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Predicting Hand Surface Area from a Two-Dimensional Hand Tracing

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Predicting Hand Surface Area from a Two-Dimensional Hand Tracing

by

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DEDICATION

I dedicate this thesis to the many sources of inspiration that helped produce it. Thank you NIOSH for sponsoring me and Capt. Cherie Estill for helping inspire my thesis topic. Thank you USF for being a wonderful refuge for development and education and the state of Florida for making that possible. Thank you to my professors for sharing your knowledge, skills and humor. Thank you Dr. Bernard for your commendable teamwork. Also thank you to the USF Rock Climbing Club and Arts in Health for engaging my spirit in art and sports between classes and semesters.

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ABSTRACT

Recent occupational health studies have focused on dermal exposure at the hands, but have been unable to accurately express dose without knowing the HSA. There is no standard method to calculate HSA, though some researchers have derived HSA formulas based on dimensions from a Taiwanese population. This research paper describes a shortcut method to estimate the hand surface area (HSA) of a human hand from a two-dimensional hand tracing, and repeated a Taiwanese HSA study in order to explore the viability of its HSA formula in an American university population. A sample of nine adult men and nine adult women, each representing one third of the population percentile in hand length and hand breadth, were selected from a population within the University of South Florida in Tampa, FL. Hand length, breadth, a 2D hand tracing and a 3D light hand scan were collected from each participant. A linear regression was used to analyze the data sets and found a correlation ($R=0.94$) between 2D HSA and 3D HSA and slope of 2.6 ($SD=0.2$), with a regression equation of $Y=2.6(X)$. A paired t-test was used to compare the Taiwanese HSA formula data against the 3D HSA. Results found that the Taiwanese data sets were significantly different from the 3D HSA ($p<0.001$), averaging 57 cm^2 less than the 3D HSA. A jackknife analysis was implemented on the 2D HSA hand tracing data, and a paired t-test was performed between the jackknife estimate predictions and 3D HSA. Mean differences were not significantly different ($p=0.97$), with 0.87 cm^2 difference between means. Results indicate that the USF Hand Tracing Method will provide a better estimate of HSA than the Taiwanese method, and can be used as a tool in HSA estimation.

INTRODUCTION

Workers exposed to hazardous chemicals are at risk of direct and systemic toxic effects from dermal contact. In 2015, approximately 28,300 cases of occupational illnesses were related to skin disease or disorders, occurring at a rate of 2.6 per 10,000 workers[1]. The rate of skin-related occupational diseases is higher than any other specific route of exposure, and the hands are often the primary dermal area affected. Chemical exposure typically occurs through four major routes, including respiration, ingestion, injection, and finally absorption onto or through the skin. Chemicals can *directly* affect the skin causing irritation or dryness, such as a prevalent hand-related occupational disorder contact dermatitis, which is the most common cause of occupational skin disease that directly of the hands and forearms[2]. Contaminants present on the skin can also be absorbed through the skin causing *systemic* toxic effects by entering the bloodstream[3] resulting in target organ toxicity, genetic mutation or other ailment[4]. Researchers at NIOSH have developed Skin Notation profiles for chemicals that have been found to be directly or systemically toxic via the dermal route[4]. The frequency of occupational skin disorders and potential for direct and systemic toxicity demonstrate that a health issue exists in some workplaces, which may require an assessment of workers' hands for exposures to hazardous chemical agents, such as pesticides, metals and polycyclic aromatic hydrocarbons[5-8].

Some researchers have suggested that there should be dermal occupational exposure levels, similar to the respiratory occupational exposure levels (OELs), in order to better control health hazards that affect the skin[9]. Although there is no OSHA exposure limit for dermal exposure as of yet[3], there are experimental methods and algorithms that are commonly used to assess dermal exposure, including dermal assessments of the hands.

The primary experimental methods of assessing dermal exposure of the hand are through hand wash sampling or hand wipes sampling that typically involve applying a solvent to the hands followed by a collection procedure[3,10-16]. These results may be presented as the dose of the chemical compound per surface area of the exposed skin. Alternatives include dermal patches or gloves[3]. It is often recommended that sampling efficiency studies be performed in order to help validate the sampling results and determine collection efficiency of the hand sampling method[16].

There are several algorithms that are recommended by different authoritative regulatory agencies and researchers for assessing dermal exposure in terms of absorbed dose and dermal toxicity. Common themes among the dermal absorption algorithms include the variables water solubility (S_w in mg/cm^3), the calculated skin permeation coefficient (K_p in cm/h), the exposed skin surface area (cm^2), and the exposure time (h) [3-4,17-18]. For instance, OSHA has recommended an algorithm as follows:

$$\text{Absorbed dose} = (\text{skin surface area [cm}^2]) \times (\text{skin permeability coefficient Kp [cm/hr]}) \times (\text{concentration of chemical on skin [mg/cm}^3]) \times (\text{exposure time [h]})$$ [3]

Estimation of the hand surface area (HSA) is the purpose of this thesis.

Literature Review

The hand is an irregular three-dimensional shape with many unusual contours. Several researchers designed techniques to calculate HSA using molds, similitude, photometry, body dimensions or formulas, tracing methods, and three-dimensional scanning technology[19-21].

Researchers have endeavored to define the surface area of the hand and other body surface areas since the 1910's. DuBois & DuBois first came up with a method to calculate the total body surface area (BSA) of the human body in 1916, which resulted in a BSA formula that multiplied a person's height (cm) by their weight (kg), each with an exponential value attached to it, shown as: $BSA = 0.007184 \times W^{0.425} \times H^{0.725}$ [21]. The original formula was created from a small sample population of nine individuals, and was later revamped by Boyd[22] in 1935 using the same variables of height and weight from a sample of 1,114 participants, shown as:

$$BSA = 0.03330 \times W^{(0.6157 - 0.0188 \times \log10(W))} \times H^{0.3}$$

From there, there was a Fujioto BSA formula[23] (1968), a Gehran and George formula[24] (1970), a Haycock formula[25] (1978), a Mostellar formula[26] (1987), and most recently a Scholich formula[27] (2010) that all used height and weight to predict body surface area. Even the US EPA in 1985 used data from Gehran & George to devise their own range of data on population dimensions, including BSA[28].

Some researchers have sought to find relationships between the BSA and HSA for medical or research purposes. During the development of a body surface area chart that was to be used during burn assessments, Lund and Brower found that the HSA was approximately 2.5% of BSA[29]. Livingston and Lee found that HSA for one hand was between 1.3-2.0% of the BSA, depending on the individual's body mass index[30]. Tikuisis used a small sample of 24 of the 4,000 North American participants of the Civilian and European Surface Anthropometry Resource (CAESAR), which used 3D laser scanning on whole bodies, and found an HSA of 2.98% for men and 2.31% for women[31]. Taiwanese researchers Hsu and Yu proposed a TBSA:HSA ratio in 2008, finding that for men and women HSA was approximately 2.29% of BSA[32]. A recent meta-analysis by Rhodes et al compared 14 different studies found that age, sex, ethnicity and BMI were variables that influenced the relationship between BSA and palmar surface area (PSA)[33]; one could suspect that these variables also play a role in determining HSA. Furthermore, many of these studies were based on the assumption that the DuBois & Dubois formula was correct, which has been contradicted by some analysts[34].

Skin molds have been another approach to measuring hand and skin surface area. A 2011 research study demonstrated that molding techniques using alginate can achieve hand surface area estimates that are at par with 3D laser scanners[20]. Other researchers have improvised techniques for HSA. An environmental health study estimated the hand surface area of an individual by tracing their hand on grid paper (with gridded squares 1 cm x 1 cm) and quantifying the area of the palm and back of the hand (equaling one full hand)[35]. Although this method accounts for individual differences in hand size, they have only served as an estimate and their accuracy is unknown.

