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EFFECT OF SEASONAL CHANGE ON THE BIOMECHANICAL AND PHYSICAL PROPERTIES OF THE HUMAN SKIN

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Abstract:

In this study, the effect of one cycle of winter to summer seasonal transition on the mechanical and physical properties of skin was investigated *in vivo*. Fourteen healthy skin volunteers aged between 22 and 42 years were studied at the volar lower and upper arms. The findings indicate a 22.15% and 34.29% decrease in trans-epidermal water loss (TEWL) and the average epidermal roughness (AER), respectively. Also, improved skin properties were observed such as a 25.48% rise in average epidermal hydration (AEH), 22.59% in skin thickness, 38.64% and 21.92% in melanin and redness, respectively, as well as an 8.25% rise in its firmness and 23.14% in elasticity when strained with axial deformations. An inverse correlation was established between TEWL and AEH with a linear relationship between stratum corneum roughness versus TEWL as well as thickness and hydration. Also, the skin firmness exhibited a direct proportionality with TEWL and an inverse correlation with skin hydration where these relationships were stronger in summer than in winter. Furthermore, time-dependent results demonstrated three-staged elastic, viscoelastic and creep deformations with high, moderate and low strain rates respectively at both anatomical locations. The winter season displayed lower skin firmness and elasticity of 0.37mm and 0.04mm compared to 0.40mm and 0.06mm in summer accordingly. Anatomically, the two arm regions displayed different results with the upper arm having more consistent results than the lower arm. These results will find relevance in sensor skins and exoskeletons in Medicare, robotic and military technologies as well as innovations in cosmetics and dermatology.

Keywords: Skin; Biomechanics; Seasons; TEWL; Hydration; Viscoelasticity;

1. Introduction

Skin conditions such as eczema, acne, rosacea, psoriasis, melanoma and contact dermatitis not only have cosmetic effects but can also impose a psychological impact on patients, psychosocial discomfort and cross-contamination hazards to clinicians, caregivers, family and friends. Financially, an economic burden of more than three million primary care hours and about £723m a year on the NHS were reported on skin conditions as of 2018. Apart from patients' health, skin diseases became the 4th non-fatal global burden stated in "years lost in disability" in 2010 and the 9th in 2017. Economically in Europe, patients with skin diseases cost €5bn annually due to a 30% fall in occupational productivity. Also, 30% of skin disease patients have remarkable levels of psychological problems including social isolation, nervousness, anger, stress, depression, shame, low self-esteem, public embarrassment and impact on their sexual and career choices. Apart from personal lifestyle, social functioning and relationships, skin conditions also affect one's mental fitness [1-3]. Psycho dermatological findings show that 3% of dermatology patients live with a primary psychiatric disorder, while 85% of them expresses psychosocial comorbidities that influence their risks of depression, suicidal ideation, anxiety, career and leisure selections [4-6]. Most of these dermal disorders can be linked to the skin properties like hydration, stiffness, thickness, roughness and TEWL. Typically, with TEWL as an indicator of skin barrier function [7], it has been reported [7-8] that patients with atopic dermatitis (AD) struggle with skin barrier dysfunction. Hence, these skin properties deserve the ongoing dermatological attention of the global research community.

To avoid further animal tests in empirical investigations, non-invasive apparatus for cutaneous *in vivo* assessments has been developed [14] which this study used to measure the effects of this seasonal change on the biomechanical properties of the human skin. Properties studied include trans-epidermal water loss (TEWL), thickness and roughness of the skin as well as skin stiffness and recovery from axial deformations. In line with the hypothesis from [14] that environmental exposure can alter skin properties, biophysical properties like hydration and pigmentation were also investigated with their statistical correlations considered.

Seasonality of skin conditions has been a global epidemiological concern with 54% of UK residents suffering from the extremes of summer and winter ambient conditions [5, 9] as the majority of skin diseases are known to break out at specific times of the year. Through these climatic changes, the extreme temperature and relative humidity changes activate skin diseases and exacerbate existing ones, a situation that does not spare any gender nor age including newborn babies. Consequently, it causes underlying skin conditions like acne, atopic dermatitis, psoriasis, senile xerosis, dandruff and other skin conditions that defy most moisturising creams. Also, ultraviolet-B (UVB) radiation exposure has been identified as a major factor in influencing cutaneous properties [10] making different anatomical locations of the skin respond differently to seasonal variations. UVB radiation in moderation is good for human wellbeing, both in vitamin D and pineal gland tryptamine, but excessive exposure triggers unpleasant skin conditions. Mutagenic effects on DNA resulting in photocarcinogenesis, photo-ageing, hyper-pigmentation and photosensitive drug reactions like photodermatitis and photoallergic conditions [11-13] are common effects of this radiation. As the cold and dry winter causes eczema to flare, the hot and humid summer aggravates acne. These show that skin conditions vary with season with this study focussing on the effects on the skin's biomechanical and biophysical properties. Although several studies have been conducted on several skin-related issues, dermal adaptations to seasonal changes as well as their impact on skin properties have not received due considerations. Based on this, this study aims at findings that will provide a wealth of knowledge and dermal recommendations that will extend the bounds of patients' management, healthcare policymaking, science and technology.

