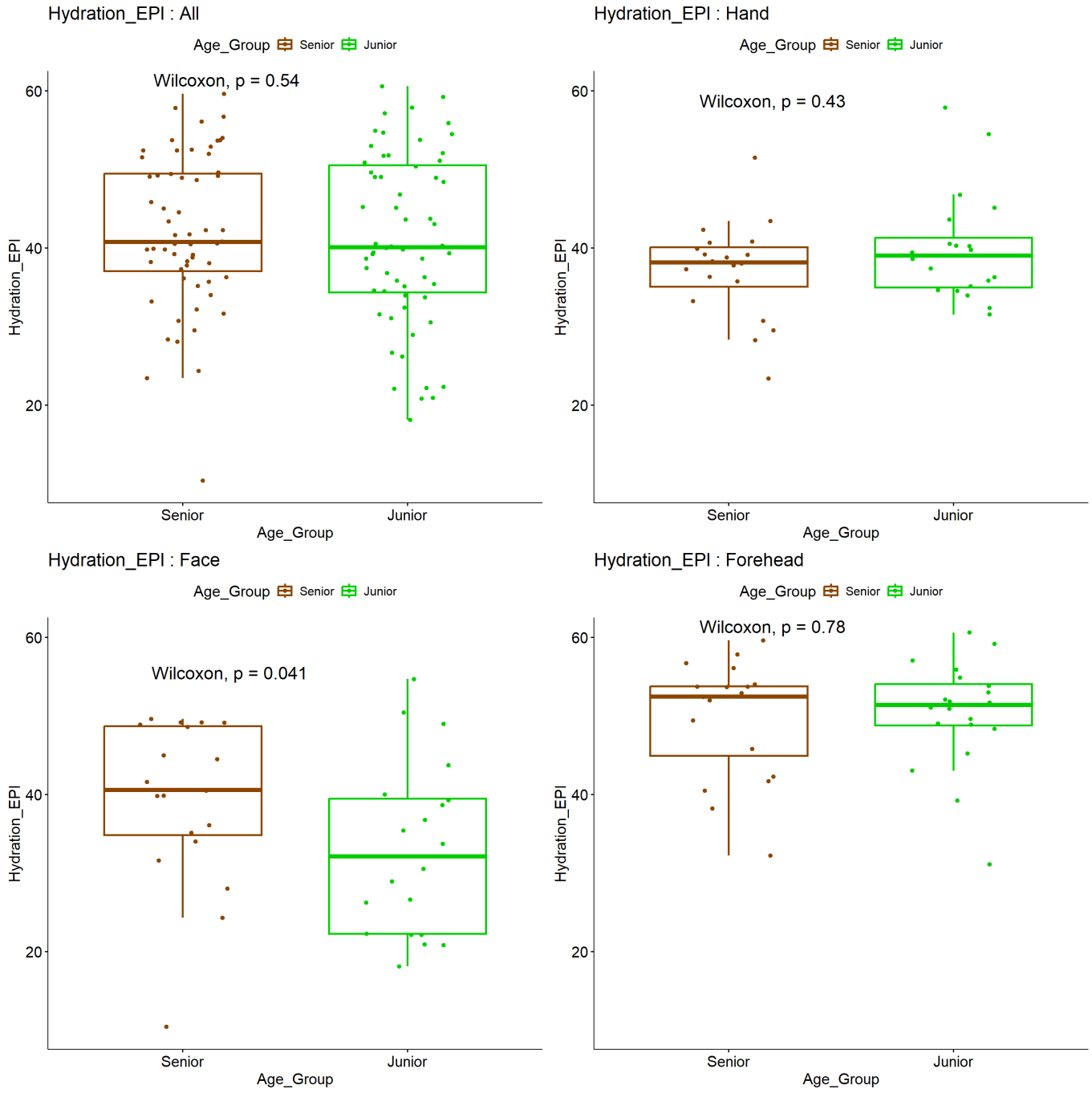


Figure S11. Comparison of gender groups for the barrier function (TEWL) of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead.