Other conventional methods to measure HSA have come from formulas. In 1919 Dubois & Dubois determined from their analysis of nine participants that HSA = hand length x hand circumference x 1.11[21]. Tikuisis also devised an HSA formula with variables of wrist circumference and arm length, shown as: $SA_{hand} = c \times (wrist)^a \times (arm\ length)^b$ [31]. Recently, Taiwanese researchers devised a hand surface area formula that demonstrated greater statistical accuracy than the DuBois & DuBois method for estimating hand surface area[36]. They devised a hand surface area formula by taking 3D hand scans of a sample population to determine the true value of their HSA, then performed linear regressions on hand dimension variables such as length and breadth until they found an optimal formula. The range of hand surface area in the Taiwan study was between 320 cm^2 – 534 cm^2, with a mean of 402 cm^2 (SD=43 cm^2). These researchers found that a single formula applied to the hand length and breadth resulted in a hand surface area, demonstrating an average absolute error of 2.49% ($p<0.001$):

<u>Taiwanese HSA Formula</u>: HSA = 2.48 x (hand length) x (hand breadth)   {eq. 1}

The method pertaining to length and breadth measurements was not included in their report, but was assumed to adhere to conventional definitions: hand length is defined as the distance between wrist crease and the dactylion, and handbreadth is defined as the distance between the outer edges of metacarpal phalygeal joint II – V[43]. This Taiwanese study, which attempted to produce an original hand surface area formula, was successful, though it has not been replicated. It also involved a sample of participants from Taiwan, which may have resulted in a hand surface area formula specific to the Taiwanese that may not be relevant to other populations. Finally, this study did not reapply this formula to a sample population in order to assess its accuracy in practice. The Taiwan study has, however, been used in several studies since, in fields such as occupational health, disease control, and physiology studies[37-39].

Although an accurate hand surface area formula would benefit occupational research, no such formula has been considered a standard for how to obtain an accurate value. In the past several years there have been advances in technology that allow researchers to scan three-dimensional objects, including human body parts[20,40]. These scanners are remarkably accurate at capturing object surface area to scale, and can be used to determine the surface area of a hand. Other scientists have used methods such as hand casting and other molding techniques, and can achieve a hand surface area as accurate as a 3D hand scan, but these methods require materials and time that are not always at the disposal of occupational health specialists performing field analysis on workforce populations[20]. Although 3D scanning is not a convenient method in many circumstances, it has been widely used as a true standard among researchers investigating inanimate and animate objects, and can stand as an objective value from which to compare other, simpler measurement methods [41,20,32].

Technology is also available to accurately measure the area of two-dimensional shapes. Modern digital drawing computer software, such as those used in digital illustration, can calculate the area of a two-dimensional surface. Traditional drawings made with paper and pencil can be scanned into a computer, uploaded into a specific computer software program (such as Inkscape ©), and the area of the drawing can then be calculated by retracing the image[42]. This approach has been validated using shapes of known dimensions (ie a paper square 10cm x 10cm) to determine if the software can calculate an accurate 2D area. This approach is useful for calculating the area of two-dimensional shapes that are difficult to measure due to their irregular or curved shape, such as hands. By uploading physical hand tracings into drawing software, it is easy to obtain their true two-dimensional surface area.

Three-dimensional surface areas are easily gathered from a 3D scanner, and two-dimensional surface areas can be readily obtained using specific computer software used for design. By applying a linear regression formula between the 2D and 3D areas, HSA can be predicted from 2D surface area tracings. This thesis is also interested in determining if a recent formula for Hand Surface Area, developed by Taiwanese researchers, is replicable in a sample of US adults.

RESEARCH QUESTIONS

Hypothesis 1: The surface area gathered from a two-dimensional hand tracing will be predictive of the total hand surface area (HSA)

Hypothesis 2: Handbreadth and hand length dimensions, taken from a sample population in an American university population, will be applicable to the hand surface area formula devised by Taiwanese researchers.

Hypothesis 3: The two-dimensional hand tracing method will serve as a more accurate representation of the total hand surface area than the Taiwanese HSA formula.

METHODS

Data Collection Methods

The sampling methodology followed a disproportionate stratified sampling method, where one participant of each particular field (or stratum) of hand length and handbreadth was recruited into the study. Participants were selected using this methodology in order to ensure that all dimensions of hand length and breadth measurements were included in the study. In order to achieve this, a 3x3 matrix was devised to include the range of hand dimensions found in a population. Using Eastman Kodak's anthropometric data with mean and standard deviation for breadth and length, nine fields were created based on the 0^{th}-33^{rd} percentile, 34^{th}-66^{th} percentile, and 67^{th}-100^{th} percentile for length and breadth[44]. Tables 1 and 2 show the separate matrices that were designed for males and females. Each field in each matrix was given a letter and number (ie "M4"), which served as the identifier for each participant.

Nine men and nine women (18 total) were selected to participate in this research study by non-random selection using inclusion and exclusion criteria, where only one participant was required for each of the 9 different parameters of hand length and handbreadth for each matrix. Each participant provided hand dimension characteristics that included hand length, handbreadth, a surface area from a tracing, and a hand-scan using a non-contact passive 3D-light scanner. Each participant was informed of the study, the risks and benefits, and consented to participate.

Three different analyses followed. First, participants' right hand was measured for hand length and handbreadth using using an architect's ruler in accordance with the anthropometric

Table 1: 3x3 Hand Dimensional Matrix for Recruiting Male Participants by Evaluation of Hand Length and Hand Breadth

	Length / Breadth	Hand Length Population Percentile		
		0-33%	34-66%	67-100%
Hand Breadth Population Percentile	0-33%	[M1] <18.5cm / <8.4cm	[M2] 18.5cm-19.6cm / <8.4cm	[M3] >19.6cm / <8.4cm
	34-66%	[M4] <18.5cm / 8.4cm-8.9cm	[M5] 18.5cm-19.6cm / 8.4cm-8.9cm	[M6] >19.6cm / 8.4cm-8.9cm
	67-100%	[M7] <18.5cm / >8.9cm	[M8] 18.5cm-19.6cm / >8.9cm	[M9] >19.6cm / >8.9cm

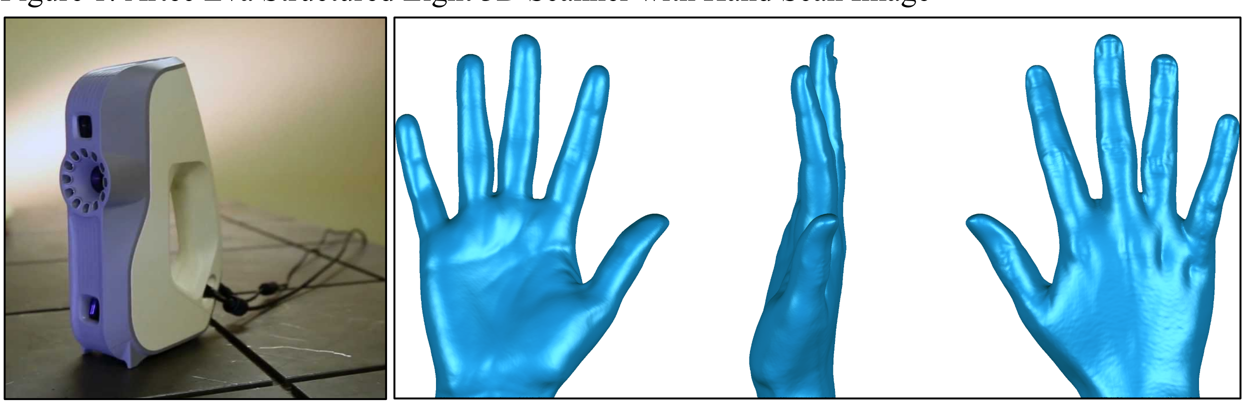
definitions described in the Human Systems Information Analysis Center (HSAIC) Data Analysis Sets Manual and the Taiwanese study[36,43]. Measurements were recorded up to 1/16th of an inch, and these values were converted to centimeters for analysis. If the participant's hand dimensions fell into a field that had not already been filled by another participant, their data was included and the remaining second and third analyses were performed. Second, participants were asked to sit in a chair and place their right hand with fingers outspread on a sheet of drawing paper with their palm facing the paper and their right wrist touching the paper. Then the investigator traced the hand using a pen by holding the pen perpendicular to the hand, while pressing inwardly towards the skin to create a tightly bound tracing of the hand. Once the area of the hand was traced, a flat ruler was place underneath the wrist at the crease line, the participant's hand was raised away from the paper, and a line was drawn connecting the hand

Table 2: 3x3 Hand Dimensional Matrix for Recruiting Female Participants by Evaluation of Hand Length and Hand Breadth

Length / Breadth		Hand Length Population Percentile		
		0-33%	34-66%	67-100%
Hand Breadth Population Percentile	0-33%	[F1] <17.8cm / <7.4cm	[F2] 17.8cm-18.8cm / <7.4cm	[F3] >18.8cm / <7.4cm
	34-66%	[F4] <17.8cm / 7.4cm-7.9cm	[F5] 17.8cm-18.8cm / 7.4cm-7.9cm	[F6] >18.8cm / 7.4cm-7.9cm
	67-100%	[F7] <17.8cm / >7.9cm	[F8] 17.8cm-18.8cm / >7.9cm	[F9] >18.8cm / >7.9cm

tracing along the crease line. Third, participants were asked to sit in a chair, place their right elbow on the table, and comfortably orient their right hand with the palm facing upward and fingers outstretched. Then a technician used an Artec Eva 3D Scanner to manually scan the right hand of each participant over a period of approximately 30 seconds.