2. Materials and Methods

2.1 Volunteers

Measurements were performed *in vivo* on fourteen male volunteers aged between 22 and 42 years living in Sheffield, the United Kingdom, on the bare skin of the volar forearm and upper arm at two-thirds from the cubital fossa. This study chooses the arm region due to its higher degree of regular environmental exposure in addition to the fair distribution of skin layers over the forehead as another freely exposed skin. Furthermore, the volar forearm was preferred due to its lower hair density relative to the dorsal forearm. The assessments were performed in the winter (from 22nd to 26th January 2018) and summer (11th to 15th June 2018) on the same participants with laboratory ambient conditions at 20±0.62°C temperature and 36±7% relative humidity. The volunteers had an average weight of 74.07 kg ± 14.06 kg SD and height of 1.76 m ± 0.02 m SD giving a BMI (body mass index, that is, weight/height) of 23.9 and were grouped into Fitzpatrick skin type III and IV as used in [10]. The exclusion criteria comprised people with their epidermis engraved with tattoos, people with scars, skin diseases, vitiligo (uneven skin pigmentation) and volunteers on medications that can interfere with results. Ethical approval for the study was obtained from The University of Sheffield research ethics committee with research ethics number 007424 as a continuation of a postgraduate study [15].

2.2 Measurement Techniques Used

Skin sites measured were first acclimatised to the laboratory ambient conditions for 15 minutes before dense hairs were trimmed off. The measured sites were then cleaned with alcoholic wipes to get rid of contaminants and left for 10 minutes. The forearm was then relaxed at 120° to the upper arm on a vacuum pillow ready for measurement. A VivoSight OCT (Optical Coherence Tomography), from Michelson Diagnostics Ltd, Orpington, Kent, UK, at a resolution of 10 µm connected to a suction device was used to capture 50 subsurface images for measuring the skin thickness and roughness. These images of area 6 mm by 6 mm at the two sites were up to 2 mm below the surface of the skin to exclude the interference with deeper layers of the skin like blood vessels. This measurement was carried out under extended (suction) and relaxed (no suction) conditions within 6 seconds to avoid time-dependent skin deformations in line with the ethical provisions of this study. The epidermal hydration was measured with a Corneometer CM 825 (Courage & Khazaka Electronic GmbH, Cologne, Germany) using a 2mm Ø aperture circular probe with a 49mm^2 measuring area to a technical accuracy of ±3%. Likewise, melanin and redness indices were measured with a Mexameter (Courage & Khazaka Electronic GmbH, Cologne, Germany) to a technical accuracy of ±5% from a 2mm Ø aperture circular probe within

19.6mm^2 measuring area. Also, the skin stiffness and recovery were measured during a 400 mbar negative pressure loading and unloading of MPA 580 Cutometer (Courage & Khazaka Electronic GmbH, Cologne, Germany). This device with a circular probe of 4 mm Ø (diameter) and 4.52cm^2 measuring area (Dimensions: 10.7 cm x Ø 2.4 cm) measures to $\pm$3% technical accuracy. Finally, Trans-epidermal water loss (TEWL) was measured using a closed chamber Biox Model AF200 Aquaflux (Biox Systems Ltd., London, UK) with a sensitivity of <0.07g/m^2/h. This sequence was followed because thickness, roughness and hydration are skin conditions that can change quickly than trans-epidermal water loss. This order of measurement is strongly believed to affect the results hence a time gap of 5 minutes between successive measurements was followed to reduce any impact. Furthermore, a structured questionnaire was administered to all volunteers to ascertain their Fitzpatrick skin types. This experimental protocol was in line with previous studies [7, 8, 15, 16] and was designed to achieve the objectives of the study. As previously stated, the interaction of the skin with seasonal variations depends on the level of exposure of anatomical regions. Based on this, a comparative analysis of the effect of seasonal change on mechanical properties of the skin was studied at two volar arm locations: the lower arm and the upper arm.

2.3 Image and Statistical Analysis

Images were extracted from the OCT files using ImageJ software from which the skin roughness and thickness were analysed using a MatLab algorithm developed in a previous study [16]. With the algorithm, two layers were identified: the yellow (stratum corneum) and the green (dermal-epidermal junction) in figure 1. The distance between yellow and green lines were indications of epidermal thickness. The MatLab algorithm was also used to analyse skin surface.