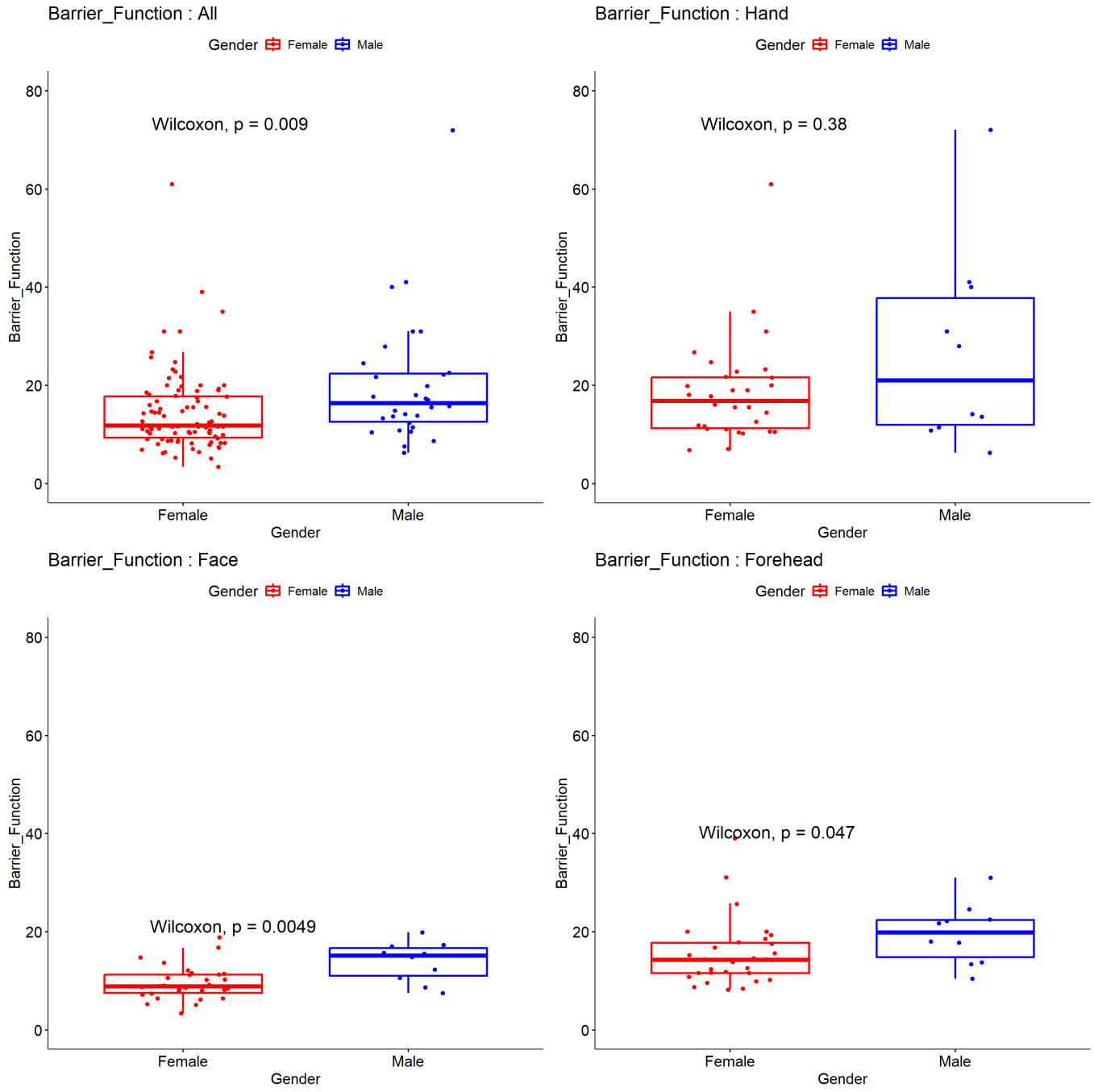


Figure S12. Comparison of age groups for the barrier function (TEWL) of the skin on different anatomical regions. A: all regions together, B: hand, C: face, D: forehead.

