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Lifelikeness in multilayered digital prostheses

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Abstract

The appearance of the skin is dependent on the optical properties of the various layers of tissue and the presence of pigments. In order to reproduce the lifelikeness of the skin in developing digital prostheses, a multiple layered moulding technique was utilised. The prosthesis was moulded in two coloured layers, an outer layer and an inner layer. Four combinations of multiple coloured layers and two single coloured layers varying in their optical properties and base colours were assessed. In two groups an additional intermediate layer of detailed colours was added between the two layers, to enhance the creaselines, nails, blood vessels, and other features. All prosthesis were moulded to a total thickness of 0.6 mm. This method of moulding was based on the anatomical characteristics of the epidermal and dermal layers of the skin and their optical characteristics.

The aim was to determine which combination of multiple layers gave the best outcome and made the prosthesis look lifelike in appearance. The appearance and lifelikeness of the prostheses were qualitatively assessed by a panel of assessers divided according to their vocation.

The study showed that the best combination for moulding the prosthesis in multiple layers was to have the outer layer translucent and the inner layer opaque. An intermediate layer should be incorporated to enhance the more prominent surface features and the nails. The base colour of the inner layer should be darker than the outer layer to allow the intermediate layer to have a reflective background.

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Introduction

An important consideration in developing a cosmetic prosthesis is the ability to simulate the appearance of the skin which is primarily composed of 3 layers with varying optical properties (Agache *et al,* 1989; Anderson and Parrish, 1981; Williams and Warwick, 1980; Edwards and Duntley, 1939). There is a thin and highly translucent outer layer of epidermis, a thicker and less translucent middle layer of dermis, and a highly opaque innermost layer of subcutaneous tissue immediately beneath the dermis. The colour of the skin is determined by five pigments within the three layers, namely melanin (brown), melanoid (brown) and carotene (yellow to orange), together with the haemoglobin (purple and bluish-green) and oxyhaemoglobin (red) in the vascular system. Light transmitted through the surface of the skin is either absorbed, scattered, or back-reflected (Fig. 1). The colour of the skin as perceived depends on the wavelength of the emerging light, the opacity of the skin layers, and the spectral characteristics of the pigments. The optical effect of scattering also modifies skin colour (Edwards and Duntley, 1939). The transmission of light into and eventually out of the skin layers produces the translucent appearance of the skin, with the apparent visibility of the underlying blood vessels and skin pigments imparting a dimension of depth to it.

To reproduce the visual effects of the skin in a prosthesis, its surface details, colour and the apparent dimension of depth which collectively gives it a lifelike appearance, must be reproduced (Leow, 1995; Leow *et al,* 1996).

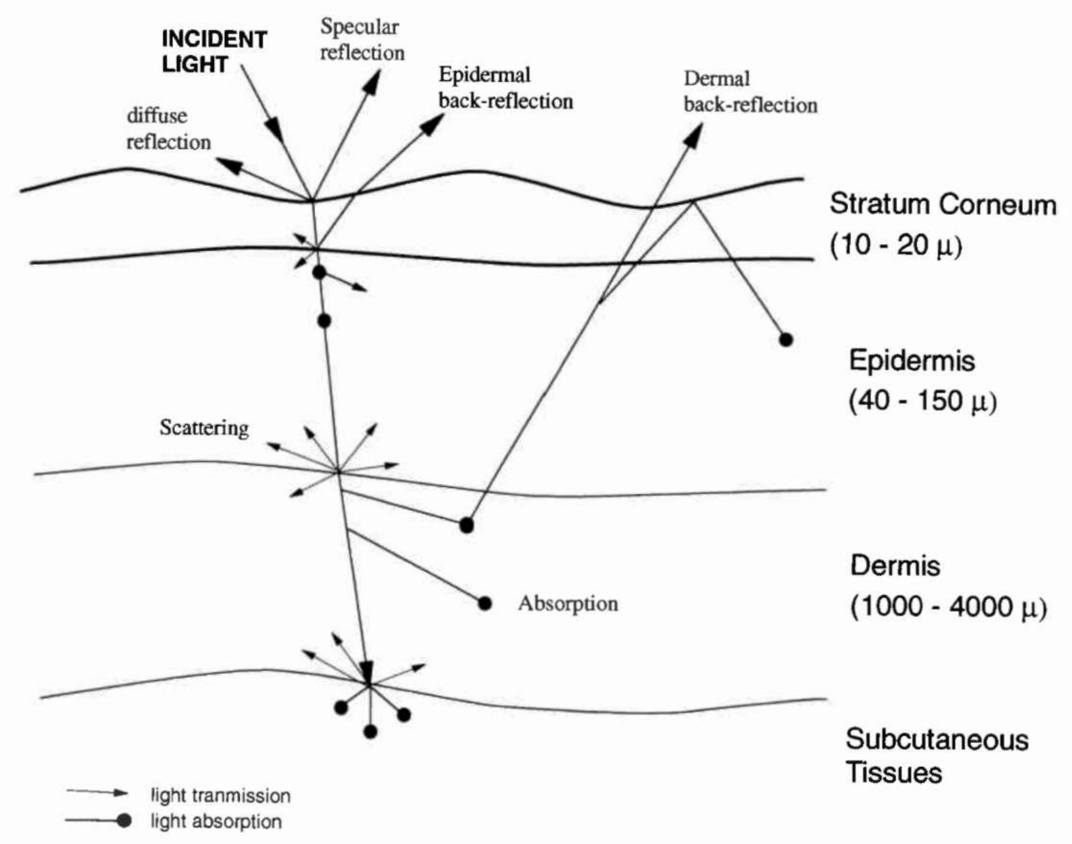

Fig. 1. Schematic diagram of the optical pathway of an incident light within the layers of skin - stratum corneum, epidermis, dermis and subcutaneous tissue layers The arrow lines indicate a transmission of light and the lines ending with a dark circle indicate light absorption.