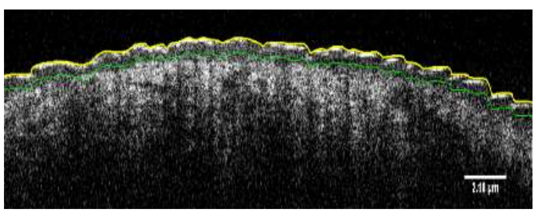

Figure 1: Skin thickness and roughness: dermal-epidermal junction boundaries (skin thickness)

Statistical analysis was performed using GraphPrism Version 7.04 (GraphPad Software Inc, San Diego, CA, USA). Clinical scores of the parameters were analysed using means, standard deviations and 99% confidence intervals. D'Agostino & Pearson test was used to run a Normality test before statistical analysis to ascertain the suitable tool to be used. As most data were normally distributed while some were not, both parametric (t-test and ANOVA) and non-parametric (box plot) statistical techniques were used in data analysis. The data were compared by expressing the correlation between seasonal change and the skin's biomechanical properties at a 95% statistical confidence level with p-values less or equal to 0.05 considered as statistically significant.

3. Results

3.1 Average Trans-Epidermal Water Loss

Under laboratory conditions of 20±0.62°C temperature and 36±7%) relative humidity, the ambient temperatures in winter and summer were 3±2°C and 20±2°C respectively, with 87% and 73% relative humidity. Results in figure 2a indicate that at the volar forearm, the average TEWL decreased from 16.53 $g/m^2/h$ (±1.41 $g/m^2/h$) in winter to 14.10 $g/m^2/h$ (±4.11 $g/m^2/h$) in summer, showing a 14.70% reduction in TEWL due to seasonal change from winter to summer. Similarly, at the upper arm, the average TEWL decreased from 15.71 $g/m^2/h$ (±1.96 $g/m^2/h$) in winter to 12.23 $g/m^2/h$ (±2.38 $g/m^2/h$) in summer, showing a 22.15% reduction in TEWL due to seasonal change from winter to summer. This shows that seasonal change from winter to summer had a significant difference at the upper arm (P=0.0041, 99% C.I.= -6.500 to -0.4588 and R^2=0.4808) with no significant effect at the lower arm (P=0.0640, 99% C.I.= -6.029 to 1.183 and R^2=0.2396) where P is the calculated probability, C.I is the confidence interval and R is the goodness-of-fit to the regression line respectively. However, there was no significant difference at the lower arm within the two seasons (P=0.0640, 99% C.I.= -6.029 to 1.183 and R^2=0.2396). Also, there was no significant difference (P=0.0750, 99% C.I.= -1.723 to 0.09456 and R^2=0.2237) between the two skin sites tested in winter but a significant difference (P=0.0197, 99% C.I.= -3.391 to -0.3507 and R^2=0.3522) between the skin sites tested in summer. Also, ANOVA results showed a significant difference (P=0.0004, R^2=0.2904) between the skin sites when compared between the two seasons.

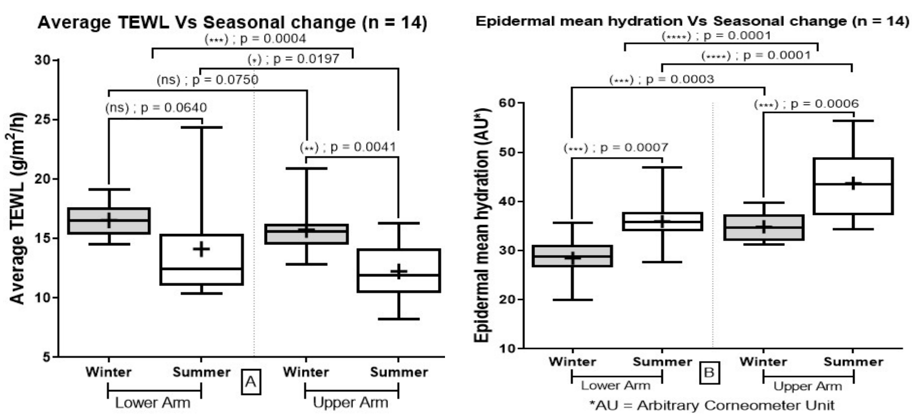

Figure 2: Average epidermal (a) TEWL (n=14) (b) Hydration (n=14)

3.2 Average Epidermal Hydration

From figure 2b, a significant difference (P=0.0007, 99% C.I.= 2.376 to 12.60 and R^2=0.5996) was observed on the average epidermal hydration (AEH) due to seasonal change at the volar forearm. This led to a 26.32% rise in AEH as a result of the 28.46 (±3.71 SD) to 35.95 (±4.30 SD) rise in arbitrary corneometer units (ACU) from winter to summer. Likewise, at the upper arm, a 25.48% rise in AEH observed when the ACU increased from 34.85 (±3.01 SD) in winter to 43.73 (±6.66 SD) in summer reveals another significant difference (P=0.0006, 99% C.I.= 2.896 to 14.86 and

R^2=0.6058) of seasonal change on the skin. In addition, comparison between the two anatomical locations showed remarkable differences (P=0.0003, 99% C.I.= 3.518 to 9.249 and R^2=0.6405 between lower and upper arm regions in winter and P=0.0001, 99% C.I.= 4.828 to 10.73 and R^2=0.7140 between lower and upper arm regions in summer) indicating that the effect of seasonal change depends on the part of the body studied. Also, ANOVA results showed a significant difference (P=0.0001, R^2=0.5968) between the skin sites when compared between the two seasons.