Figure 1: Artec Eva Structured Light 3D Scanner with Hand Scan Image



Hand length and handbreadth measurements were input into the Taiwanese Hand Surface Area formula (eq. 1). Hand tracings were scanned using an HP Photosmart C1180 All-In-One printer-scanner into a 2015 Macbook Pro. The scanner was calibrated using a 10cm x 10cm square sheet of paper that was created by hand using a ruler and right angle. Once scanned, the scanned images were digitally retraced using a drawing software Inkscape © (v0.91), and the two-dimensional surface area of the hand tracing was computed using a feature imbedded in the Inkscape software. 3D hand scans that were recorded by the Artec Eva 3D Scanner were computed using Artec Studio 12 Ultimate computer software (0.03% inaccuracy)[40].

Statistical methods

All analyses were performed using SPSS (version 23) and Microsoft Excel for Mac (2011). Mathematical relationships were determined to be significant at the alpha=0.05 level.

Hypothesis 1

A multiple linear regression analysis was performed to determine if there was a relationship between the two-dimensional hand surface area and the three-dimensional hand surface area; this multiple regression looked at the significance of sex in influencing the relationship between 2D hand tracing areas and 3D HSAs. Once sex was determined to not be a significant variable, a simple linear regression was performed between the 18 data sets of 2D hand tracing area and 3D HSA. A prediction equation was derived from the linear regression model.

Hypothesis 2

Paired t-tests were performed to determine the validity of the Taiwanese hand surface area formula compared to the 3D hand surface areas for men, women and total samples.

Hypothesis 3

A jackknife analysis was performed on the 18 2D and 3D data sets to resample the data set and assess the variance. Using the Jackknife partial estimates, a regression equation was modeled and compared to the regression model from hypothesis 1, and a paired t-test was performed in order to compare with the Taiwanese Hand Surface Area formula.

RESULTS

Hypothesis 1: The surface area gathered from a two-dimensional hand tracing will be predictive of the total hand surface area (HSA)

Two-dimensional hand tracings were taken for each of the nine men and nine women, along with 3D light scans of each hand. The results are shown in Table 5. Women had an average hand tracing area of 154 cm^2 (SD=13 cm^2) and Light Scan HSA of 394 cm^2 (SD=32 cm^2). Men had an average hand tracing area of 180 cm^2 (SD=12 cm^2) and Light Scan HSA of 467 cm^2 (SD=36 cm^2). Two-dimensional hand tracings for the pooled males and females had an average hand tracing area of 167 cm^2 (SD=18 cm^2) and an average Light Scan HSA of 430 cm^2 (SD=50 cm^2).

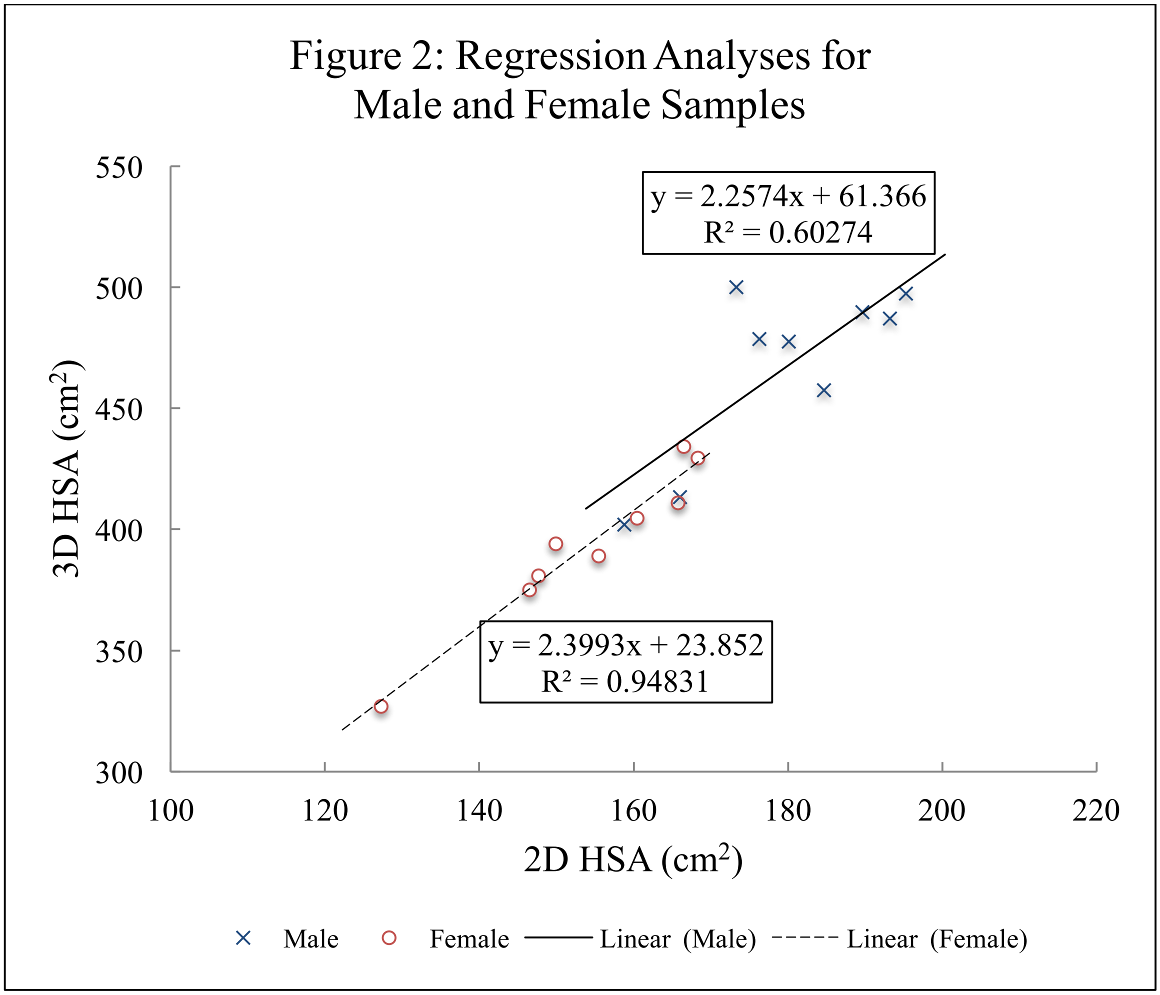
A multiple linear regression was performed with 3D HSA as a dependent variable and 2D tracing HSA and Sex as independent variables. A multiple regression correlation found a Pearson's R-value of R=0.95 (SEE=17 cm^2) for 2D tracing area, 3D HSA and Sex. Sex was a dichotomous variable where M=1 and F=2. Figure 1 shows the slope of the male and female regression equations (*dashed*: male, *solid*: female) when analyzed separately. Total 2D HSA was a significant variable in the multiple regression equation ($p<0.001$) with a slope (B) of 2.3 (SD=0.34). Sex was not a significant variable in the regression equation (p=0.27) with a slope of 13.7 (SD=12). Therefore after concluding that sex was not significant, a linear regression analysis was performed among the 18 data sets of total 2D tracing areas and 3D HSAs. Figure 2 helps to visualize the path of the data comparing 2D hand tracings and 3D hand scans. There is a

Table 3: Hand Tracing Area and Scanning Area for Total Sample

Field	2D Tracing Surface Area (cm^2)	3D Light Scan Surface Area (cm^2)
F1	127	327
F2	150	394
F3	160	405
F4	148	381
F5	147	375
F6	166	434
F7	155	389
F8	166	411
F9	168	429
Female Mean	154	394
Female SD	13	32
M1	159	402
M2	185	457
M3	195	497
M4	166	413
M5	190	490
M6	173	500
M7	176	479
M8	180	478
M9	193	487
Male Mean	180	467
Male SD	12	36
Total Mean	167	430
Total SD	18	50

line of best fit through the data that summarizes the slope relationship between 2D and 3D areas from the 18 data sets that were collected.