Additionally, a tinge of surface shine due to the skin's oily secretion which gives it a healthy look should be reproduced. In producing a prosthesis for the hand, the greater pigmentation at the joints of the digits, the eponychium, the pinkish tones of the nail and the difference between the hues of the dorsal and palmar skin are important considerations.

Silicone rubber has been used to produce cosmetic prostheses for the hand (Pillet, 1983; Beasley, 1987; Alison and MacKinnon, 1992; Campbell *et al,* 1992; Leow, 1995; Leow *et al.*, 1996; Pereira *et al,* 1996). To mimic the aesthetic effects of the skin, a multilayered moulding technique has been reported by several researchers (Campbell *et al.,* 1992; Law and Dick, 1982; Leow, 1995; Leow *et al.,* 1996: Pereira *et al.,* 1996). A prosthesis moulded in multiple layers, with the layers varied in opacity and colour, helps to break up the 'solid-like' appearance and better reproduces the life-likeness of the skin. However, no reports have been published which compared the aesthetic quality of multiple layered prostheses to single layered prostheses. This study investigates and compares the aesthetic properties of six digital prostheses moulded in different combinations of coloured layers. The different layers were varied in terms of the colour and opacity. In addition, the effects of a layer of detailed colouration incorporated between the inner and outer layers to reproduce certain features like the nails, creases, vessels and skin pigmentations were also studied.

Materials and methods

Master negative impression moulds using polyvinylsiloxane dental impression material (Dent Silicone-V, Shofu Inc. Kyoto, Japan) were made from the same stone impression mould of the left index finger of Subject A (LEL). The digital prostheses were then moulded in multiple layers (Leow, 1995) from these master negative impression moulds (Appendix). A clear commercial grade of silicone elastomer was used (KE1300T, ShinEtsu Chemical Co., Japan). Six different combinations of layers were studied, varying in the colour and opacity of the layer (Fig. 2). Colour matching of each layer was done under white light illumination, 36 watts, white light, temperature 4000°K at an intensity of 740 Lux (Phillips, Netherlands). In