3.3 Average Epidermal thickness and roughness

At the lower arm, (figure 3a), winter to summer transition led to a 22.73% (93.20 μm (±9.90 μm SD) to 114.38 μm (±9.24 μm SD) rise in the average epidermal thickness (AET) at the lower arm ($p<0.0006$, 99% C.I.= 11.53 to 30.83 and R^2=0.7938). Likewise, a 22.59% increase in the AET was observed at the upper arm due to a significant rise ($p<0.0001$, 99% C.I.= 14.74 to 28.34 and R^2=0.8891) from 95.36 μm (±10.23 μm SD) to 116.90 μm (±11.72 μm SD) from winter to summer. However, in figure 3b, the average epidermal roughness (AER) dropped significantly ($p<0.0007$, 99% C.I.= -4.518 to -1.644 and R^2=0.7860) from 6.42 μm (±1.74 μm SD) to 3.34 μm (±1.71 μm SD), a 23.65% AER decrease due to winter to summer transition, similar to the upper arm's 34.29% fall ($p<0.0002$, 99% C.I.= -4.960 to -2.221 and R^2=0.8459) in AER as a result of reduction from 5.97 μm (±1.66 μm SD) to 2.38 μm (±0.26 μm SD) from winter to summer. ANOVA results showed significant differences of (P=0.0001, R^2=0.5537) and (P=0.0001, R^2=0.6031) for thickness and roughness respectively between the skin sites when compared between the two seasons.

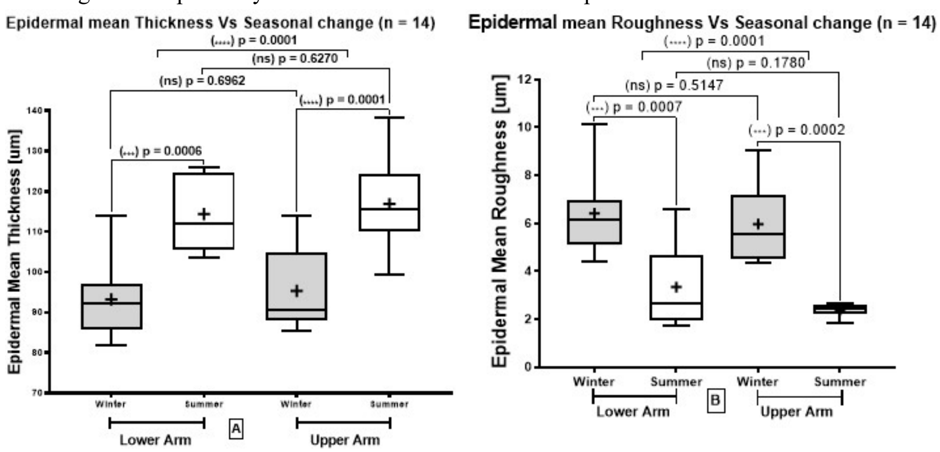

Figure 3: Epidermal average (a) Roughness (n=14) (b) Thickness (n=14)

3.4 Average Melanin and Redness Indices

Lower arm results in figure 4 indicate that seasonal change from winter to summer caused a significant increase in average melanin index (AMI) by 59.11% due to a rise from 139.98 to 222.72 arbitrary mexameter units. Similarly, the upper arm had an AMI increase of 38.64% as a result of a rise from 144.57 to 200.43 arbitrary mexameter units. Also, at the lower arm, the winter-summer transition increased the average erythema index (AEI) by 27.06% due to a rise from 232.95 to 295.98 arbitrary mexameter units. In addition, the upper arm had a 21.92% rise in AEI because of the rise from 226.83 to 276.55 arbitrary mexameter units.

Hence, seasonal change from winter to summer was observed to increase both melanin and redness indices at the lower arm with significant differences of (p=0.0001, 99% C.I.= 51.11 to 114.4 and R^2=0.8730) and (p=0.0001, 99% C.I.= 44.67 to 81.40 and R^2=0.9221), respectively. Similarly, the seasonal change increased both indices at the upper arm with significant differences of (p = 0.0130, 99% C.I.= -2.893 to 114.6 and R^2=0.4759) and (p = 0.0060, 99% C.I.= 4.291 to 95.16 and R^2=0.5461) for melanin and redness, respectively. These statistical differences and percentage increases indicate that seasonal change affects the lower arm more than the upper arm. ANOVA results showed significant differences of (P=0.0003, R^2=0.3760) and (P=0.0001, R^2=0.4142) for melanin and redness indices respectively between the skin sites compared between the seasons.