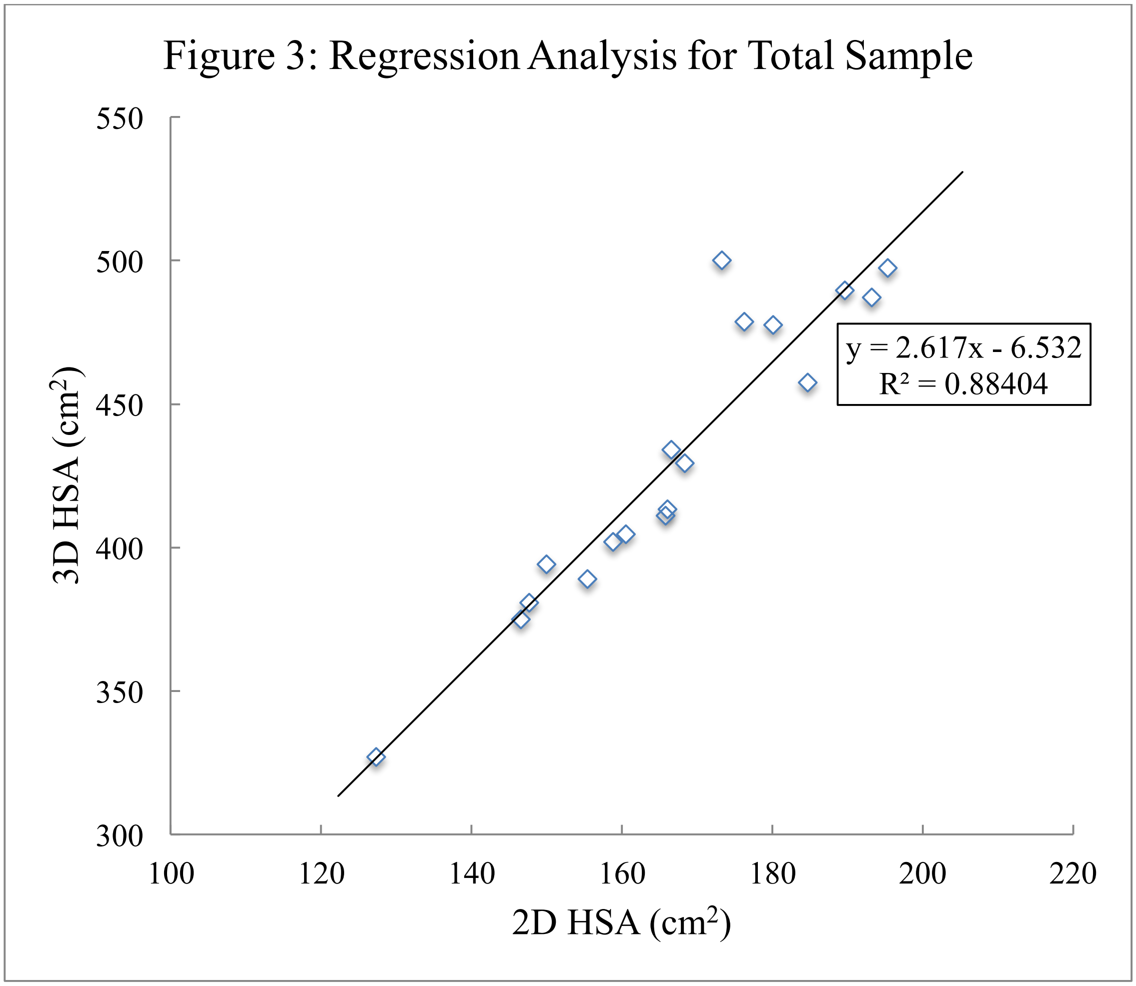
The linear regression analysis found a Pearson's R correlation of R=0.94 (R^2=0.88) between 2D tracing areas and 3D HSAs, with a standard error of the estimate of approximately 18 cm^2. The slope represented in Figure 2 was approximately 2.6 with a standard error of 0.2 ($p<0.001$). The y-intercept, also found in Table 9, was found to be -6.5 ($p=0.87$) and was not a



significant characteristic of the regression equation; for simplified purposes the y-intercept was taken as zero. Based on the slope for both male and female two dimensional hand tracings a prediction factor was determined to be approximately 2.6 with a standard error of 0.2.

Hypothesis 2: Hand length and handbreadth dimensions, taken from a sample within an American university population, will be applicable to the hand surface area formula (HSA = 2.48 x hand length x hand breadth) devised by Taiwanese researchers and result in accurate values of HSA.

Length and breadth measurements were taken from the 18 participants. Males had an



average length of 19.0 cm (SD=0.91 cm) and breadth of 8.6 cm (SD=0.47 cm). Females had an average length of 18.0 cm (0.91 cm) and average breadth of 7.6 cm (SD=0.61 cm). The pooled males and females had a total average length of ___ and average breadth of ____. The HSA was then calculated using the hand length and breadth dimensions using the Taiwanese hand surface area formula: HSA = 2.48 x L x B. The results for male participants can be seen in Table 6 below. For males, the mean Taiwan HSA was 406 cm^2 (SD=29 cm^2). The mean male 3D HSA was 467 cm^2 (SD=36 cm^2). The average male Taiwanese HSA data value differed from its corresponding 3D HSA data value by 61 cm^2 (SD=23 cm^2), indicating an average 13.1% error. The data for female participants is listed in Table 4. For females, the mean Taiwan HSA was

Table 4: Female, Male and Total Taiwan HSA Compared with 3D HSA					
Field	Hand length [L] (cm)	Hand breadth [B] (cm)	HSA [2.48 x L x B] (cm^2)	3D HSA (cm^2)	Difference (cm^2)
F1	16.2	6.4	255	327	-72.0
F2	18.3	7.3	331	394	-63.6
F3	18.9	7.3	342	405	-62.7
F4	17.5	7.6	330	381	-50.7
F5	17.9	7.6	339	375	-36.0
F6	18.9	7.8	364	434	-69.6
F7	17.5	7.9	344	389	-45.2
F8	17.9	8.1	360	411	-50.6
F9	19.1	8.6	405	429	-24.5
Female Mean		Mean	341	394	-52.8
		SD	40	32	15.9
M1	17.8	8.1	357	402	-44.9
M2	18.9	8.3	387	457	-70.3
M3	20.2	7.8	389	497	-108.3
M4	17.9	8.6	381	413	-32.1
M5	19.2	8.8	420	490	-70.0
M6	20.0	8.7	433	500	-67.0
M7	18.4	9.1	413	479	-65.2
M8	18.7	9.1	420	478	-57.1
M9	20.0	9.1	449	487	-38.2
Male		Mean	405	467	-61.5
		SD	29	36	22.6
Total		Mean	373	430	-57.1
		SD	47	50	19.5

341 cm^2 (SD=40 cm^2). The mean female 3D HSA was 394 cm^2 (SD=32 cm^2). The average Female Taiwanese HSA data value differed from its corresponding 3D HSA data value by 53 cm^2 (SD=16 cm^2), indicating an average 13.5% error. The data for the pooled male and female participants are listed in Table 6. The mean Total Taiwan HSA was 373 cm^2 (SD=47 cm^2). The

mean Total 3D HSA was 430 cm^2 (SD=50 cm^2). The average Taiwanese HSA data value differed from its corresponding 3D HSA data value by 57 cm^2 (SD=19 cm^2), indicating an average 13.3% error.