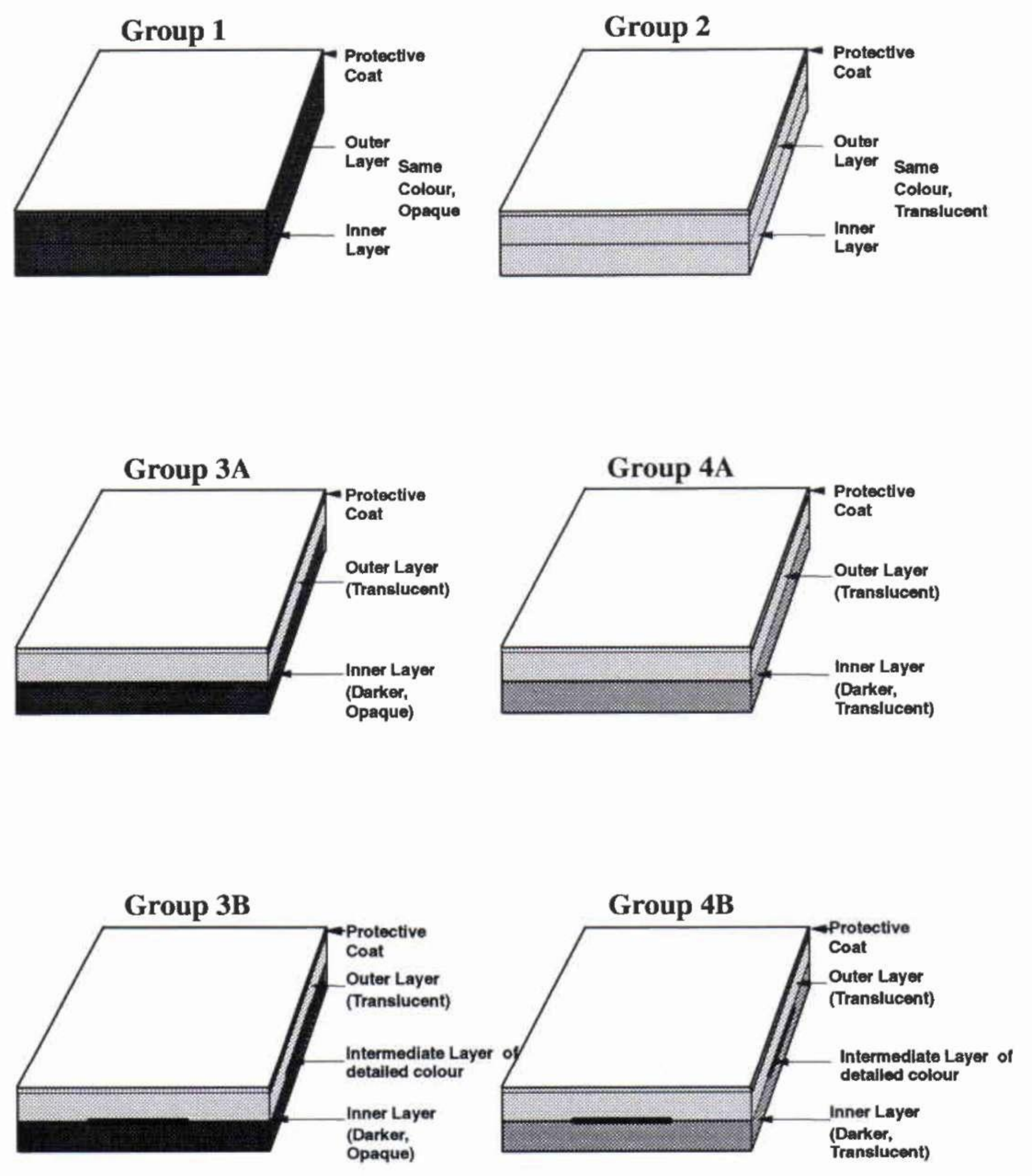

Fig 2. Schematic representation of a through thickness section of the various prostheses moulded. Each prosthesis was moulded with an inner and outer layer where the colour and opacity of each layer were varied. Prosthesis-1 and Prosthesis-2 were considered as single layer prosthesis as both layers were moulded in the same colour and opacity. Prosthesis-3 and Prosthesis-4 were moulded with both layers different in colour and opacity. Both these groups had an additional sub-group where an intermediate layer of detailed colour was included to enhance certain surface and internal features.

a preliminary study (Leow, 1995), standard silicone rubber sheets of 0.3mm thickness of the desired colour were prepared. A repetitive syringe dispenser (Nichiryo Model 8100, Tokyo, Japan) was used to quantify the amount of colour pigments (Cosmesil, Cosmedica Ltd, UK) in colouring the silicone rubber sheets. The colour hue was adjusted by varying the amount and the type of pigments used (Appendix). The colour of the silicone sheets was recorded in their *L, a* and *b* values using a tristimulus colorimeter (Chroma Meter CR-300, Minolta, Osaka, Japan). The degree of opacity of the silicone sheets was also controlled and adjusted by varying the amount of colour pigments used per l0g of silicone rubber for a 0.3 ± 0.01mm sheet thickness. For a translucent layer, the amount of pigment used was 0.15ml/10g of silicone rubber. For an opaque layer, 1.0ml/10g of silicone rubber was used. The colour contrast and opacity were measured using the tristimulus colorimeter and expressed as a contrast ratio *(CR)* defined as (Osmer, 1978):

$$CR = (Y_b / Y_w) \times 100$$

where Y_b and Y_w are the reflectance readings when the standard colour sheets of 0.3 mm thickness were measured over black and white colour standard plates respectively. The *L, a, b* values and the *CR* of the outer and inner layers used to mould the six combinations are summarised in Table 1. Prosthesis-1 and Prosthesis-2 were both moulded with both layers having the same opacity and colour. For Prosthesis-1 both layers were opaque while for Prosthesis-2 both layers were translucent. For Prosthesis-1 and Prosthesis-2, the *CR* values for the outer and inner layers in each prosthesis were not significantly different (p>0.5). Thus both prostheses were considered as single layered prostheses. The total thickness of both these prostheses was maintained at 0.6 mm. Prosthesis-3 had a translucent outer layer and an opaque inner layer, while Prosthesis-4 had both inner and outer layers translucent with the inner having a darker shade of colour than the outer layer. The thickness of each layer was maintained at 0.3 mm, giving a total of 0.6 mm in thickness. Prosthesis-3 and Prosthesis-4 were further divided into sub-groups A and B. Sub-group B had an intermediate layer of detailed

Table 1. L, a, b values and contrast ratio (CR) of the various prostheses assessed

Prostheses	Outer layer (thickness = 0.30 ± 0.01 mm)		Inner Layer (thickness = 0.30 ± 0.01 mm)		Remarks
	L, a, b Value	CR Value	L, a, b Value	CR Value	
Single coloured layers Prosthesis-1	L=66.22±0.02 a=14.95±0.01 b=24.92±0.02	96.75±0.68 (Opaque)	L=66.22±0.02 a=14.95±0.01 b=24.92±0.02	96.75±0.68 (Opaque)	Outer and inner layer identical in colour
Prosthesis-2	L=81.84±0.01 a= 7.91±0.02 b=25.45±0.02	47.26±0.74 (Translucent)	L=81.84±0.01 a= 7.91±0.02 b=25.45±0.02	47.26±0.74 (Translucent)	Outer and inner layer identical in colour
double coloured layers Prosthesis-3A	L=82.62±0.02 a= 4.85±0.02 b=25.55±0.02	43.98±0.65 (Translucent)	L=63.81±0.02 a=19.24±0.02 b=30.71±0.01	88.50±0.16 (Opaque)	Inner layer darker than outer layer
Prosthesis-3B (with touch-up)	L=82.62±0.02 a= 4.85±0.02 b=25.55±0.02	43.98±0.65 (Translucent)	L=63.81±0.02 a=19.24±0.02 b=30.71±0.01	88.50±0.16 (Opaque)	Outer layer and inner layer identical to Prosthesis-3A
Prosthesis-4A	L=82.62±0.02 a= 4.85±0.02 b=25.55±0.02	43.98±0.65 (Translucent)	L=80.32±0.02 a=11.13±0.02 b=27.95±0.02	47.30±0.70 (Translucent)	Inner layer darker than outer layer
Prosthesis-4B (with touch-up)	L=82.62±0.02 a= 4.85±0.02 b=25.55±0.02	43.98±0.65 (Translucent)	L+80.32±0.02 a=11.13±0.02 b=27.95±0.02	47.30±0.70 (Translucent)	Outer layer and inner layer identical to Prosthesis-4A

(Mean±Standard Deviation).

colouration to enhance and reproduce the greater pigmentation at the joints, the eponychium, the nails and the blood vessels, while sub-group A did not have any intermediate layer. The cross-sectional thickness of the intermediate layer in sub-group B was less than 0.1 mm as observed under microscope. In Prosthesis-3A and 3B, the *CR* value between the inner and outer layer were significantly different, with the inner having twice the value of the outer layer. The overall *CR* values for both Prosthesis-4A and Prosthesis-4B were not significantly different however, both prostheses had an inner layer which had a substantially higher but not a significantly different *CR* value than the outer layer.