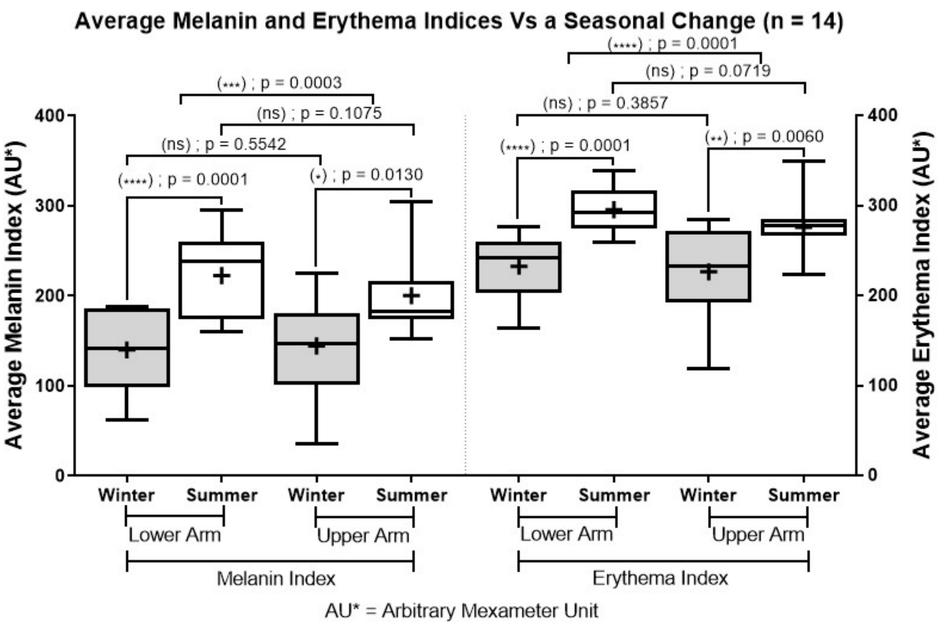

Figure 4: Average melanin and redness indices

3.5 Cutometer Results: Stiffness (R0), Recovery (R1), Viscoelasticity, Elastic and Creep Deformations.

From figure 5a, cutometer results indicate an 8.25% rise in skin firmness (R0 values) from 0.3673 mm to 0.3976 mm due to seasonal change from winter to summer at the upper arm. At the lower arm, a negligible change (1.56% fall in stiffness) from 0.3085 mm to 0.3037 mm drop in stiffness from winter to summer was observed. In addition, seasonal change from winter to summer demonstrated a rise of R1 values from 0.0446 mm to 0.0594 mm leading to a 33.18% rise in skin elasticity at the lower arm with 23.14% (0.0471 mm to 0.0580 mm) at the upper arm.

Statistically, there was a significant difference (p=0.0489, 95% C.I.= 0.0021 to 0.0499 and R^2=0.0058) due to the seasonal transition at the upper arm with no significant difference (p=0.9098, 95% C.I.= -0.0095 to 0.0223 and R^2=0.0008) at the lower arm. Also, ANOVA results showed a significant difference between the seasons and anatomical locations (P=0.0001, R^2=0.0241).

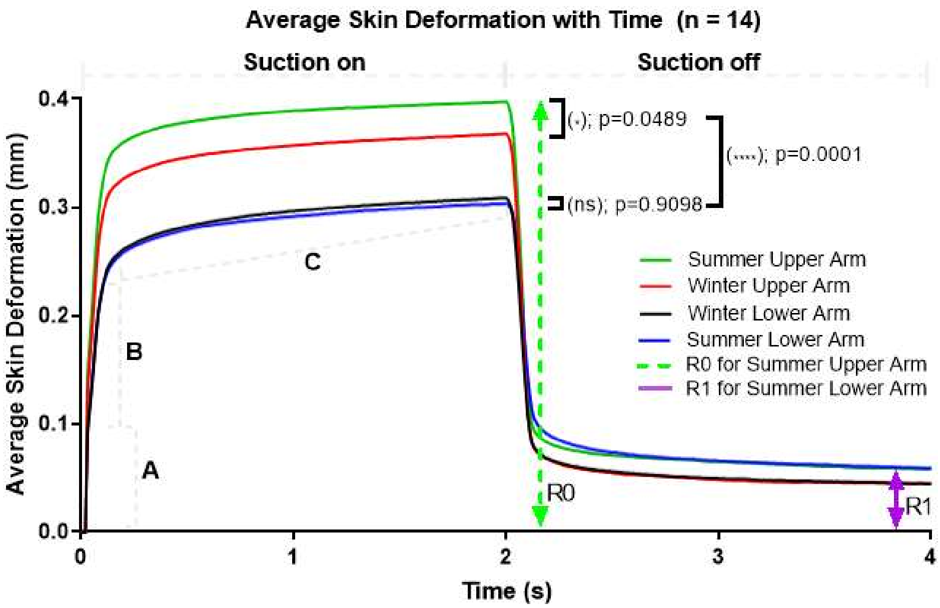

Figure 5: Skin firmness (R0) and recovery (R1)