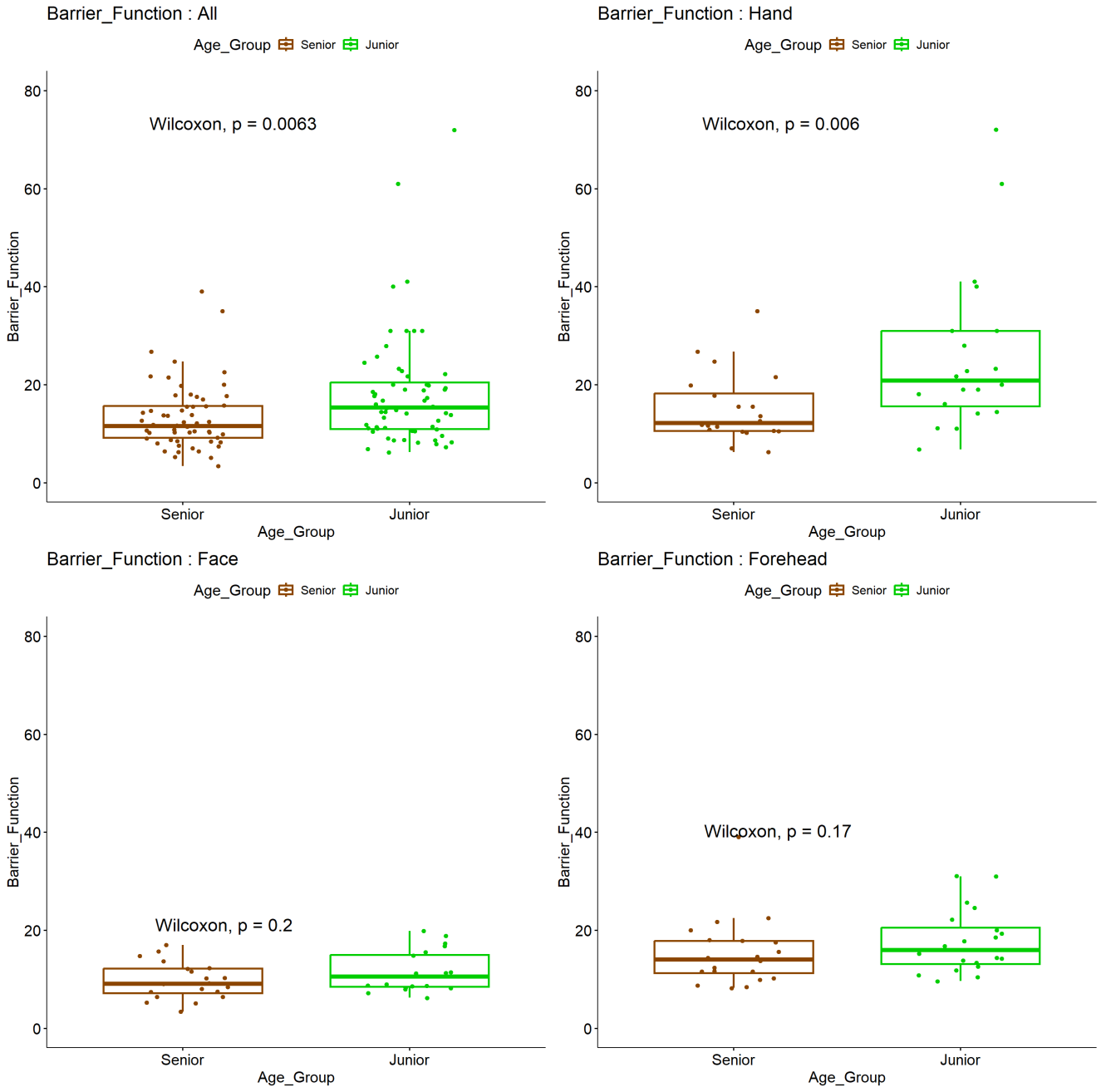


Figure S13. Comparison of gender groups for the skin surface pH values on the hand skin.