Assessment of prostheses

The completed prostheses were assessed quantitatively using the tristimulus colorimeter (Minolta, Japan) as well as qualitatively by a panel of assessers.

Quantitative assessment of opacity and colour difference: The *L, a, b* values of the whole prosthesis (i.e. combined effect of all layers together) were measured. The contrast ratio *(CR)* was used to quantify the relative opacity of the prostheses. The total colour difference, ΔE[1] which is a measure of the size of the colour difference, was calculated by the equation:

$$\Delta E = [\ (\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2\ ]$$

where, ΔL, Δa, and Δb are the differences in the *L, a,* and *b* values respectively of the prosthesis and index finger of subject A.

A small ΔE value suggests a close colour match while a larger ΔE suggests a wider difference in the colour match.

Qualitative visual assessment: The aesthetic quality of the prostheses was assessed against the actual index finger (Subject A) from which the mould was taken. Individuals from six different vocational cohorts were selected to participate in the assessment. For each cohort, a sample size of more than 10 individuals $(n > 10)$ was taken, the total number of individuals involved for the six cohorts being 76 $(n = 76)$. The six vocational cohorts were: doctors (n = 17); engineers $(n = 13)$; artists and photographers $(n = 11)$; business and marketing personnel $(n = 12)$; clerical and secretarial personnel $(n = 11)$; factory workers $(n = 12)$. The cohorts were chosen to ensure that a general opinion was obtained.

The visual assessment was done under the same lighting conditions as in the colour-matching procedure, with the prostheses placed adjacent to the index finger of subject A for a more accurate comparison. The prostheses were evaluated using a score/questionnaire sheet addressing five specific aesthetic features. The five specific aesthetic features were: 1) how distinct the surface details (SD) were; 2) whether the prosthesis appeared to have a surface shine (SS) similar to the normal skin; 3)

Table 2. Definition of aesthetic effects: surface details, surface shine, dimension of depth, overall colour match, and lifelikeness.

Aesthetic effects	Definition
Surface details (SD)	Surface features of the prosthesis as defined by the lines, creases, and pores replicated from the finger under investigation.
Surface shine (SS)	The perception of a tinge of shine on the surface of the prosthesis as perceivable on the surface of the skin due to its oily secretion and the keratin content of the cornified epidermis, as contrasted to a dry skin.
Dimension of depth (DD)	The perception of depth as communicated by the partial vision of something underlying, such as that perceivable in the skin as imparted by the partial vision of the underlying tissues, pigmentation, and vascular system through its translucent superficial layers.
Overall colour match (OC)	The colour of the prosthesis as compared to the skin of the finger under investigation.
Lifelikeness (LL)	The perception of a healthy appearance such as that perceivable in a living tissue with adequate blood supply, as opposed to a gangrenous and cyanosed tissue.

whether the prosthesis had dimension of depth (DD) or the visual effects of an underlying layer of colours rather than the one solid layer; 4) the overall colour (OC) as compared to the subject's digit and lastly 5) the overall life-likeness (LL) of the prosthesis. These features were based on the patients' perception and on questions raised by the patients or their family members concerning the quality of the prosthesis during the course of daily use of the prosthesis. The definitions of these aesthetic parameters are described in Table 2.

Each assesser was assigned a separate score sheet and asked to score each prostheses from between 1 and 10 for each of the above aesthetic features. The statistical method used in this study was the analysis of variance (ANOVA) with the multiple range test (Bonferroni). A significance level of the null hypothesis was set at $p<0.05$.

Results

The six prostheses assessed are shown in Figure 3. The *L, a, b* values, contrast ratio, and colour difference indicator, ΔE of each prosthesis are summarised in Table 3.

The mean aggregate scores from the qualitative assessment of the five aesthetic features for the six prostheses are graphically represented in Figure 4. The mean score takes average of the total scores of the entire panel of assessers. No significant difference between each of the cohorts was noted in their visual assessment of the prostheses for the various aesthetic qualities (ANOVA, $p>0.5$).

Surface details (SD): The surface details for all six prostheses were similar as they were all made from the same mould. However, the distinctness of these details between the six prostheses and how they were perceived by the assessers differed (ANOVA, $p = 0.1$). The opaque single-layered prosthesis (Prosthesis-1) received a significantly low score (3.8) as the distinctness of the features, although accentuated by the opaque background, were over-exaggerated and did not match the subject's finger. In the other prostheses where all had a translucent outer layer, this

Table 3. L, a b values, contrast ratio, and ΔE of the overall colour of the actual index finger and the 6 types of layered moulded prostheses.