In addition, figure 5 indicates a three-staged strain history (elastic deformation region A, viscoelastic region B and creep region C) of the skin under the seasonal effect investigated. It can be noticed that region A is associated with high strain rates of 3.01mm/s and 3.15mm/s at the lower arm in winter and summer respectively while 4.34mm/s and 4.78mm/s at the upper arm in winter and summer accordingly. Likewise, region B demonstrated moderate strain rates of 2.11mm/s and 2.14mm/s at the lower arm in winter and summer respectively while 2.73mm/s and 3.01mm/s at the upper arm in winter and summer accordingly. However, region C is seen to display low strain rates of 0.15mm/s at the lower arm in both winter and summer with 0.18mm/s and 0.19mm/s at the upper arm in winter and summer accordingly.

Interestingly, figure 6 demonstrates the correlation between the skin firmness (R0) and biomechanical properties like TEWL and skin hydration in summer represented by the upper arm.

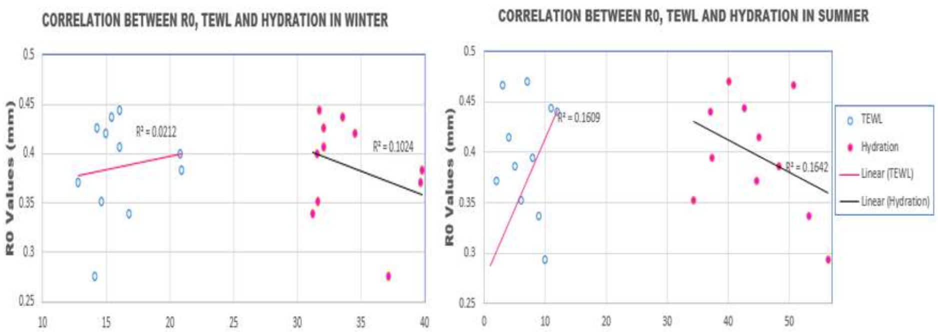

Figure 6: Correlation between R0, TEWL and Hydration at the upper arm in (a) Winter (a) Summer

Another remarkable result is the correlation between skin elasticity (R1) and both TEWL and Hydration as biomechanical properties of the skin represented by the upper arm in summer as shown in figure 7.

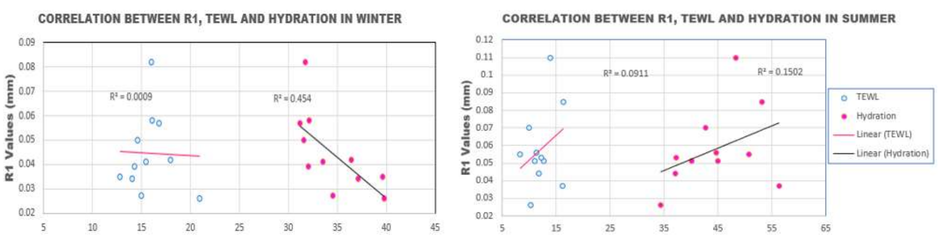

Figure 7: Correlation between R1, TEWL and Hydration at the upper arm in (a) Winter (a) Summer

4. Discussion

Results from the study of biomechanical properties of the human skin have found significant applicability in several industries. In this study, the effect of seasonal change on biomechanical and physical skin properties have been investigated at two anatomical locations. The 22.15% drop in TEWL (reduction by 3.48 $g/m^2/h$) due to seasonal change from winter to summer at the upper arm is in line with the previous study [17]. The decreased TEWL in this study due to winter to summer transition can be linked to the effect of higher relative humidity (RH) in summer on the skin. Increased RH leads to a moist and warm condition that lowers skin pH, increases sebum and sweat secretion and consequently improves both amino acid secretion and filaggrin gene mutations. These are vital factors in lipid metabolism for intercellular water-retention and terminal epidermal differentiation as supported by existing literature [13, 24-27] which suggest that higher RH decreases cutaneous TEWL. This is also in line with Brandon and co-authors [20] where premature infants born before 33 weeks who were cared for in higher humidity recorded significantly reduced TEWL. This shows that reduced TEWL in high RH is not restricted to youthful ages as recorded in this study since clinical reductions in TEWL have been observed in other ages. For instance, 6.80$g/m^2/h$ reduction in TEWL of neonates in [18] during coconut oil application likewise a novel approach to infants' eczema and atopic disease controls in [19-22]. Likewise, in adults, marginal reductions in TEWL, [8], to reduce the risk of relapse future of eczema by 33% through skin barrier strengthening using urea moisturizer has been reported. Similarly, a reduction in TEWL in [23] due to the application of a semipermeable membrane and changes in TEWL due to a negative emollient in [7] has also been presented. In addition, the insignificant effects on the lower arm can be attributed to its more exposure to other factors like ultraviolet-B (UVB) radiation than the upper arm that is regularly covered by clothes. Hence, previous findings [10-17], suggest increasing the effect of TEWL due to UVB radiation exposure. This has been linked to the influence of UV radiation in altering several skin conditions like epidermal calcium distribution pattern, decrease in epidermal differentiation proteins such as filaggrin. This is also responsible for the reduction of secretion and structural arrangement of lipids, especially the covalently bound ceramide within the stratum corneum intercellular spaces which are responsible for TEWL in [28-31]. Though the effect of UVB radiation was not extensively investigated in our present study, it will be considered in subsequent ones.