Table 5 shows the paired t-tests performed between the Taiwan HSA data sets and their corresponding 3D data sets in order to determine if there was a difference between the two methods. The paired t-tests matched the male Taiwan HSA and the male 3D HSA, the female

Table 5: Paired Samples Statistics and Correlations for Taiwanese HSA Formula

Pair Units	Mean (cm^2)	Std. Deviation (cm^2)	Std. Error Mean (cm^2)	Correlation	Sig.
3D HSA Total	430	50.2	11.8	.92	<.001
Taiwan HSA Total	373	47.3	11.1		
3D HSA Male	467	36.0	12.0	.78	.013
Taiwan HSA Male	406	28.8	9.6		
3D HSA Female	394	32.3	10.8	.92	<.001
Taiwan HSA Female	341	39.8	13.3		

Taiwan HSA and the female 3D HSA, and the Total Taiwan HSA and Total 3D HSA. The Total paired t-test, which included pooled male and female data, indicated a Pearson R correlation of R=0.92 ($p<0.001$). The male paired t-test had a Pearson's R correlation of R=0.78 ($p=0.013$). The female-paired t-tests indicated a strong correlation R=0.92, ($p<0.001$). Only the Total and Female data sets had significant correlations.

The results from the paired t-test analysis are presented in Table 6. The total paired t-test showed a significant ($p<0.001$) mean difference of 57 cm^2 (SD=20 cm^2). The male paired t-test shows a significant ($p<0.001$) mean difference of 62 cm^2 (SD=23 cm^2). The female paired t-test shows a significant ($p<0.001$) mean difference of 53 cm^2 (SD=16 cm^2). In the male only, female only and total data sets the two means were statistically significantly different from one another ($p<0.001$).

Table 6: Paired Differences Among Taiwan HSA and 3D HSA Data Sets

Pair Units	Mean difference (cm^2)	Std. Deviation (cm^2)	Std. Error Mean (cm^2)	Sig. (2-tailed)
3D HSA Total Taiwan HSA Total	57	20	4.6	<.001
3D HSA Male Taiwan HSA Male	62	23	7.5	<.001
3D HSA Female Taiwan HSA Female	53	16	5.3	<.001

Hypothesis 3: The two-dimensional hand tracing method will perform as a more accurate representation of the total hand surface area than the Taiwanese HSA formula.

Jackknife analysis was performed according to the procedure established by Abdi & Williams[46]. Of the 18 observed data sets for males and females, one data set was removed, and a linear regression analysis was performed on the remaining 17 data sets in order to derive partial estimates of slope intercept variables b_{-n} (slope), a_{-n} (y-intercept), as well as R^2_{-n}. Descriptive statistics were generated for the mean and standard deviation of b_{-n}, a_{-n}, and R^2_{-n} values as shown in Table 7. The $\hat{Y}$ column represents the predicted hand surface area from the linear regression equation that was derived from the partial estimates. The variable b_{-n} was applied to the excluded observation's X_n value, to produce a new $\hat{Y}$ value, also known as jackknife-Y. Means and standard deviations were calculated for the Y, $\hat{Y}$, and the difference of the means. The mean $\hat{Y}$ value was 431 cm^2 (SD=50 cm^2), the mean Y value was 431 cm^2 (SD=48 cm^2), and the difference between means was 0.18 cm^2 (SD=18.5 cm^2). To determine if the total jackknife analysis results were similar to the total 3D HSA values, a paired t-test and linear regression

Table 7: Partial Estimates of Linear Regression Prediction Equation Using Jackknife Analysis and Jackknife 3D HSA Estimates

Obs_n	X_n	Y_n	Partial Estimates			$\hat{Y}$ (cm^2)	Δ (cm^2)
			b_{-n}	a_{-n}	R^2_{-n}		
F1	127	327	2.62	-7.21	0.842	326	-0.5
F2	150	394	2.65	-11.8	0.882	385	-9.2
F3	160	405	2.61	-4.17	0.884	414	9.4
F4	148	381	2.62	-7.11	0.877	380	-0.9
F5	147	375	2.61	-4.96	0.875	377	2.3
F6	167	434	2.62	-6.88	0.885	429	-5.1
F7	155	389	2.59	-1.57	0.882	401	12.3
F8	166	411	2.61	-4.95	0.890	428	17.4
F9	168	429	2.62	-6.46	0.885	434	4.9
M1	159	402	2.61	-4.24	0.883	410	7.6
M2	185	457	2.69	-17.0	0.892	479	21.8
M3	195	497	2.66	-13.8	0.871	506	9.0
M4	166	413	2.61	-5.24	0.889	429	15.4
M5	190	490	2.62	-6.61	0.873	490	0.1
M6	173	500	2.55	1.17	0.948	443	-56.5
M7	176	479	2.57	-0.724	0.892	453	-25.6
M8	180	478	2.58	-1.78	0.882	464	-13.9
M9	193	487	2.69	-17.4	0.879	502	14.7
	Mean		2.62	-6.70	0.884	431	0.18
	SD		0.0351	5.24	0.0195	47.5	18.5

* b – slope
* a – y-intercept
* X – the 2D trace area
* Y – the 3D HSA Scan area
* $\hat{Y}$ – the predicted HSA from the linear regression equation with n value excluded
* Δ – the difference between the $\hat{Y}$ and the Y
* n – the observation that was removed for the partial estimate

were performed in SPSS to look at the relationship between the data sets. A paired t-test indicated that there was a mean difference of approximately 0.18 cm^2 (SD=19 cm^2), and that the difference between the means was not statistically significant ($p=0.97$). A Pearson's R correlation coefficient of $R=0.93$ was found with a standard error of the estimate of about 18 cm^2. A linear regression found a slope of approximately 2.6 ($p<0.001$) and a slope intercept of -6.7, though it was not a significant variable.

DISCUSSION & CONCLUSIONS

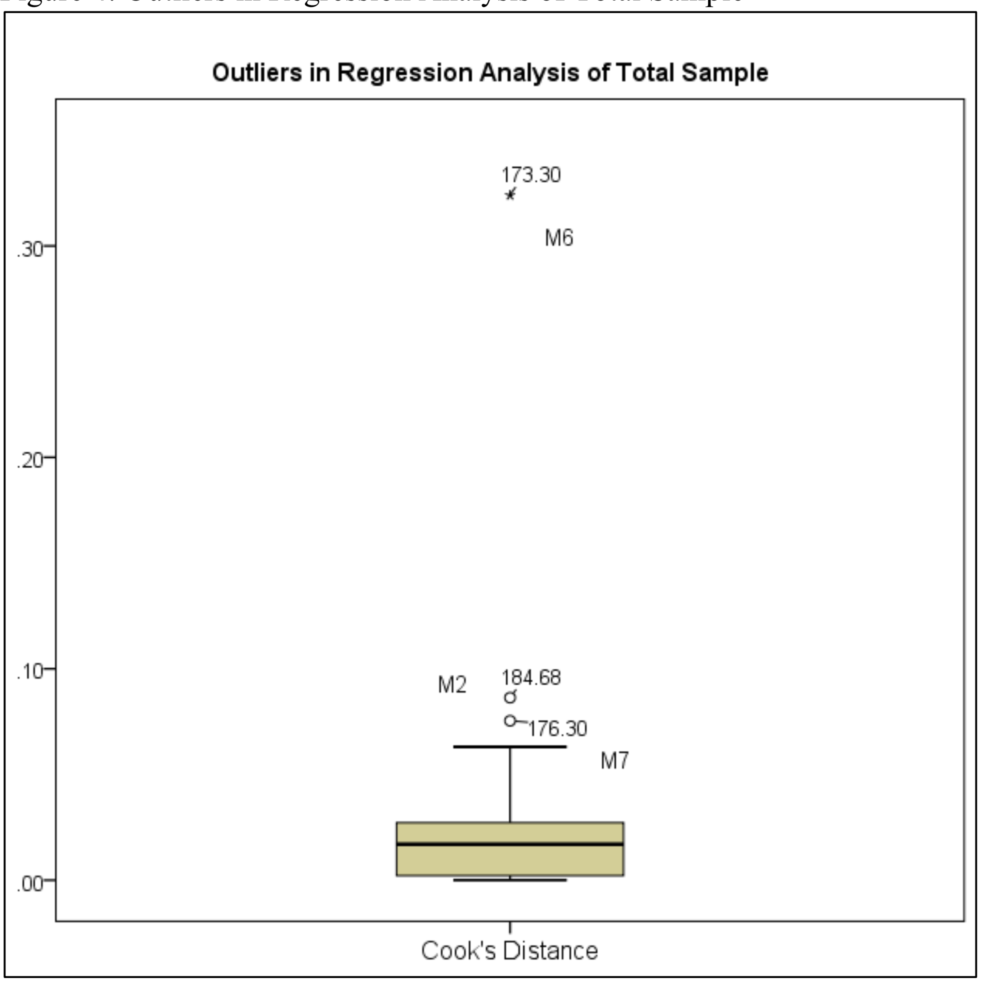
Hypothesis 1: The surface area gathered from a two-dimensional hand tracing will be predictive of the total hand surface area (HSA)