Subject	L, a, b value (colour)	Contrast ratio (opacity/translucency)	ΔE
Actual index finger	L=59.32±0.76 a=12.26±0.42 b=22.18±0.27	Not measurable due to the volume of finger	0
Prosthesis-1	L=61.07±0.05 a=12.14±0.04 b=23.26±0.05	CR=99.14±0.43	2.06
Prosthesis-2	L=60.94±0.04 a=11.76±0.07 b=22.61±0.02	CR=71.55±0.60	1.75
Prosthesis-3A	L=60.36±0.05 a=11.49±0.09 b=23.21±0.03	CR=96.53±1.83	1.62
Prosthesis-3B	L=59.80±0.52 a=12.90±0.06 b=22.54±0.48	CR=98.84±1.02	0.88
Prosthesis-4A	L=62.35±0.13 a=12.12±0.03 b=23.21±0.03	CR=67.81±0.35	3.17
Prosthesis-4B	L=58.97±0.06 a=13.09±0.15 b=21.45±0.04	CR=72.62±0.42	1.21

(Mean ± Standard Deviation)

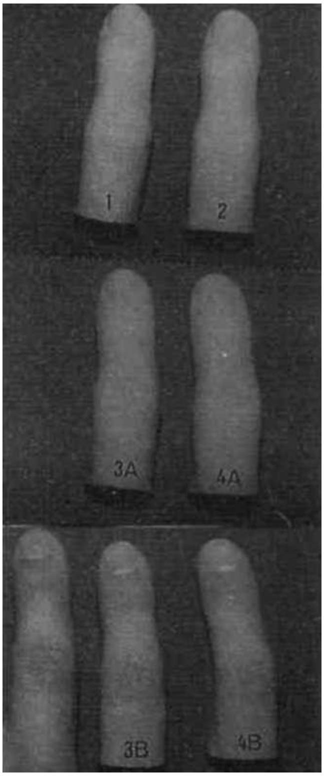

Fig. 3. The various moulded Prostheses-1, -2, -3A, -3B, -4A and -4B compared to the index finger of subject A from which the impression was taken

accentuation of the details decreased resulting in the surface details having a closer resemblance to that of the subject's finger. With an opaque inner layer and translucent outer layer (as in Prosthesis-3A). the surface details visually resembled the subject's finger highly with a mean score of 6.8. With the addition of the intermediate layer as in Prosthesis-3B, which enhanced the details, the mean score increased to 8.8. The same effect was seen in Prosthesis-4 but to a lesser extent, where both layers were translucent with the inner layer having a darker shade. With the inner layer translucent, the colour of the inner layer (Prosthesis-4A compared to Prosthesis-2) did not have any significant effect on the assessment scores for the distinctness of the surface details. With the intermediate layer detailed colour, the assessment scores were significantly higher as seen in Prosthesis-3B and 4B.

Surface shine (SS), dimension of depth (DD) and overall colour (OC): For the assessment of surface shine, dimension of depth, overall colour-match and overall lifelikeness, the prostheses which had the intermediate layer scored highest. In assessing the overall colour-match of the prostheses, the marginal colour differences as indicated by the ΔE values (Table 3) suggest a close match of the base colour of

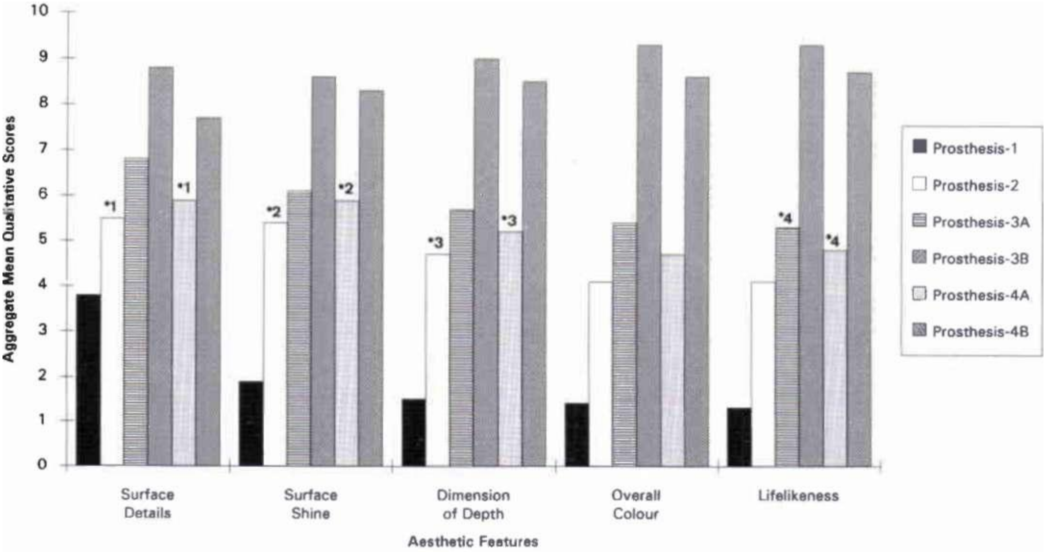

Fig. 4. Column chart summarising the aggregate mean qualitative assessment scores on the various aesthetic features for the single-layered prostheses (Prosthesis-1, Prosthesis-2) and the multi-layered prostheses (Prostheses-3A, -3B, -4A and -4B). Statistical significance (one way ANOVA) - *I:(NS, p=0.10), *2: (NS, p=0.06), *3: (NS, p=0.06), *4: (NS, p=0.10). (note: NS = not significantly different).

the sample prostheses to the subject's index finger. However, there were substantial differences in the perceived colour of the prostheses. When the inner layer was opaque (as in Prosthesis-3) as compared to one which is translucent (as in Prosthesis-4) the results of the assessment showed that the overall colour-match of the prosthesis was better with an opaque inner layer (Prosthesis-3). Between Prosthesis-2 and 4A, where the difference was that the inner layer had a darker shade of colour in the latter, the prostheses with the darker inner layer (Prosthesis-4A) scored statistically higher in its colour-match to the subject's finger. In addition, prostheses with the intermediate coloured layer gave a superior colour-match with a much higher score statistically in the visual assessment.