According to the literature, the low relative humidity and temperature in winter are known for depleting the stratum corneum intercellular hydrophobic lipids, osmolytic intracellular fatty acids and ceramide levels. These limit the trapping of unbound water (water that is not directly linked to the stratum corneum components). These also delay the generation of natural moisturising factors (NMFs) that reduce the rate of dehydration which improves from winter to summer as indicated in several studies [24, 27, 32-38]. Furthermore, most of these authors show that the mechanism of stratum corneum hydration is osmotic-gradient triggered such that in the presence of moisture, dead hydrophilic corneocytes get swollen and their glycosyl ceramide lipids shrink along with dispersed corneodesmosomes. Hence, the dryness in winter inhibits this swelling mechanism of corneocytes resulting in reduced skin hydration but improves towards summer as supported by [17]. This aligns with the 26.32% and 25.48% rise in AEH recorded at the lower and upper arms, respectively, due to seasonal change from winter to summer.
In addition, the more hydration of the upper arm than the lower arm can be attributed to its less exposure, as earlier discussed which aligns with previous results [10, 14, 39-40]. UVB radiation that has more access to the lower arm is known to decrease both differentiation proteins and epidermal covalently bound ceramides as well as increasing skin pH. This condition causes epidermal desquamation and reduced permeability consequently reduces AEH but increases TEWL [8]. By this mechanism, our findings reveal an inverse correlation between AEH and TEWL as supported by [10, 39-43]. This is why [43] suggests that to protect against allergens and pathogens in atopic dermatitis patients, it is necessary to restore skin hydration by reducing TEWL.

Results also show that winter to summer transition caused a 22.73% and 22.59% rise in average epidermal thickness (AET) at the lower and upper arms, respectively. According to [38], the mechanism of stratum corneum hydration which is activated by osmotic gradients causes the swelling of dead hydrophilic corneocytes in the presence of moisture. This gives rise to intercellular space dilations and pouches of water called cisternae where the contention of the engrossed corneocytes with the cisternae over the available water gives rise to increased SC thickness.

Also, 23.65% and 34.29% reductions in the average epidermal roughness (AER) at the lower and upper arms were observed respectively. Previous findings [44] indicate that the proliferation of the skin barrier function through TEWL affects the skin topographical integrity, hence increases stratum corneum average roughness. Hence, our results, which align with existing findings [24, 45-48], indicate a direct link between skin roughness and TEWL while stratum corneum thickness and hydration correlate (figures 2 and 3).

Another suggestion that lower arm results were influenced by higher exposure to UVB radiation can be validated by the 59.11% rise in AMI relative to the 38.64% at the upper arm as well as 27.06% and 21.92% rise in AEI at the lower and upper arms, respectively. These can be linked to melanogenesis being a UV radiation-activated process where the mutagenic effects of sunrays are inhibited as the skin produces melanocytes to absorb and scatter incidental rays. This pigmentation which is less in winter and higher in the lower arm, aligns with existing findings [10, 33, 44, 49-53]. Reduced redness level occurs as blood supply is shunted by dilated vessels and capillaries due to the cold winter to conserve hydration. Also, the dryness in winter limits sebum secretion which facilitates the movement of desquamating cells and is also another cause of increasing TEWL in winter. The accumulation of these dead cells gives the skin a darker outlook [54] which is not melanin alone and reduces the skin vascularity (redness) as a measure of the erythema index.
The 8.12% rise in stiffness due to the summer season shows that winter reduces skin stiffness can be attributed to skin moisture content. Skin dehydration which is activated by low relative humidity in winter has been identified in other studies [27, 55-56] as the root cause of fine lines and under-eye circles. Furthermore, the increase in skin recovery with no statistical difference between the skin locations also indicates that skin recovery is hydration dependent which aligns with [56-57]. Hence, improved relative humidity in summer relative to winter induces a rise in skin hydration causing the corresponding positive effect on both firmness and elasticity of the skin.

