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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 4<sup>th</sup> non-fatal global burden stated in "years lost in disability" in 2010 and the 9<sup>th</sup> 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

41 common effects of this radiation. As the cold and dry winter causes eczema to flare, the hot and  
42 humid summer aggravates acne. These show that skin conditions vary with season with this study  
43 focussing on the effects on the skin's biomechanical and biophysical properties. Although several  
44 studies have been conducted on several skin-related issues, dermal adaptations to seasonal changes  
45 as well as their impact on skin properties have not received due considerations. Based on this, this  
46 study aims at findings that will provide a wealth of knowledge and dermal recommendations that  
47 will extend the bounds of patients' management, healthcare policymaking, science and technology.

## 48 **2. Materials and Methods**

### 49 **2.1 Volunteers**

50 Measurements were performed *in vivo* on fourteen male volunteers aged between 22 and 42 years  
51 living in Sheffield, the United Kingdom, on the bare skin of the volar forearm and upper arm at  
52 two-thirds from the cubital fossa. This study chooses the arm region due to its higher degree of  
53 regular environmental exposure in addition to the fair distribution of skin layers over the forehead  
54 as another freely exposed skin. Furthermore, the volar forearm was preferred due to its lower hair  
55 density relative to the dorsal forearm. The assessments were performed in the winter (from 22<sup>nd</sup> to  
56 26<sup>th</sup> January 2018) and summer (11<sup>th</sup> to 15<sup>th</sup> June 2018) on the same participants with laboratory  
57 ambient conditions at  $20 \pm 0.62^\circ\text{C}$  temperature and  $36 \pm 7\%$  relative humidity. The volunteers had  
58 an average weight of  $74.07 \text{ kg} \pm 14.06 \text{ kg SD}$  and height of  $1.76 \text{ m} \pm 0.02 \text{ m SD}$  giving a BMI  
59 (body mass index, that is, weight/height) of 23.9 and were grouped into Fitzpatrick skin type III  
60 and IV as used in [10]. The exclusion criteria comprised people with their epidermis engraved with  
61 tattoos, people with scars, skin diseases, vitiligo (uneven skin pigmentation) and volunteers on  
62 medications that can interfere with results. Ethical approval for the study was obtained from The  
63 University of Sheffield research ethics committee with research ethics number 007424 as a  
64 continuation of a postgraduate study [15].

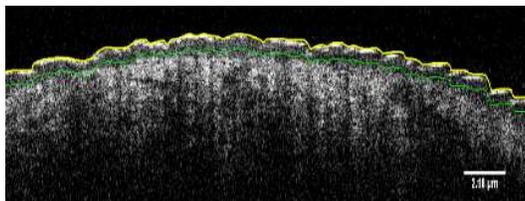
### 65 **2.2 Measurement Techniques Used**

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

81 19.6mm<sup>2</sup> measuring area. Also, the skin stiffness and recovery were measured during a 400 mbar  
82 negative pressure loading and unloading of MPA 580 Cutometer (Courage & Khazaka Electronic  
83 GmbH, Cologne, Germany). This device with a circular probe of 4 mm Ø (diameter) and 4.52cm<sup>2</sup>  
84 measuring area (Dimensions: 10.7 cm x Ø 2.4 cm) measures to ±3% technical accuracy. Finally,  
85 Trans-epidermal water loss (TEWL) was measured using a closed chamber Biox Model AF200  
86 Aquaflux (Biox Systems Ltd., London, UK) with a sensitivity of <0.07g/m<sup>2</sup>/h. This sequence was  
87 followed because thickness, roughness and hydration are skin conditions that can change quickly  
88 than trans-epidermal water loss. This order of measurement is strongly believed to affect the results  
89 hence a time gap of 5 minutes between successive measurements was followed to reduce any  
90 impact. Furthermore, a structured questionnaire was administered to all volunteers to ascertain  
91 their Fitzpatrick skin types. This experimental protocol was in line with previous studies [7, 8, 15,  
92 16] and was designed to achieve the objectives of the study. As previously stated, the interaction  
93 of the skin with seasonal variations depends on the level of exposure of anatomical regions. Based  
94 on this, a comparative analysis of the effect of seasonal change on mechanical properties of the  
95 skin was studied at two volar arm locations: the lower arm and the upper arm.