Discussion

Visual assessment

The primary concern in colouring a prosthesis is to achieve a close visual match to the recipient hand. The summary of assessment in Figure 4 agrees with the earlier reports (Campbell *et al,* 1992; Law and Dick, 1982; Leow, 1995; Pereira *et al,* 1995) that a prosthesis moulded in several layers of silicone rubber tinted to different shades of colour is aesthetically superior to one which is colour matched to a single shade. The study showed that the prosthesis which scored highest for the various features assessed and was considered the most life-like was Prosthesis-3B.

Light transmission and its effects on multilayered prostheses

The differences in the aesthetic effects of the prostheses can be explained using fundamental theories of light (Hunter, 1975; Rubin and Walls, 1969; Stroebel, 1980; Falk *et al,* 1986). The schematic diagram (Fig. 5) is a close-up view of the longitudinal sections though the prosthesis where the V-shape wedge models a "crease" on the surface of the prosthesis. The observed variations in the surface details between the prostheses is attributed to the visual effects of shadow formation and colour contrast

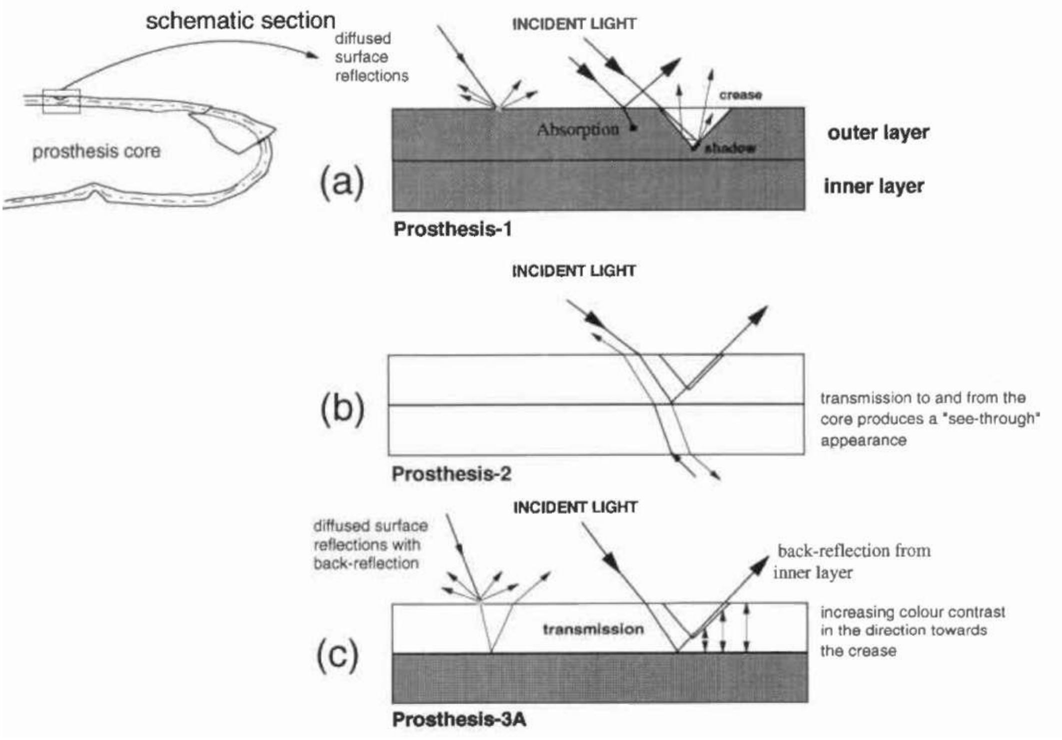

Fig. 5. Schematic diagrams of the optical pathway for an incident light on the surface of the various prostheses. A crease on the surface is also modelled to illustrate the effects it would have on the incident light in (a) Prosthesis-1, (b) Prosthesis-2 and (c) Prosthesis-3A.

interplaying in varying quantities in the different layers (Mullen and Kingdom, 1991; Falk *et al.,* 1986; Stroebel, 1980; Watt, 1991). Both these optical effects emphasise the impression of depth in the creases and interplay in different extents in the prostheses due to the differences in their layers.

Surface details (SD): In Prosthesis-1 (Fig. 5a) the highly opaque contours occlude the incident light and cast "hard" shadows on the crease. The shadow effects, strongest at the valley of the crease, create a strong visual contrast against the surface of the prosthesis at large, emphasising its depth and thus account for the grossly exaggerated surface details as observed by the assessers. In Prosthesis-2 (Fig. 5b), however, the shadow effects at the creases are diluted by light transmitted through the translucent inner layer from the core of the prosthesis thus reducing the distinctness of the surface details and giving a uniform appearance. In Prosthesis-3 (Fig. 5c) the otherwise excessive shadow at the creases is moderated by light rays transmitted through the translucent contour thus explaining the improved assessment as compared to Prosthesis-1 and Prosthesis-2.