To test hypothesis 1, two-dimensional hand tracings were regressed with 3D hand scans. The linear regression demonstrated that there was a strong correlation ($R=0.940$) between the total 2D hand tracing area data set and the total 3D-HSA data set. Sex was a variable that could influence the linear regression, and so a multiple regression was performed to assess for the significance of Sex in predicting the linear regression. As seen in Table 9, Sex was not a significant influence on the regression line ($p=0.27$). The slope was 2.6 ($SD=0.2$, $p<0.001$) and the y-intercept was -6.5 ($SD=40$, $p=0.87$). The slope is a significant variable but there is a large standard deviation. The high standard deviation is thought to be due to having had a small sample size as well as one data point ("M6") that was determined to be an extreme outlier (see figure 3 below). The average residual differed from the line of best fit by 18 cm^2, according to the standard error of the estimate, which is approximately 4% error from the regression line of both the total 3D sample, as well as the Jackknife total sample. Sex was not a significant influence on the regression formula, and so a singular correction coefficient is appropriate, instead of using a separate formula for males and females. The final correction coefficient within the HSA equation is:

$$HSA = 2.6 \times \text{hand tracing area} \quad \{eq\ 2\}$$

The male and female hand surface areas in this sample ranged from 327 cm^2 – 500 cm^2; in the US population, it is thought to range from 380 cm^2 – 655 cm^2 (5^{th}%ile female – 95^{th}%ile male)[28]. Given the range in human hand sizes as well as the need for accuracy when collecting data on exposure assessments, the hand tracing method is a viable approach to achieve accurate estimates of hand surface area without causing the participant discomfort or inconvenience. If the average hand tracing with this equation was within 18 cm^2 of the surface area of the hand, the formula would generally be more accurate than using average anthropometric values, would account for individual differences, and would have a low error.

Figure 4: Outliers in Regression Analysis of Total Sample



o mild outlier – x > Q3 + 1.5*IQ
* extreme outlier – x > Q3 + 3*IQ

Hypothesis 2: Hand length and handbreadth dimensions, taken from a sample within an American university population, will be applicable to the hand surface area formula (HSA = 2.48 x hand length x hand breadth) devised by Taiwanese researchers and result in accurate values of HSA.

The Taiwan HSA study defined hand surface area as the surface area of the hand distal to the wrist, including the front and back of the hand. They did not, however, go into detail about how they defined hand length and handbreadth. Hand length is typically defined as the wrist crease to the tip of the middle finger, also known as the distance from the center of the interstylion to the tip of the middle finger[43,47]; handbreadth has at least two definitions. Amersheybani defines hand breadth as the distance between the base of the small finger near the palmar digital crease extending a line across the palm to the point where the thumb meets the side of the hand at the base of the index finger[47]; the HSAIC defines it as the breadth of the right hand between the landmarks at metacarpal II and metacarpal V, with the middle finger parallel to the long axis of the forearm[43]. This paper referenced the latter, as the former definition was a self-made, esoteric, and arguably false definition devised for the purposes of a palm surface area formula.

Using these definitions, we repeated their study to determine if the HSA formula was applicable in a US population using a 3D light scanner to serve as a true standard. Length and breadth measurements were recorded and input into the formula: L x B x 2.48. Paired t-tests were performed for the male, female, and total sample. Paired t-tests for all three pairs resulted in significant mean differences between the Taiwanese HSA prediction and the 3D HSA values. On average, the Taiwan HSA values were approximately 13% less than their 3D HSA counterpart values. This is a much larger error than what the Taiwanese researchers found in their study, which is listed as an absolute percent error of only 2.49%. Therefore the Taiwan HSA formula was not as applicable in a US population as it was in a Taiwanese population because it exhibited approximately 4x more error than its original study.

These results indicate that the Taiwanese hand surface area formula, that had previously garnered significance in a population of Taiwanese participants, was not as accurate within an American university population. Despite this deficiency in the Taiwanese formula, the correlation coefficient was still relatively strong, and had a low standard deviation. This could indicate that, with adjustments made to the formula to adapt to US hand dimensions, the technique may still be viable, but will require revision before proving its usefulness.

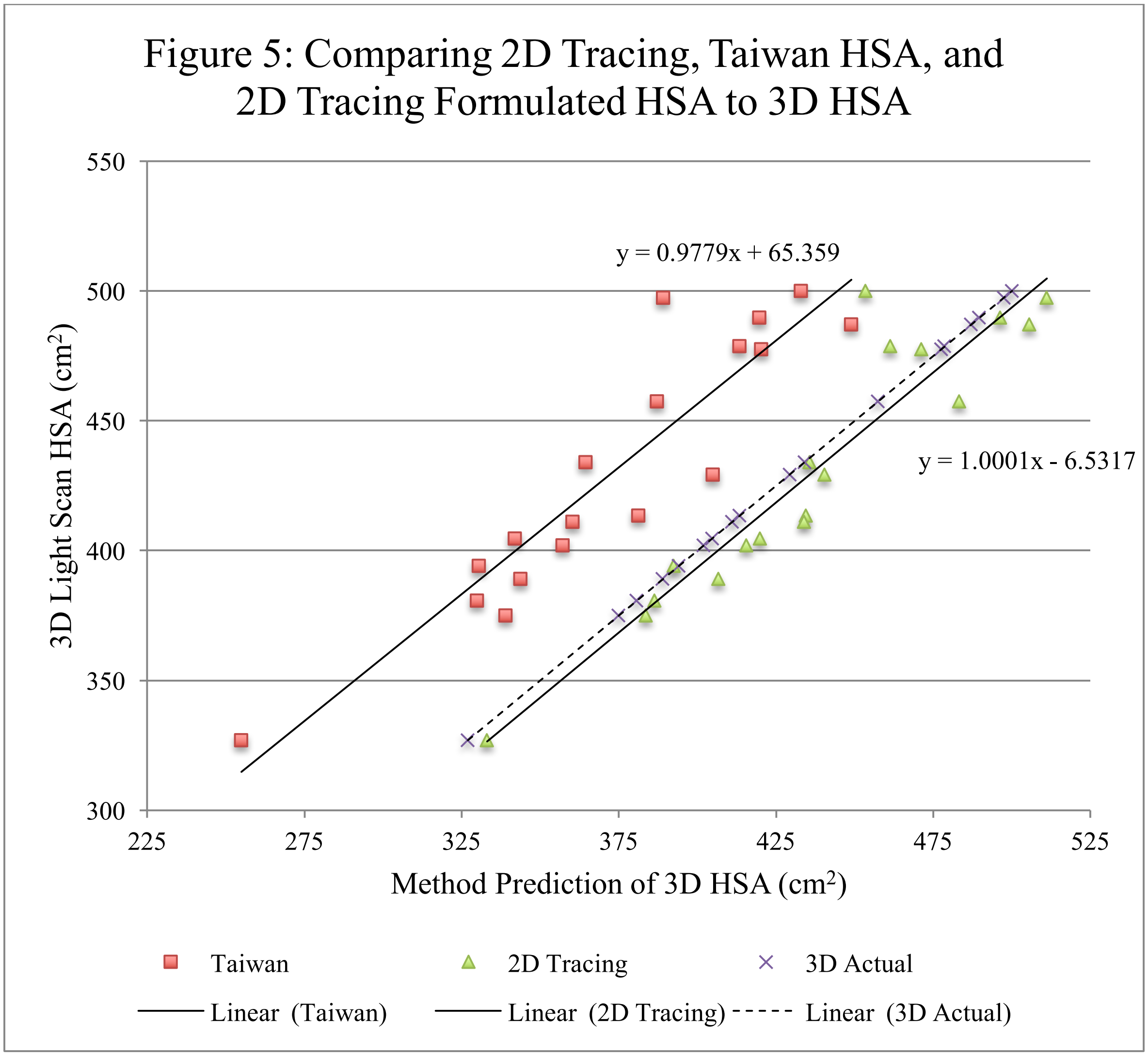
Hypothesis 3: The two-dimensional hand tracing method will perform as a more accurate representation of the total hand surface area than the Taiwanese HSA formula.