### 96 2.3 Image and Statistical Analysis

97 Images were extracted from the OCT files using ImageJ software from which the skin roughness  
98 and thickness were analysed using a MatLab algorithm developed in a previous study [16]. With  
99 the algorithm, two layers were identified: the yellow (stratum corneum) and the green (dermal-  
100 epidermal junction) in figure 1. The distance between yellow and green lines were indications of  
101 epidermal thickness. The MatLab algorithm was also used to analyse skin surface.  
102

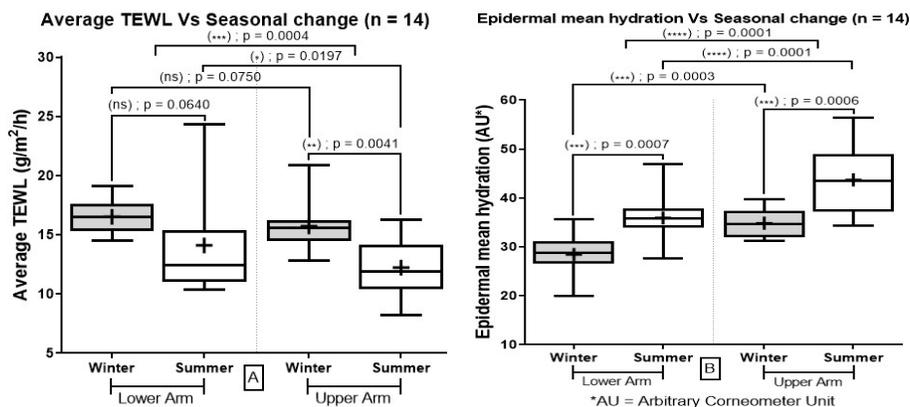


103  
104 **Figure 1:** Skin thickness and roughness: dermal-epidermal junction boundaries (skin thickness)  
105 Statistical analysis was performed using GraphPrism Version 7.04 (GraphPad Software Inc, San  
106 Diego, CA, USA). Clinical scores of the parameters were analysed using means, standard  
107 deviations and 99% confidence intervals. D'Agostino & Pearson test was used to run a Normality  
108 test before statistical analysis to ascertain the suitable tool to be used. As most data were normally  
109 distributed while some were not, both parametric (t-test and ANOVA) and non-parametric (box  
110 plot) statistical techniques were used in data analysis. The data were compared by expressing the  
111 correlation between seasonal change and the skin's biomechanical properties at a 95% statistical  
112 confidence level with p-values less or equal to 0.05 considered as statistically significant.

### 113 3. Results

114 **3.1 Average Trans-Epidermal Water Loss**

115 Under laboratory conditions of  $20 \pm 0.62^\circ\text{C}$  temperature and  $36 \pm 7\%$  relative humidity, the ambient  
 116 temperatures in winter and summer were  $3 \pm 2^\circ\text{C}$  and  $20 \pm 2^\circ\text{C}$  respectively, with 87% and 73%  
 117 relative humidity. Results in figure 2a indicate that at the volar forearm, the average TEWL  
 118 decreased from  $16.53 \text{ g/m}^2/\text{h}$  ( $\pm 1.41 \text{ g/m}^2/\text{h}$ ) in winter to  $14.10 \text{ g/m}^2/\text{h}$  ( $\pm 4.11 \text{ g/m}^2/\text{h}$ ) in summer,  
 119 showing a 14.70% reduction in TEWL due to seasonal change from winter to summer. Similarly,  
 120 at the upper arm, the average TEWL decreased from  $15.71 \text{ g/m}^2/\text{h}$  ( $\pm 1.96 \text{ g/m}^2/\text{h}$ ) in winter to  
 121  $12.23 \text{ g/m}^2/\text{h}$  ( $\pm 2.38 \text{ g/m}^2/\text{h}$ ) in summer, showing a 22.15% reduction in TEWL due to seasonal  
 122 change from winter to summer. This shows that seasonal change from winter to summer had a  
 123 significant difference at the upper arm ( $P=0.0041$ , 99% C.I.= -6.500 to -0.4588 and  $R^2=0.4808$ )  
 124 with no significant effect at the lower arm ( $P=0.0640$ , 99% C.I.= -6.029 to 1.183 and  $R^2=0.2396$ )  
 125 where P is the calculated probability, C.I is the confidence interval and R is the goodness-of-fit to  
 126 the regression line respectively. However, there was no significant difference at the lower arm  
 127 within the two seasons ( $P=0.0640$ , 99% C.I.= -6.029 to 1.183 and  $R^2=0.2396$ ). Also, there was no  
 128 significant difference ( $P=0.0750$ , 99% C.I.= -1.723 to 0.09456 and  $R^2=0.2237$ ) between the two  
 129 skin sites tested in winter but a significant difference ( $P=0.0197$ , 99% C.I.= -3.391 to -0.3507 and  
 130  $R^2=0.3522$ ) between the skin sites tested in summer. Also, ANOVA results showed a significant  
 131 difference ( $P=0.0004$ ,  $R^2=0.2904$ ) between the skin sites when compared between the two seasons.