Apart from shadow effects, colour contrast at the creases can also enhance the visual perception of surface details. This was seen for Prosthesis-3 where the outer layer is translucent and the inner layer is opaque, and also when there was an intermediate touch-up layer. Colour contrast at the creases arises as a result of the combined effect of three factors, namely, a translucent outer layer, a darker inner layer, and the surface slant at the crease. In Prosthesis-3A (Fig. 5c) the colour of the inner layer becomes increasingly visible towards the valley of the crease due to the reducing distance from the inner layer along its gradients. The resulting colour contrast at the crease against the surface of the prosthesis, strongest at the valley, has the effect of increasing its depth impression and visual perception. The appropriate tinge of colour added to the crease at the joint areas with the touch-up colouration and combined with the moderated shadow effects may account for the close match in surface details in Prosthesis-3B.

Surface shine (SS): Although there were no differences in the topography as observed under magnification for all the prostheses (Leow, 1995), there were significant differences in the manner the assessers judged the quality of the prostheses with regards to surface texture. The opaque single-layered prosthesis (Prosthesis-1) was assessed as grossly matted in appearance with the texture described as being "rough", "dry", and "powdery" in appearance. The surface texture of the prosthesis is mainly contributed to by the pattern of light reflections on its ridged topography comprising of fine lines, creases, pores, and the plateau. With the uneven microtopography, reflections on the surfaces of the prostheses are predominantly diffuse, thus producing a more matted appearance (Falk *et al.,* 1986; Burnham *et al.,* 1963; Stroebel, 1980). However, when the outer layer is opaque an overly matted appearance results because the same process of shadow formation can occur at the fine lines and pores throughout its surfaces due to the uneven topography and the opacity of the outer layer. The subtle visual effects of a mosaic of shaded and unshaded areas over the surfaces of the prosthesis can give rise to an apparent perception of a grossly matted texture. In contrast, the prostheses with a translucent outer layer were found to allow the perception of a tinge of shine from the inner layer onto the surface. This was because a translucent outer layer can modify the highly matted appearance caused by an uneven microtopography (Watt, 1991; Mullen and Kingdom, 1991). The transmission of light and thus increased brightness within the outer layer has the effect of moderating the shadow effects at the lines, creases, and pores, and this can reduce the matted appearance. In addition to this, the relatively directional emerging back-reflections from the smoother outer-inner layer interface can give rise to the apparent perception of a tinge of surface shine.

Dimension of depth (DD): In the prosthesis having a translucent outer layer, part of the incident light at the surface is transmitted through the layer (Fig. 6). The optical processes of absorption and scattering as light traverses down and its subsequent back-reflection and emergence produces the translucent appearance in the outer layer. It is the apparent vision of the inner layer through an outer translucent layer that imparts the dimension of depth to the prosthesis. Such translucent quality and depth impression are apparent in the human skin and these play an important role in the lifelike

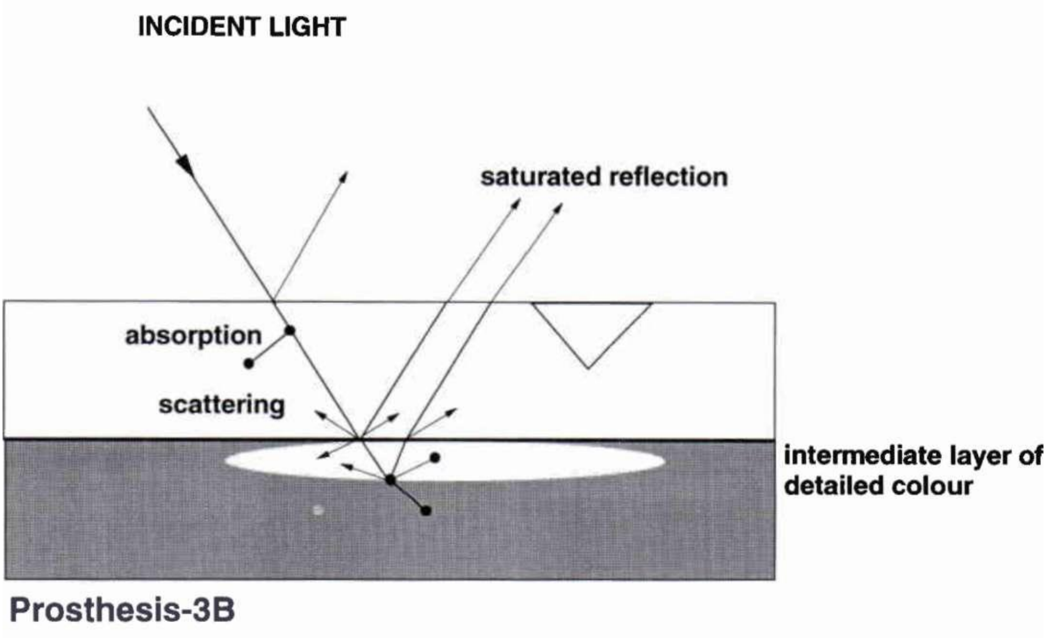

Fig. 6. Schematic diagram of the optical pathway for an incident light on a prosthesis - with an intermediate layer of detailed colour. The light transmission, absorption and scattering of the incident light on the intermediate layer through the outer layer and its subsequent back-reflection produces a dimension of depth characteristic of the prosthesis in Prosthesis-3B and Prosthesis-4B.

appearance of a prosthesis (Leow, 1995; Leow *et al.,* 1996; Fine *et al.,* 1978). In contrast, a major proportion of the light impinging on an opaque single layered prosthesis (Fig. 5a) is absorbed at a superficial level with little transmission (penetration) due to its opacity. The unabsorbed portion of the light is diffusely reflected thus producing predominantly surface visual effect. The prosthesis gives a "solid" and lifeless appearance. In the other extreme, when both layers were translucent (Fig. 5b), a portion of the light may be transmitted into the core of the prosthesis. This, together with some transmission from the core of the prosthesis in the opposite direction, produces a "see-through" appearance.