Time and resources prohibited a second wave of data collection to the prediction equation from test hypothesis 1 on a new sample. Instead, in order to test the applicability of the results from hypothesis 1, and to compare it to the Taiwanese HSA formula in hypothesis 2, we decided to perform a jackknife analysis on the data to assess partial estimates of the hand tracing formula.

To perform a jackknife on the 18 participants, one 2D/3D data set was excluded from analysis (i.e. "F7"), leaving only 17 data sets. Then a regression analysis was performed between the 2D and 3D on the remaining 17 data sets, resulting in a new partial estimate of the linear regression equation from hypothesis 1. That new partial estimate was then applied to the absent 2D value (ie "F7") in order to test the new linear regression formula on data that was not included in the original formula. The partial estimate result was then compared with its corresponding 3D data taken from the laser scanner, and assessed for accuracy. This was performed on each of the 18 data points, and the averages of the partial estimates can be seen in Table 18. The results were almost identical to the original 2D regression formula. The original 2D tracing linear regression equation was y = 2.62x - 6.53. The jackknife Y had a regression equation of y = 2.62x -6.71.

In all 18 jackknife data points, the average predicted HSA was 431 cm^2 (SD=48 cm^2), while the 3D HSA yielded an average of 430 cm^2 (SD=50 cm^2). The mean difference was less than one cm^2 (SD=19 cm^2). The results indicate that the partial estimates of the formula predicted 3D HSA with <5% inaccuracy. The Taiwanese HSA formula yielded an inaccuracy of over 13%.

Finally, a paired t-test was performed, pairing the total Jackknife-Y values and the total 3D HSA values. Mean differences were not significant, so we failed to reject that the means were different. This t-test indicated that the partial estimates of the 2D Hand Tracing linear regression equations were more similar to the 3D HSA values than the Taiwanese HSA values. Therefore, based on the results of multiple paired t-tests and jackknife analysis, it is the conclusion of this author to say that the two-dimensional tracing technique is a more accurate predictor of hand surface area in a US population than the Taiwanese HSA formula. Figure 4 below indicates the linear regression of the Taiwan HSA values (in red squares), the hand tracing Jackknife HSA values (in green triangles), and the true value, the 3D HSA values (in purple X's).



Further Discussion of Error

The sample size used to determine the prediction equation was small, though the correlation and linear regression was consistent for the total data set when comparing to the three dimensional data set. This study design can benefit from a larger sample size to solidify the method and investigate outliers in the population where the method may not work (such as "M6"). This method has not been tested on children, for instance, and has only been tested in a population from an American university that includes international students.

There are also several sources of experimental error in this study. Some of these sources include administrator variability in tracing, as well as differences across tracers or administrators in tracing technique. A known source of error is the accuracy of the 3D light scanner itself, which advertises a 0.03% error over 100 cm[40]. Also related to the accuracy of the 3D hand scan is the cut-off point at the wrist, where the Artec technician manually erases the forearm, and is another source of experimental error. A technician performs the process used to “clean” the 3D hand tracing, which contributes some error in the cleaning process that was unaccounted for. The scanner used to scan in the 2D hand tracings was calibrated using a 10cm x 10cm sheet of paper, though the percent error of the scanner is unknown, and the operator variability in digitally retracing each hand in a software program could also be tested and accounted for as a source of experimental error. A calibration technique was devised for the three dimensional Artec 3D Scanner, but no perfectly geometric sphere or cube could be found so as to calibrate the devise. Further, a very small bias may be associated with one of the 3D hand scans because the participant was unable to remove their wedding ring. The experimental and systemic error associated with this study is acceptable for a pilot study, though future research will benefit from making improvements.

Dermal Exposure Assessments

Dermal assessments themselves are rife with analytic challenges, though new and improved approaches are steadily reaching the scientific community. Increasingly hand wipe samples are being taken in NIOSH led occupational research, though there is still a sizeable error associated with hand wipes sampling[48]. Improvements in analytical techniques and quantitative structure activity relationship modeling are helping to reveal the potential health effects of chemicals that come into contact with humans[17]. With the advent of 3D scanning technology still budding, 3D hand scanning in field research is still a tall order for some industries such as agriculture, where there may not be a power source or the allotted time for employee participation. While there is no doubt that technology will catch up to allow fast, effective 3D hand scanning on an individual level, current conventions in occupational research can take few liberties while performing exposure assessments so as not to interfere overtly with workers workdays.

Thus far the use of anthropometric data to portray hand wipe sampling results has been an acceptable approach, but its glaring deficiency is that it neglects individual differences among participants. For instance, the EPA has predicted the average surface area of a human hand, neglecting sex, to be 420 cm^2, a value that has been used by several researchers to express chemical loading on hands[5]. Although this area is scientifically valid, it does not represent the actual surface area of the individual's hands that were sampled. For hands with surface areas greater than 465 cm^2 or less than 380 cm^2 the error is greater than 10%, and for hands with surface areas greater than 525 cm^2 or less than 350 cm^2 the error is more than 20%. The 2D Hand Tracing method with the prediction equation would reduce error to <5% on average for all hand sizes.

A hand tracing is a quick, efficient and inexpensive way to capture a unique identifier of an individual to estimate their hand surface area. Researchers may benefit from this hand tracing technique that takes roughly 15 seconds to collect, and can later be analyzed to produce appreciable, accurate results. With improvements in hand wipe methods, hand rinse methods and dermal exposure research as it relates to bioavailability of toxins, this research may become more useful. Future studies interested in this research would benefit from including other HSA formulas beyond the Taiwanese formula, including the DuBois and DuBois HSA formula, among others. Repeatability studies, such as this study, aid scientific literature because they help to find weaknesses and strengths within research studies. They often result in contributing new data to an already accepted idea, carrying the original idea into a new phase of history and of science. Thus far there is not a perfect technique or formula, but as the saying goes, necessity is the mother of all invention. Many researchers have already demonstrated the need for hand surface area determination, and with larger, diverse populations to sample from improvements can be made on the hand tracing technique as well as other methods such as the Taiwan HSA formula.

REFERENCES

1. U.S. Bureau of Labor Statistics, U.S. Department of Labor (2016). News Release. (USDL-16-2056).

2. Plog, B. A., and P. J. Quinlan, eds. (2012). Fundamentals of Industrial Hygiene. 6th ed. Itasca, IL: National Safety Council.

3. Occupational Safety & Health Administration [OSHA] (2012). Surface Contaminants, Skin Exposure, Biological Monitoring and Other Analyses. OSHA Technical Manual (Sec. II, Ch. 2, Pt. II). Retrieved from https://www.osha.gov/dts/osta/otm/otm_ii/otm_ii_2.html

4. United States. Centers for Disease Control and Prevention (2017). Revised: Current Intelligence Bulletin 61: A Strategy for Assigning New NIOSH Skin Notations. Cincinnati, OH. CDC, 2017.

5. Curwin, B. et al. (2003).Acephate exposure and decontamination on tobacco harvesters' hands. J of Exposure Analysis and Environmental Epidemiology 13, 203-210. Nature Publishing Group

6. Ceballos, D et al (2017). Evaluation of Chromium, Hexavalent Chromium, Cadmium, and Isocyanate Exposures in an Aircraft Refinishing Plant. Health Hazard Evaluation Report No. 2013-0011-3278.

7. Rowley, Utah (2005). US Magnesium. Health Hazard Evaluation Report No. 2004-0169-2982.

8. Boeniger M, Neumeister C, Booth-Jones A [2008]. Sampling and analytical method development and hand wipe measurements of dermal exposures to polycyclic aromatic hydrocarbons. J Occ Env Hyg 5(7):417–425

9. P. M. J. Bos, D. H. Brouwer, H. Stevenson, P. J. Boogaard, W. L. A. M. de Kort, J. J. van Hemmen (1998). Proposal for the Assessment of Quantitative Dermal Exposure Limits in Occupational Environments: Part 1. Development of a Concept to Derive a Quantitative Dermal Occupational Exposure Limit. Occupational and Environmental Medicine, Vol. 55, No. 12 (Dec., 1998).