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

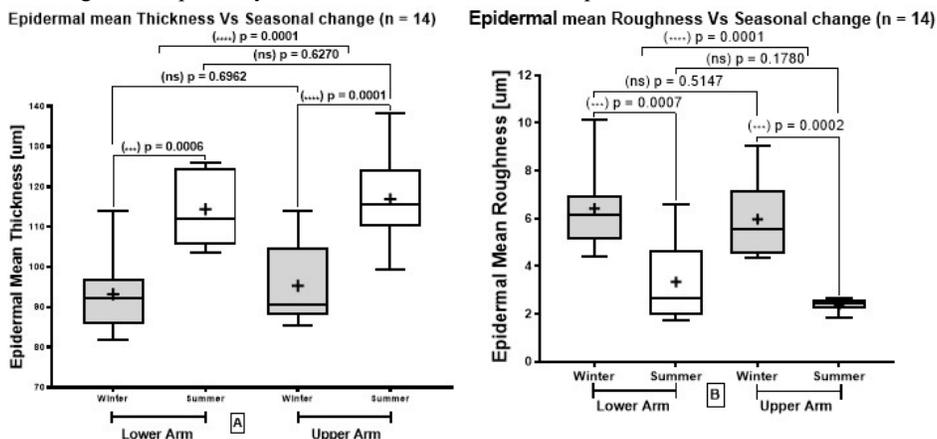
134 **3.2 Average Epidermal Hydration**

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

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

147 **3.3 Average Epidermal thickness and roughness**

148 At the lower arm, (figure 3a), winter to summer transition led to a 22.73% ( $93.20 \mu\text{m}$  ( $\pm 9.90 \mu\text{m}$  SD)  
 149 to  $114.38 \mu\text{m}$  ( $\pm 9.24 \mu\text{m}$  SD) rise in the average epidermal thickness (AET) at the lower arm  
 150 ( $p<0.0006$ , 99% C.I.= 11.53 to 30.83 and  $R^2=0.7938$ ). Likewise, a 22.59% increase in the AET  
 151 was observed at the upper arm due to a significant rise ( $p<0.0001$ , 99% C.I.= 14.74 to 28.34 and  
 152  $R^2=0.8891$ ) from  $95.36 \mu\text{m}$  ( $\pm 10.23 \mu\text{m}$  SD) to  $116.90 \mu\text{m}$  ( $\pm 11.72 \mu\text{m}$  SD) from winter to summer.  
 153 However, in figure 3b, the average epidermal roughness (AER) dropped significantly ( $p<0.0007$ ,  
 154 99% C.I.= -4.518 to -1.644 and  $R^2=0.7860$ ) from  $6.42 \mu\text{m}$  ( $\pm 1.74 \mu\text{m}$  SD) to  $3.34 \mu\text{m}$  ( $\pm 1.71 \mu\text{m}$  SD),  
 155 a 23.65% AER decrease due to winter to summer transition, similar to the upper arm's  
 156 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  
 157 from  $5.97 \mu\text{m}$  ( $\pm 1.66 \mu\text{m}$  SD) to  $2.38 \mu\text{m}$  ( $\pm 0.26 \mu\text{m}$  SD) from winter to summer. ANOVA results  
 158 showed significant differences of ( $P=0.0001$ ,  $R^2=0.5537$ ) and ( $P=0.0001$ ,  $R^2=0.6031$ ) for thickness  
 159 and roughness respectively between the skin sites when compared between the two seasons.