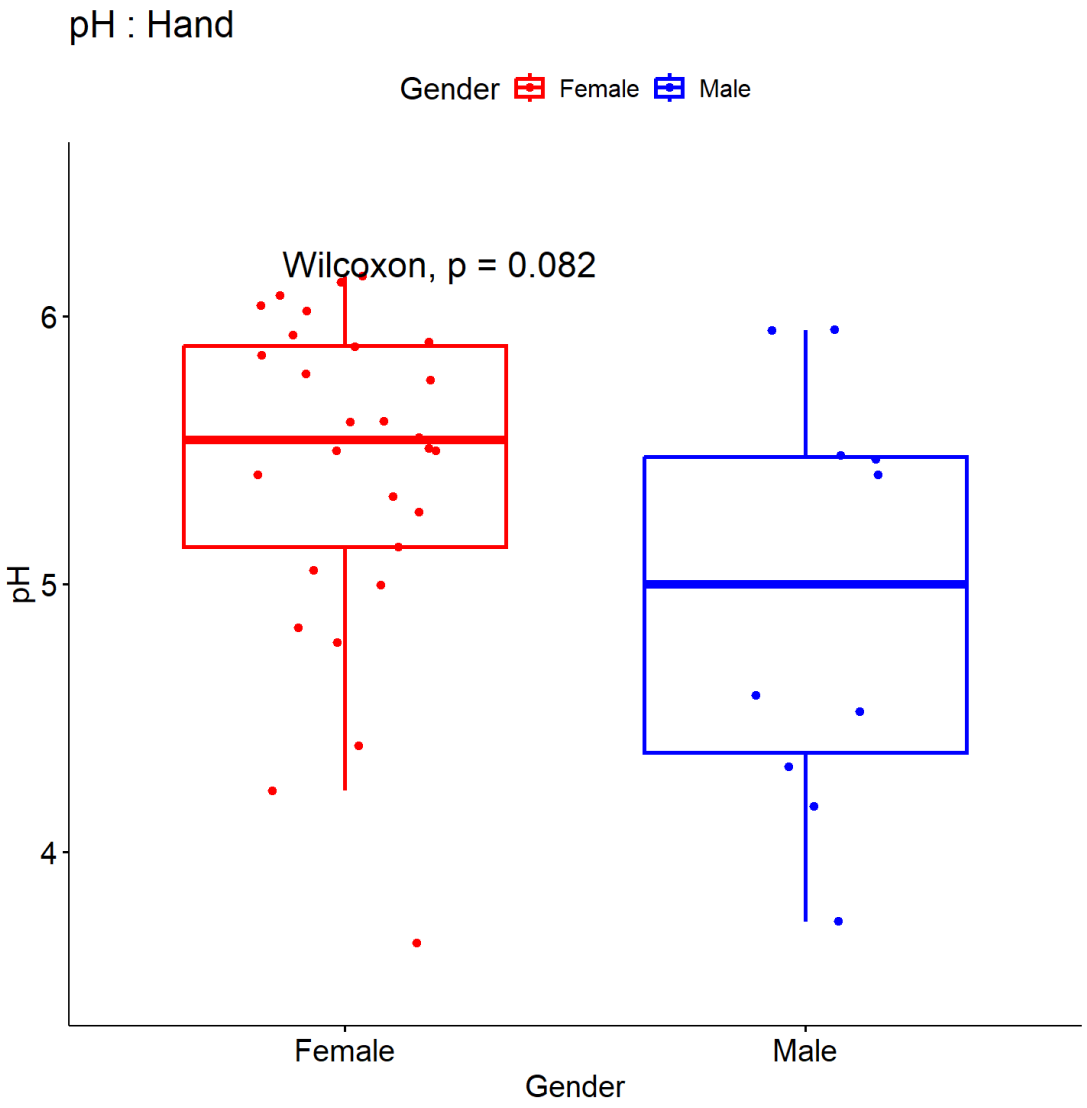


Figure S14. Comparison of age groups for the skin surface pH values on the hand skin.