10. Durhman, W.F. & Wolfe H.R. (1962). Measurement of the Exposure of Workers to Pesticides. Bull. Wld Hlth Org. Vol 26, pp. 75-91.

11. Organization for Economic Co-operation and Development. (1997). Guidance document for the Conduct of Studies of Occupational Exposure to Pesticides During Agricultural Application. Series: Testing and Assessment (No. 9). Paris, FR.

12. U.S. Government. National Institute for Occupational Safety and Health. (2003). NIOSH Method 9102 (issue 1): Elements on Wipes. NIOSH Manual of Analytical Methods (4th ed.).

13. U.S. Government. National Institute for Occupational Safety and Health. (2003). NIOSH Method 9105 (issue 1): Lead in Dust Wipes by Chemical Spot Test (Colorimetric Screening Method). NIOSH Manual of Analytical Methods (4th ed.).

14. U.S. Government. National Institute for Occupational Safety and Health. (1998). NIOSH Method 9200 (issue 1): Chlorinated and Organonitrogen Herbicides (Hand Wash). NIOSH Manual of Analytical Methods (4th ed.).

15. U.S. Government. National Institute for Occupational Safety and Health. (1998). NIOSH Method 3601 (issue 1): Maneb Hand Wash. NIOSH Manual of Analytical Methods (4th ed.).

16. Brouwer, D. Boeniger, M. & Van Hemmen J. (2000). Hand Wash and Manual Skin Wipes. Ann. Occup. Hyg., Vol. 44, No. 7, pp. 501–510.

17. G.P., Dearden, H.P., & Cronin, M.T.D. (2002). Quantitative structure-permeability relationships (QSPRs) for percutaneous absorption. Toxicology in Vitro, Vol. 16, pp. 299-317. Liverpool, UK.

18. U.S. Government. Agency for Toxic Substances and Disease Registry. (2005). Public Health Assessment Guidance Manual (update). pp. G5-G7. Atlanta, GA.

19. Kaye, R. & Konz, S. (1986). Volume and Surface Area of the Hand. Proceedings of the Human Factors Society – 30th Annual Meeting. Manhattan, KS.

20. Lee, J.Y. & Choi J.W. (2006). Validity and Reliability of an Alginate Method to Measure Body Surface Area. J Physiol Anthropol 25(3): 247–255, (2006) http://www.jstage.jst.go.jp/browse/jpa2

21. Du Bois D., Du Bois E.F. (1916). A formula to estimate the approximate surface area if height and weight be known. Arch Intern Med 1916; 17: 863–871

22. Boyd, Edith (1935). The Growth of the Surface Area of the Human Body. University of Minnesota. The Institute of Child Welfare, Monograph Series, No. x. London: Oxford University Press

23. Fujimoto S. et al. (1968). Studies on the physical surface area of Japanese. 18. Calculation formulae in three stages over all ages. Nippon Eiseigaku Zasshi. Vol. 5, pp. 443-50.

24. Gehan E.A. & George S.L. (1970). Cancer Chemotherapy Rep. Vol. 54, pp. 225-235

25. Haycock G.B., Schwartz G.J., Wisotsky D.H. (1978). Geometric method for measuring body surface area: A height-weight formula validated in infants, children and adults. Journal of Pediatrics. Vol. 93, pp. 62-66.

26. Mosteller, R.D. (1987). Simplified calculation of body-surface area. New England Journal of Medicine; Vol. 317 pp. 1098. PMID 3657876.

27. Schlich E, Schumm M, Schlich M. (2010). 3D Body Scan als anthropometrisches Verfahren zur Bestimmung der spezifischen Korperoberflafche. Ernahrungs Umschau 2010; Vol. 57, pp. 178-183.

28. Anderson, E., N. Browne, S. Duletsky, J. Ramig, & T. Warn. (1985). Development of Statistical Distributions or Ranges of Standard Factors Used in Exposures Assessments. U.S. Environmental Protection Agency, Washington, D.C., EPA/600/8-85/010

29. Lund C.C. & Browder NC. (1944). The estimation of areas of burns. Surgery, Gynecology, and Obstetrics. 1944;79:352–8.

30. Livingston E.H., & Lee S. (2000). Percentage of burned body surface area determination in obese and non-obese patients. Journal of Surgical Research. 2000;91:106–10.

31. Tikuisis P., Meunier P., & Jubenville C.E. (2001). Human body surface area: measurement and prediction using three dimensional body scans. European Journal of Applied Physiology 2001;85

32. Yu, C., Hsu, Y. & Chen C. (2008). Determination of hand surface area as a percentage of body surface area by 3D anthropometry. Burns. 2008, Vol. 3, pp. 1183-1189.

33. Rhodes, J., Clay, C., & Phillips, M. (2013). The surface area of the hand and the palm for estimating percentage of total body surface area: results of a meta-analysis. British Journal of Dermatology. 2013, Vol. 169, pp. 76-84. DOI: 10.1111/bjd.12290

34. Jones, P., Wilkinson, S., & Davies P. (1985). A revision of body surface area estimations. European Journal of Applied Physiology. 1985, Vol. 53, pp. 376-379.

35. Gong M., Zhang Y. & Weschler C. (2014). Measurement of Phthalates in Skin Wipes: Estimating Exposure from Dermal Absorption. Environmental Science & Technology (2014) 48: pp. 7428-7435. American Chemistry Society.

36. Yao-Wen Hsu & Chi-Yuang Yu. (2010). Hand Surface Area Estimation Formula Using 3D Anthropometry. Journal of Occupational and Environmental Hygiene (2010) 7:11, pp. 633-639.

37. Jin, K. et al. (2012). Scandinavian Journal of Work, Environment & Health, Vol. 38, No. 2 (March 2012), pp. 163-170

38. Bellissimo-Rodrigues, et al. (2016). Should Alcohol-Based Handrub Use Be Customized to Healthcare Workers' Hand Size? Infection Control & Hospital Epidemiology, 37(2), 219-221. DOI: 10.1017/ice.2015.271.

39. Taylor, N. & Machado-Moreira, C. (2013). Regional variations in transepidermal water loss, eccrine sweat gland density, sweat secretion rates and electrolyte composition in resting and exercising humans. Extreme Physiology & Medicine. 2013, Vol. 2:4. DOI: https://doi.org/10.1186/2046-7648-2-4

40. Artec 3D. (2017). Professional 3D scanning solutions. Booklet. Santa Clara, CA. pp. 5

41. McPherron, S., Gernat, T., & Hublin, J. (2009). Structured light scanning for high-resolution documentation of in situ archaeological finds. Journal of Archaeological Science. 2009, Vol. 36, pp. 19-24.

42. Inkscape ©. Computer Software. Version 2, 1991. Copyright © 1989, 1991 Free Software Foundation, Inc. Boston, MA.

43. Human Systems Information Analysis Center. (1994). Anthropometric Data Analysis Sets Manual. Manual. AFRL/HEC/HSIAC. Wright-Patterson AFB, OH.

44. Eastman Kodak Company, Ergonomics Group. (1986). Ergonomic design for people at work, vol. 1. New York: Van Nostrand Reinhold.

45. Wickens CD, Lee, JD, Liu Y., & Gordon-Becker SE (2004). An Introduction to Human Factors Engineering, 2nd edition, 2004. p. 252. New Jersey: Pearson Prentice Hall.

46. Abdi, H. & Williams L.J. (2010). Jackknife. Encyclopedia or Research Design. Thousand Oaks, CA. Sage, pp. 1-10.

47. Amirsheybani, H.R. et al. (2001). The Natural History of the Growth of the Hand: I. Hand Area as a Percentage of Body Surface Area. Plastic and Reconstructive Surgery. Vol. 107 (3), pp. 726-733.

48. Broadwater, K. et al. (2017). Evaluation of Occupational Exposure to Flame Retardants at Four Gymnastics Studios. National Institute for Occupational Safety and Health, Health Hazard Evaluation Program. Report No. 2014-0131-3268.