160  
 161 Figure 3: Epidermal average (a) Roughness (n=14) (b) Thickness (n=14)

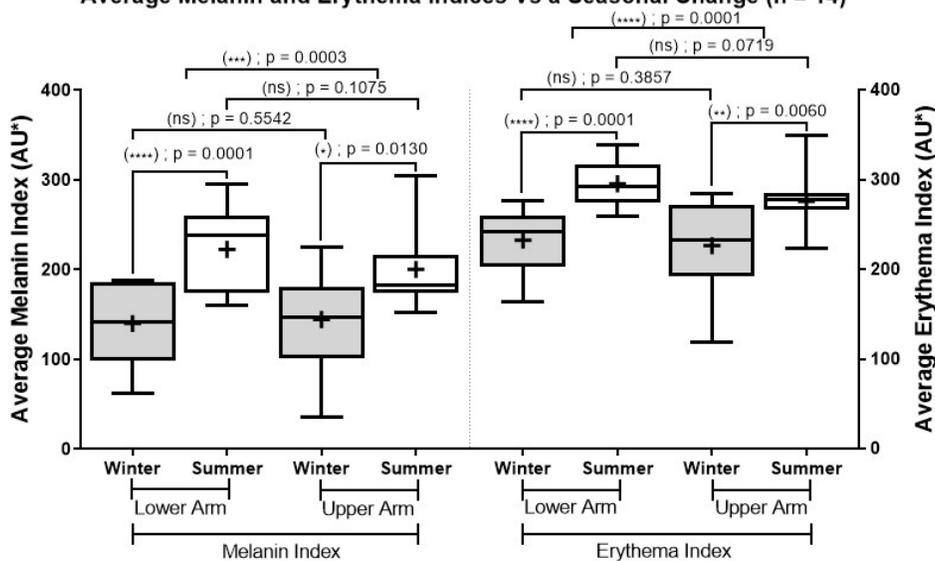
162 **3.4 Average Melanin and Redness Indices**

163 Lower arm results in figure 4 indicate that seasonal change from winter to summer caused a  
 164 significant increase in average melanin index (AMI) by 59.11% due to a rise from 139.98 to 222.72  
 165 arbitrary mexameter units. Similarly, the upper arm had an AMI increase of 38.64% as a result of

166 a rise from 144.57 to 200.43 arbitrary mexameter units. Also, at the lower arm, the winter-summer  
 167 transition increased the average erythema index (AEI) by 27.06% due to a rise from 232.95 to  
 168 295.98 arbitrary mexameter units. In addition, the upper arm had a 21.92% rise in AEI because of  
 169 the rise from 226.83 to 276.55 arbitrary mexameter units.

170 Hence, seasonal change from winter to summer was observed to increase both melanin and redness  
 171 indices at the lower arm with significant differences of ( $p=0.0001$ , 99% C.I.= 51.11 to 114.4 and  
 172  $R^2=0.8730$ ) and ( $p=0.0001$ , 99% C.I.= 44.67 to 81.40 and  $R^2=0.9221$ ), respectively. Similarly, the  
 173 seasonal change increased both indices at the upper arm with significant differences of ( $p = 0.0130$ ,  
 174 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  
 175  $R^2=0.5461$ ) for melanin and redness, respectively. These statistical differences and percentage  
 176 increases indicate that seasonal change affects the lower arm more than the upper arm. ANOVA  
 177 results showed significant differences of ( $P=0.0003$ ,  $R^2=0.3760$ ) and ( $P=0.0001$ ,  $R^2=0.4142$ ) for  
 178 melanin and redness indices respectively between the skin sites compared between the seasons.