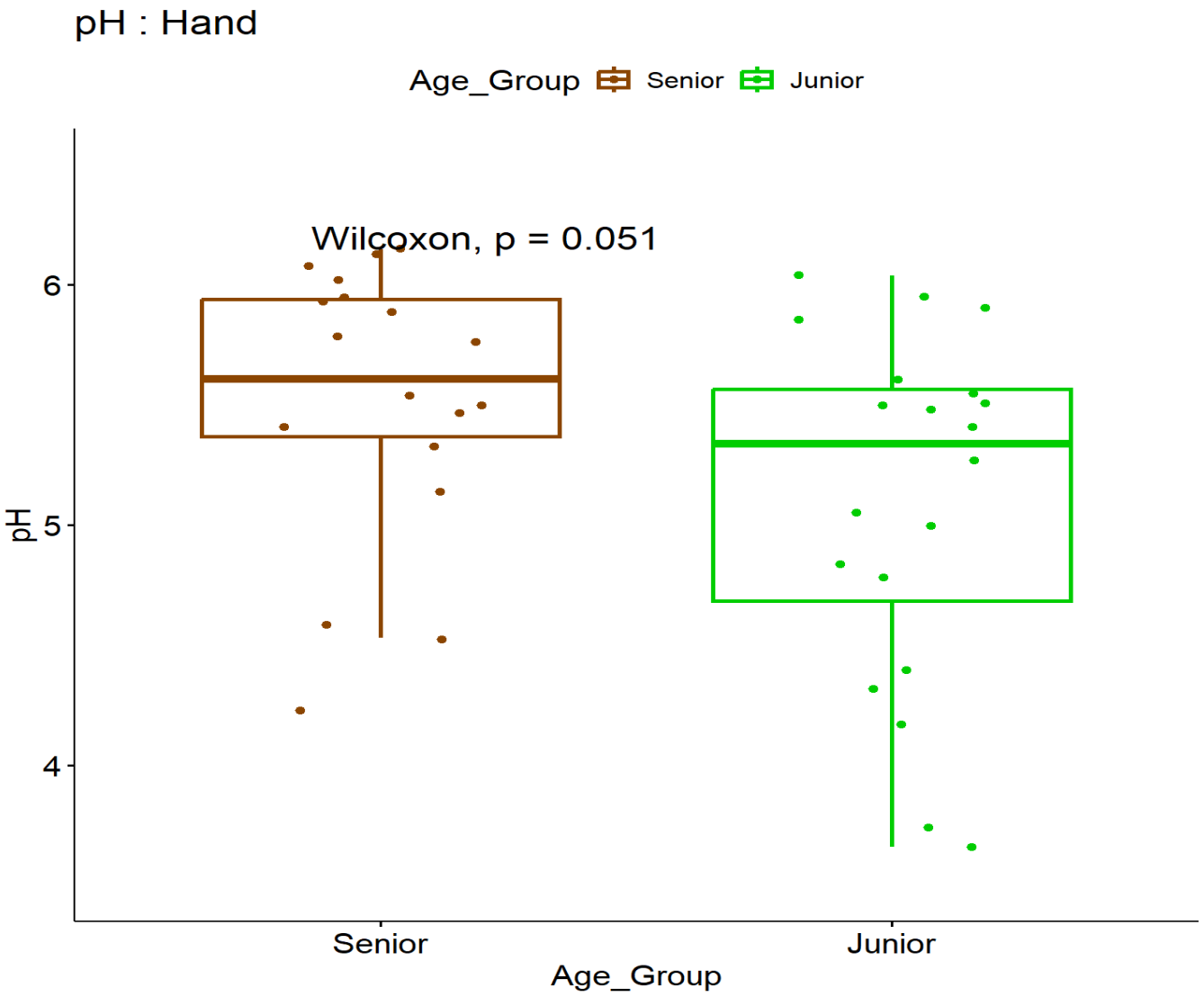
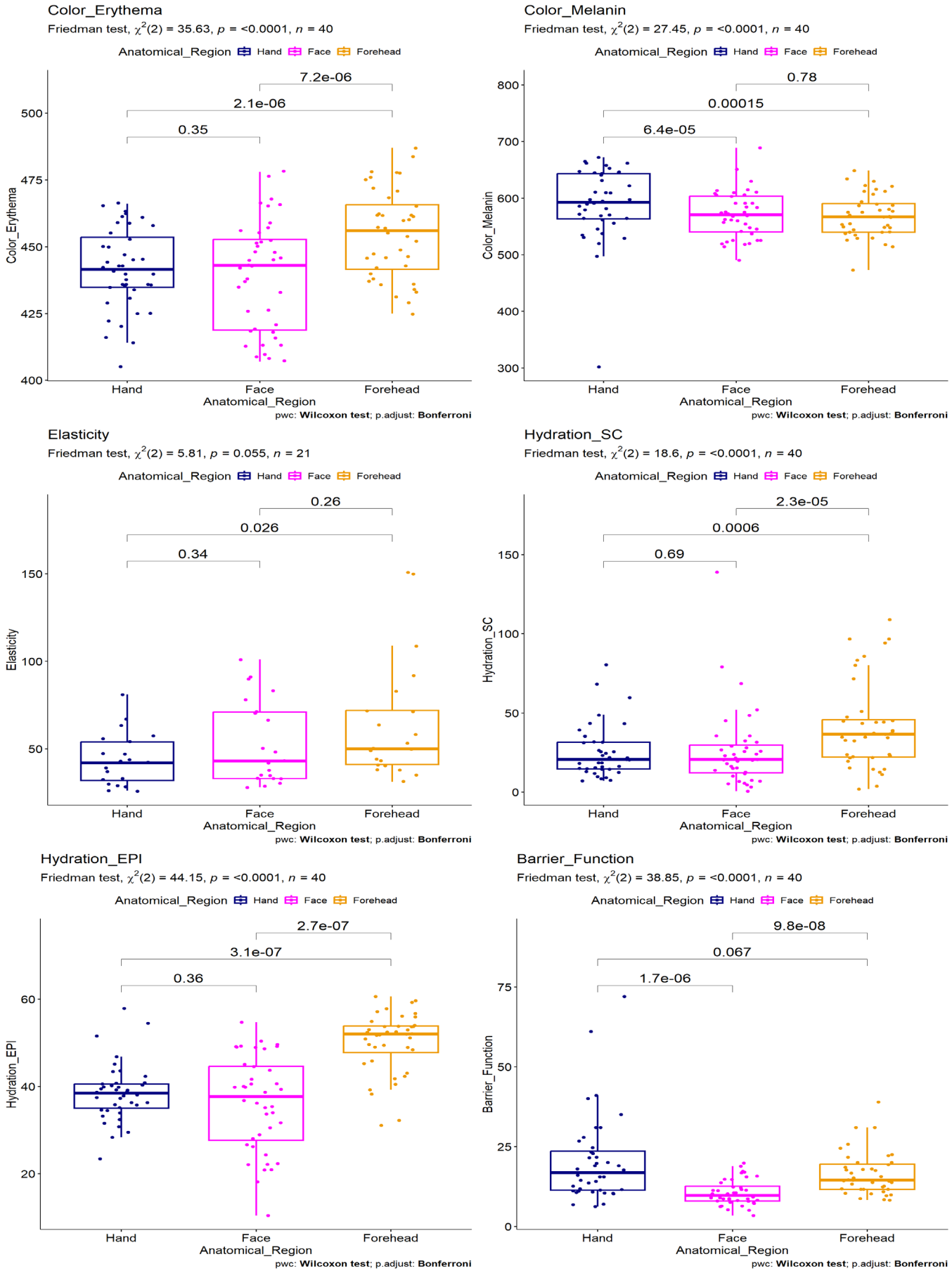


Figure S15. Comparison of anatomical regions (hand, face, forehead) for on different skin parameters (color-erythema, color-melanin, elasticity, skin surface hydration, skin deep layer hydration, barrier function) paired by the participants. Adjusted p-value threshold=0.0167 for pairwise comparisons.



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