The curves in figure 5 are typical stress-strain graphs with the stages signifying different mechanical properties due to the heterogeneous network of the skin's elastin-collagen fibrils and their responses to applied loading/unloading. The high strain rate at region A can be linked to the elastic response of elastin as load-bearing fibrils in line with [58-60]. Region B is a region of nonlinearity and viscoelasticity due to the combined effects of the end of stretched elastin fibres and the onset of collagen reorientation to the loading direction. This nonlinearity occurs as the elastin fibrils exhaust their flexibility allowing the randomly oriented collagen mesh to untangle in the direction of applied loading. Region C is another region of linearity due to the full stretching of the collagen fibres well aligned to the direction of loading. At the terminal stage, no additional deformation is allowed due to maximum stretching of the inextensible collagen fibrils before the onset of skin recovery from the applied loading. Hence, the first stage A is purely a region of linear elastic deformation, region B is the yield or transition while C is the plastic deformation region [62] before reaching the maximum (R0 values). This trend of linear-nonlinear-linear behaviour was replicated in the relaxation mode. R0 values of 0.40mm and 0.37mm for the upper arm skin in summer and winter respectively while 0.30mm at the lower arm in both seasons were recorded before the onset of relaxation (unloading). Likewise, R1 values of 0.06mm and 0.04mm were recorded in summer and winter respectively at both arm regions. The R0 value is defined as the firmness or resistance to the applied suction load which is a measure of biomechanical strength of the skin while the R1 value is the ability of the skin to return to its original position as a measure of skin elasticity. Figure 5 shows that summer had the highest firmness (0.40mm) and elastic (0.06mm) values than winter (Firmness of 0.37mm and elasticity of 0.04mm).

Our findings as shown in figure 6 reveal that skin firmness is favoured by increasing TEWL with an inverse correlation with skin hydration. This correlation of skin firmness is stronger in summer (R^2 = 0.1609 and 0.1642 for TEWL and hydration respectively) than in winter (R^2 = 0.0212 and 0.1024 for TEWL and hydration accordingly). However, the winter season demonstrated inverse correlations with both the skin TEWL and hydration while it displayed positive correlations with these properties in summer. Remarkably, winter reduces skin hydration thereby decreases its recovery from applied tension while the well-hydrated nature of the skin in summer increases skin elasticity. No permanent deformation of the tested skins was observed.

The results in this study were within the accuracies and limitations of the individual measuring instruments used in accessing properties within the skin's depth profile. For instance, the main limitations of the OCT are the lack of resolution which is less than 10µm and the short coherence length (low penetration depth) which is due to the high intensity of light scattering and absorption [62-64]. In addition, the size of the OCT machine reduces its portability. The Mexameter faces the challenges of ambient light interference and the Corneometer probe is often occlusive [64-65]. The validity of Corneometer, Mexameter, Cutometer and Biox Aquaflux results in demands that the probe is vertically placed and can be influenced by air convection, probe pressure on the skin surface and speed of measurements could also be analysed in future. Furthermore, as benchtop devices, they are restricted from certain anatomical locations/positions [64]. Subsequent studies will be conducted to quantify the effect of other factors such as ageing, ethnicity, gender, geographical location and migration which can influence the biomechanical and biophysical properties of the skin due to different seasons (Summer, Winter, Spring and Autumn). Also, further studies recruiting a higher number of volunteers with broader Fitzpatrick skin types will be considered.

5. Conclusions

The study demonstrates the effects of seasonal change on various skin biomechanical and underlying biophysical properties at two anatomical locations. Observations show that winter to summer transition decreases cutaneous TEWL but increases skin hydration indicating an inverse correlation between AEH and TEWL. Remarkably, changes from winter to summer led to a rise in both skin melanin and erythema (vascularity) indices. Also, a decline in skin roughness was observed from this seasonal change while skin thickness was observed to increase, indicating a correlation between stratum corneum roughness and TEWL as well as its thickness and hydration. Other findings include improved skin stiffness and recovery from axial deformations due to changes from winter to summer. Interestingly, the effect of winter to summer seasonal change affected the three-staged deformation history differently with a high strain rate at the elastic region,

Commented [SD1]: Is it remarkable? I suggest it is expected

Commented [SD2]: irrelevent

Commented [SD3]: rather than listing the limitations of each it would be better to provide context – exampes of how they are informative in the context of your findings.

Commented [SD4]: irrelevent

moderate strain and low strain at the viscoelastic and creep regions respectively. Generally, these effects of the seasonal change were attributed to the corresponding effect of relative humidity changes with slight deviations on the lower arm, which was believed to be exposed to other factors like UVB radiations more frequently than the upper arm tested. This suggests the upper arm to be a better anatomical location for this study than the lower arm. The data reported in this paper will be useful in designing sensor skins, exoskeletons in Medicare and humanoids in both robotic and military technologies as well as current innovations in cosmetics and dermatology. The effect of seasonal changes should be incorporated in the future for consideration of studies related to cosmetics.

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Disclosure

The authors report no conflicts of interest in this work.

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