**Average Melanin and Erythema Indices Vs a Seasonal Change (n = 14)**



AU\* = Arbitrary Mexameter Unit

Figure 4: Average melanin and redness indices

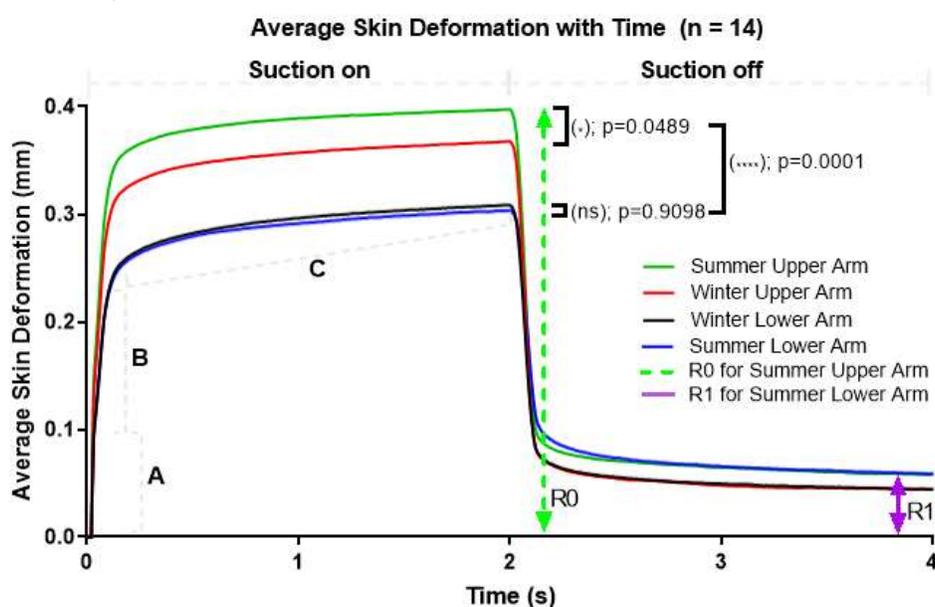
179  
 180

181 **3.5 Cutometer Results: Stiffness (R0), Recovery (R1), Viscoelasticity, Elastic and Creep**  
 182 **Deformations.**

183 From figure 5a, cutometer results indicate an 8.25% rise in skin firmness (R0 values) from 0.3673  
 184 mm to 0.3976 mm due to seasonal change from winter to summer at the upper arm. At the lower arm,  
 185 a negligible change (1.56% fall in stiffness) from 0.3085 mm to 0.3037 mm drop in stiffness

186 from winter to summer was observed. In addition, seasonal change from winter to summer  
 187 demonstrated a rise of R1 values from 0.0446 mm to 0.0594 mm leading to a 33.18% rise in skin  
 188 elasticity at the lower arm with 23.14% (0.0471 mm to 0.0580 mm) at the upper arm.

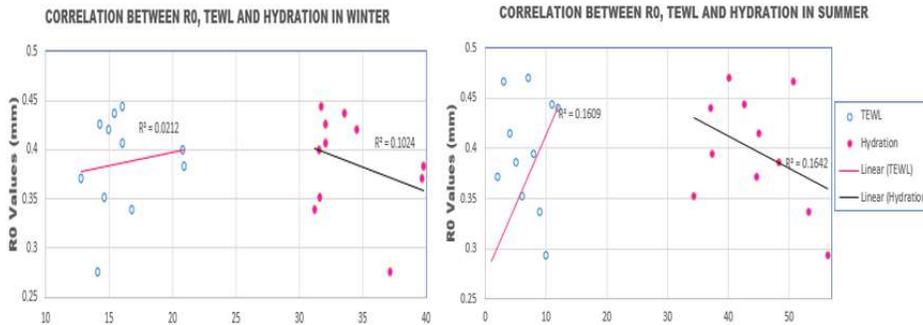
189 Statistically, there was a significant difference ( $p=0.0489$ , 95% C.I.= 0.0021 to 0.0499 and  
 190  $R^2=0.0058$ ) due to the seasonal transition at the upper arm with no significant difference  
 191 ( $p=0.9098$ , 95% C.I.= -0.0095 to 0.0223 and  $R^2=0.0008$ ) at the lower arm. Also, ANOVA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



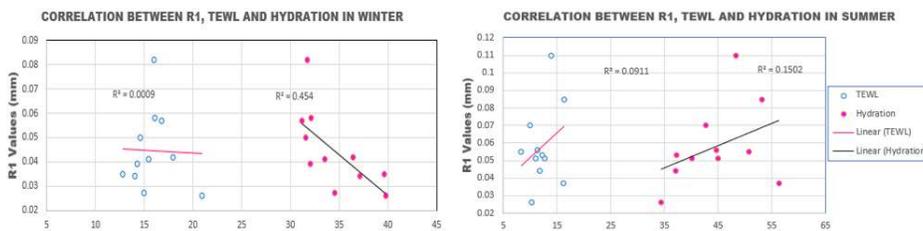
194 Figure 5: Skin firmness (R0) and recovery (R1)  
 195