Overall colour match (OC): The differences in the perception of the colour in the prostheses can be attributed to: (i) the perceived variations in their appearance attributes such as surface details, surface shine, and dimension of depth; (ii) the modifying effects of additive colour mixing of light (Burnham *et al.,* 1963) emerging from the detailed coloured areas and non-detailed coloured areas (where the base colour was taken). The intermediate layer of detailed colour in the prosthesis reproduces the aesthetics of the skin in which light emerging from the more pigmented finger joints, eponychium, veins, arteries, etc., and the less pigmented mid-shafts enters the eye additively.

For Prosthesis 3-B, light incident at the prosthesis surface is partly reflected and partly transmitted (Fig. 6). The transmitted light traverses the outer layer and a fraction of it is reflected at the interface between the outer layer and the intermediate layer of detailed colour. The portion of light transmitted through the intermediate layer is subsequently reflected from the interface between the intermediate layer and the inner layer. The colour of the prosthesis is produced by a subtractive process (Falk *et al,* 1986; Burnham *et al,* 1963), the transmitted light becoming more saturated as part of its spectrum is selectively absorbed by the pigments within the layers. All reflected rays from different spots combined additively to give the resultant colour of the prosthesis. The colour produced depends on the spectral composition of each of the emerging reflections, which in turn, depend on the type and spectral characteristics of the colour pigments. With a highly opaque inner layer and the added intermediate colour details, a higher concentration of pigments are involved in the light subtraction, thus the emerging reflections are theoretically more saturated, producing a saturated colour. The additive effects of light emerging from the touched-up and non-touched-up areas further modify the colour of the prosthesis towards a closer match with the skin. Thus, the colour difference between the subject's index finger and Prosthesis-3B was the smallest ($\Delta E = 0.88$, Table 3) in comparison to all groups. In Prosthesis-4B however, the emerging reflections may be relatively less saturated by reasons of the lower concentration of pigments incorporated in the translucent inner layer. The translucency of the inner layer also allows light transmission to and from the core of the prosthesis, thereby giving rise to a "see through" appearance. The relatively less saturated colour produced and the translucent appearance may have accounted for the less satisfactory colour match results as judged by the assessers.

Conclusion

Six variations of multilayered digital prosthesis were investigated to identify the combination of layers which best reproduce the aesthetic colouration and lifelike appearance of the skin. The variations were in terms of colour and opacity of the outer and the inner layer as well as the effect of incorporating an additional intermediate layer of detailed colouration to highlight certain features in the hand. Qualitative assessment of the prostheses demonstrated that the prosthesis having a translucent outer layer, an opaque inner layer plus an added intermediate layer of touch-up produced the most lifelike prosthesis of the six variations. In this prosthesis, the colour of the inner layer was also darker than the outer layer. This technique of colouring a prosthesis is based on the natural pigmentation and the optical characteristics of the human skin.

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Appendix

Moulding procedure

The liquid RTV silicone rubber (KE 1300T, ShinEtsu Chemical Co., Japan) is poured into the hollow negative mould, after which the mould is inverted to drain off the excess material, leaving behind a thin layer of the silicone adhering to inner surfaces. The silicone layer is then cured to a solid but supple and flexible state, following which it is withdrawn from the mould.

An outermost layer referred to as the protective coat was first moulded followed by the outer layer (thickness = 0.30 ± 0.01 mm). Following curing of the outer layer, the partially completed prosthesis was removed from the mould and a layer of touch-up colouration was applied extrinsically on the inner surfaces. The touch-up was then "sandwiched" with the inner layer (thickness = 0.30 ± 0.01 mm) to the final prosthesis thickness (0.78 ± 0.01 mm).

The thickness of each layer was controlled with a consistent moulding procedure by fixing the determinants of thickness i.e. silicone/solvent ratio, ambient temperature (24°C), and the angle of tilt of the mould when slush moulding.

Colour pigments

The colour pigments used for the outer layer and inner layer were basic yellow (L=68, a=10, b=26), basic brown (L=64, a=12, b=24), master sienna (L=42, a=38, b=37), master brown (L=27, a=23, b=27), master yellow (L=70, a=3, b=50), master blue (L=18, a=30, b=49) and master white (L=100, a=0, b=0). These were prepared and mixed into the silicone rubber material in different proportions to obtain standard colour mixes for the outer and inner layers (Leow, 1995). The colour of the cured silicone sheets was recorded in their *L, a* and *b* values using a tristimulus colorimeter (Chroma Meter CR-300, Minolta, Osaka, Japan). The pigments used for the intermediate layer mixed with the clear silicone rubber material were: master red (L=40, a=47, b=40), master yellow (L=70, a=3, b=50), master sienna (L=42, a=38, b=37), blue (L=18, a=30, b=49) and master white (L=100, a=0, b=0). These were mixed in standard proportions to highlight vessels, variations in the dorsal and palmar aspects, the eponychium and digital creases. This was done under the outer layer.

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