196 In addition, figure 5 indicates a three-staged strain history (elastic deformation region A,  
 197 viscoelastic region B and creep region C) of the skin under the seasonal effect investigated. It can  
 198 be noticed that region A is associated with high strain rates of 3.01mm/s and 3.15mm/s at the lower  
 199 arm in winter and summer respectively while 4.34mm/s and 4.78mm/s at the upper arm in winter  
 200 and summer accordingly. Likewise, region B demonstrated moderate strain rates of 2.11mm/s and  
 201 2.14mm/s at the lower arm in winter and summer respectively while 2.73mm/s and 3.01mm/s at  
 202 the upper arm in winter and summer accordingly. However, region C is seen to display low strain  
 203 rates of 0.15mm/s at the lower arm in both winter and summer with 0.18mm/s and 0.19mm/s at  
 204 the upper arm in winter and summer accordingly.

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



207  
 208 Figure 6: Correlation between R0, TEWL and Hydration at the upper arm in (a) Winter (a) Summer  
 209 Another remarkable result is the correlation between skin elasticity (R1) and both TEWL and  
 210 Hydration as biomechanical properties of the skin represented by the upper arm in summer as  
 211 shown in figure 7.



212  
 213 Figure 7: Correlation between R1, TEWL and Hydration at the upper arm in (a) Winter (a) Summer  
 214 **4. Discussion**

215 Results from the study of biomechanical properties of the human skin have found significant  
 216 applicability in several industries. In this study, the effect of seasonal change on biomechanical  
 217 and physical skin properties have been investigated at two anatomical locations. The 22.15% drop  
 218 in TEWL (reduction by 3.48 g/m<sup>2</sup>/h) due to seasonal change from winter to summer at the upper  
 219 arm is in line with the previous study [17]. The decreased TEWL in this study due to winter to  
 220 summer transition can be linked to the effect of higher relative humidity (RH) in summer on the  
 221 skin. Increased RH leads to a moist and warm condition that lowers skin pH, increases sebum and  
 222 sweat secretion and consequently improves both amino acid secretion and filaggrin gene  
 223 mutations. These are vital factors in lipid metabolism for intercellular water-retention and terminal  
 224 epidermal differentiation as supported by existing literature [13, 24-27] which suggest that higher  
 225 RH decreases cutaneous TEWL. This is also in line with Brandon and co-authors [20] where  
 226 premature infants born before 33 weeks who were cared for in higher humidity recorded  
 227 significantly reduced TEWL. This shows that reduced TEWL in high RH is not restricted to  
 228 youthful ages as recorded in this study since clinical reductions in TEWL have been observed in  
 229 other ages. For instance, 6.80g/m<sup>2</sup>/h reduction in TEWL of neonates in [18] during coconut oil

230 application likewise a novel approach to infants' eczema and atopic disease controls in [19-22].  
231 Likewise, in adults, marginal reductions in TEWL, [8], to reduce the risk of relapse future of  
232 eczema by 33% through skin barrier strengthening using urea moisturizer has been reported.  
233 Similarly, a reduction in TEWL in [23] due to the application of a semipermeable membrane and  
234 changes in TEWL due to a negative emollient in [7] has also been presented. In addition, the  
235 insignificant effects on the lower arm can be attributed to its more exposure to other factors like  
236 ultraviolet-B (UVB) radiation than the upper arm that is regularly covered by clothes. Hence,  
237 previous findings [10-17], suggest increasing the effect of TEWL due to UVB radiation exposure.  
238 This has been linked to the influence of UV radiation in altering several skin conditions like  
239 epidermal calcium distribution pattern, decrease in epidermal differentiation proteins such as  
240 filaggrin. This is also responsible for the reduction of secretion and structural arrangement of  
241 lipids, especially the covalently bound ceramide within the stratum corneum intercellular spaces  
242 which are responsible for TEWL in [28-31]. Though the effect of UVB radiation was not  
243 extensively investigated in our present study, it will be considered in subsequent ones.

244 According to the literature, the low relative humidity and temperature in winter are known for  
245 depleting the stratum corneum intercellular hydrophobic lipids, osmolytic intracellular fatty acids  
246 and ceramide levels. These limit the trapping of unbound water (water that is not directly linked  
247 to the stratum corneum components). These also delay the generation of natural moisturising  
248 factors (NMFs) that reduce the rate of dehydration which improves from winter to summer as  
249 indicated in several studies [24, 27, 32-38]. Furthermore, most of these authors show that the  
250 mechanism of stratum corneum hydration is osmotic-gradient triggered such that in the presence  
251 of moisture, dead hydrophilic corneocytes get swollen and their glycosyl ceramide lipids shrink  
252 along with dispersed corneodesmosomes. Hence, the dryness in winter inhibits this swelling  
253 mechanism of corneocytes resulting in reduced skin hydration but improves towards summer as  
254 supported by [17]. This aligns with the 26.32% and 25.48% rise in AEH recorded at the lower and  
255 upper arms, respectively, due to seasonal change from winter to summer.

256 In addition, the more hydration of the upper arm than the lower arm can be attributed to its less  
257 exposure, as earlier discussed which aligns with previous results [10, 14, 39-40]. UVB radiation  
258 that has more access to the lower arm is known to decrease both differentiation proteins and  
259 epidermal covalently bound ceramides as well as increasing skin pH. This condition causes  
260 epidermal desquamation and reduced permeability consequently reduces AEH but increases  
261 TEWL [8]. By this mechanism, our findings reveal an inverse correlation between AEH and  
262 TEWL as supported by [10, 39-43]. This is why [43] suggests that to protect against allergens and  
263 pathogens in atopic dermatitis patients, it is necessary to restore skin hydration by reducing TEWL.

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

269 engrossed corneocytes with the cisternae over the available water gives rise to increased SC  
270 thickness.

271 Also, 23.65% and 34.29% reductions in the average epidermal roughness (AER) at the lower and  
272 upper arms were observed respectively. Previous findings [44] indicate that the proliferation of the  
273 skin barrier function through TEWL affects the skin topographical integrity, hence increases  
274 stratum corneum average roughness. Hence, our results, which align with existing findings [24,  
275 45-48], indicate a direct link between skin roughness and TEWL while stratum corneum thickness  
276 and hydration correlate (figures 2 and 3).

277 Another suggestion that lower arm results were influenced by higher exposure to UVB radiation  
278 can be validated by the 59.11% rise in AMI relative to the 38.64% at the upper arm as well as  
279 27.06% and 21.92% rise in AEI at the lower and upper arms, respectively. These can be linked to  
280 melanogenesis being a UV radiation-activated process where the mutagenic effects of sunrays are  
281 inhibited as the skin produces melanocytes to absorb and scatter incidental rays. This pigmentation  
282 which is less in winter and higher in the lower arm, aligns with existing findings [10, 33, 44, 49-  
283 53]. Reduced redness level occurs as blood supply is shunted by dilated vessels and capillaries due  
284 to the cold winter to conserve hydration. Also, the dryness in winter limits sebum secretion which  
285 facilitates the movement of desquamating cells and is also another cause of increasing TEWL in  
286 winter. The accumulation of these dead cells gives the skin a darker outlook [54] which is not  
287 melanin alone and reduces the skin vascularity (redness) as a measure of the erythema index.

288 The 8.12% rise in stiffness due to the summer season shows that winter reduces skin stiffness can  
289 be attributed to skin moisture content. Skin dehydration which is activated by low relative humidity  
290 in winter has been identified in other studies [27, 55-56] as the root cause of fine lines and under-  
291 eye circles. Furthermore, the increase in skin recovery with no statistical difference between the  
292 skin locations also indicates that skin recovery is hydration dependent which aligns with [56-57].  
293 Hence, improved relative humidity in summer relative to winter induces a rise in skin hydration  
294 causing the corresponding positive effect on both firmness and elasticity of the skin.

295 The curves in figure 5 are typical stress-strain graphs with the stages signifying different  
296 mechanical properties due to the heterogeneous network of the skin's elastin-collagen fibrils and  
297 their responses to applied loading/unloading. The high strain rate at region A can be linked to the  
298 elastic response of elastin as load-bearing fibrils in line with [58-60]. Region B is a region of  
299 nonlinearity and viscoelasticity due to the combined effects of the end of stretched elastin fibres  
300 and the onset of collagen reorientation to the loading direction. This nonlinearity occurs as the  
301 elastin fibrils exhaust their flexibility allowing the randomly oriented collagen mesh to untangle  
302 in the direction of applied loading. Region C is another region of linearity due to the full stretching  
303 of the collagen fibres well aligned to the direction of loading. At the terminal stage, no additional  
304 deformation is allowed due to maximum stretching of the inextensible collagen fibrils before the  
305 onset of skin recovery from the applied loading. Hence, the first stage A is purely a region of linear  
306 elastic deformation, region B is the yield or transition while C is the plastic deformation region  
307 [62] before reaching the maximum (R0 values). This trend of linear-nonlinear-linear behaviour  
308 was replicated in the relaxation mode. R0 values of 0.40mm and 0.37mm for the upper arm skin

309 in summer and winter respectively while 0.30mm at the lower arm in both seasons were recorded  
310 before the onset of relaxation (unloading). Likewise, R1 values of 0.06mm and 0.04mm were  
311 recorded in summer and winter respectively at both arm regions. The R0 value is defined as the  
312 firmness or resistance to the applied suction load which is a measure of biomechanical strength of  
313 the skin while the R1 value is the ability of the skin to return to its original position as a measure  
314 of skin elasticity. Figure 5 shows that summer had the highest firmness (0.40mm) and elastic  
315 (0.06mm) values than winter (Firmness of 0.37mm and elasticity of 0.04mm).

316 Our findings as shown in figure 6 reveal that skin firmness is favoured by increasing TEWL with  
317 an inverse correlation with skin hydration. This correlation of skin firmness is stronger in summer  
318 ( $R^2 = 0.1609$  and  $0.1642$  for TEWL and hydration respectively) than in winter ( $R^2 = 0.0212$  and  
319  $0.1024$  for TEWL and hydration accordingly). However, the winter season demonstrated inverse  
320 correlations with both the skin TEWL and hydration while it displayed positive correlations with  
321 these properties in summer. Remarkably, winter reduces skin hydration thereby decreases its  
322 recovery from applied tension while the well-hydrated nature of the skin in summer increases skin  
323 elasticity. No permanent deformation of the tested skins was observed.

324 The results in this study were within the accuracies and limitations of the individual measuring  
325 instruments used in accessing properties within the skin's depth profile. For instance, the main  
326 limitations of the OCT are the lack of resolution which is less than  $10\mu\text{m}$  and the short coherence  
327 length (low penetration depth) which is due to the high intensity of light scattering and absorption  
328 [62-64]. In addition, the size of the OCT machine reduces its portability. The Mexameter faces the  
329 challenges of ambient light interference and the Corneometer probe is often occlusive [64-65]. The  
330 validity of Corneometer, Mexameter, Cutometer and Biox Aquaflux results in demands that the  
331 probe is vertically placed and can be influenced by air convection, probe pressure on the skin  
332 surface and speed of measurements could also be analysed in future. Furthermore, as benchtop  
333 devices, they are restricted from certain anatomical locations/positions [64].

334 Subsequent studies will be conducted to quantify the effect of other factors such as ageing,  
335 ethnicity, gender, geographical location and migration which can influence the biomechanical and  
336 biophysical properties of the skin due to different seasons (Summer, Winter, Spring and Autumn).  
337 Also, further studies recruiting a higher number of volunteers with broader Fitzpatrick skin types  
338 will be considered.

## 339 5. Conclusions

340 The study demonstrates the effects of seasonal change on various skin biomechanical and  
341 underlying biophysical properties at two anatomical locations. Observations show that winter to  
342 summer transition decreases cutaneous TEWL but increases skin hydration indicating an inverse  
343 correlation between AEH and TEWL. Remarkably, changes from winter to summer led to a rise  
344 in both skin melanin and erythema (vascularity) indices. Also, a decline in skin roughness was  
345 observed from this seasonal change while skin thickness was observed to increase, indicating a  
346 correlation between stratum corneum roughness and TEWL as well as its thickness and hydration.  
347 Other findings include improved skin stiffness and recovery from axial deformations due to  
348 changes from winter to summer. Interestingly, the effect of winter to summer seasonal change  
349 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]: irrelevant

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

Commented [SD4]: irrelevant

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

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### 361 Disclosure

362 The authors report no conflicts of interest in this work.

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