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A Study to Assess the Variables that Influence the Degree of Mummification and Skeletonization in a modern USA Population.

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Abstract

Taphonomic studies through experimental research at Forensic Anthropological Research Facilities are continuously developing our understanding of soft tissue decomposition in controlled environments. Photographic archives provide an alternative means to study decomposition using associated detailed case notes, environmental variables surrounding the death and (if known) post-mortem interval (PMI). Leccia, Alunni and Quatrehomme (2018) utilized this resource to calculate the total body surface area (TBSA) in bodies with extensive and complete mummification using "the rule of nines", a method where the body is sectioned into nine anatomical sections to assess TBSA burnt however they did not test this statistically.

This paper aims to revise their study by implementing the more representative Lund and Browder chart (Yastı et al. 2015) to visually assess all degree of mummification and skeletonization, through a secondary data analysis study using autopsy photographs of 17 cases from Allegheny County Medical Examiner's Office, Pittsburgh, between 2007–2016. Principal component analysis (PCA) was conducted on the body section scores to reveal high correlation co-efficients (>0.95) between anatomical sections indicating a high confidence, mummification and/or skeletonization on multiple body parts will co-exist on a decomposed body. PCA of recorded variables revealed that after body position was removed from analysis, the majority of variables had strong values. i.e., those with a numerically large magnitude (.750 to .850, -.767 to -.840). Multiple regression analysis and ANOVA revealed age to be the significant independent variable at 10% significance level.

The results of this study have forensic application for crime scene investigators, mummification and skeletonization percentages can be effectively recorded upon examination of a body, whilst also demonstrating variables that have a significant effect on presentation of these two post-mortem changes. Further examination of globally dependant variables affecting modern mummification is encouraged.

Introduction

Mummification is the phenomenon whereby the decomposition process is halted and soft tissue of a corpse becomes physically preserved. Individual circumstances will determine the state of preservation, often mummification will only affect certain tissues to different extents. Soft tissue with high collagen content (dermis, tendons, muscle etc.) are most commonly found preserved, whereas those of the digestive tract are often highly decomposed (Lynnerup 2007, 162-90).

Many authors agree that mummified human tissue is a result of the removal of all nutritional value. The most common cause of mummification is desiccation, the process of extreme dehydration of soft tissue (Aturaliya, Wallgren and Aufderheide 1995, 803-812; Vass 2001, 190-192; Aufderheide 2003a, 41-71). Mummification caused by desiccation is often observed in arid environments, which are favourable conditions for dehydration, as well as dry microenvironments, for example concealed rooms, caves, buried graves (Galloway et al. 1989, 607-616; Aufderheide 2003a, 41-71; Janaway et al. 2009, 341-356; Ubelaker 2017, 45-50). Other factors that influence mummification include: severe reduction in temperature, chemical effects or chelation from contact with heavy metals or compounds. Evisceration, a component of Egyptian mummification that began in the Old Kingdom, does lead to mummification, however this is encompassed within ‘artificial’ mummification or ‘manipulation’ of the body (Schulting 1992, 771-780; Kaufmann 1996, 231-238; Hess et al. 1998, 521-532; Wade 2013, 1-28).

The taphonomic literature shows that mummified remains have been found to occur within a variety of different settings. These include enclosed spaces such as residences, catacombs and plastic bags, outdoor exposure and even aquatically “wet” mummies such as bog bodies and frozen mummies (Aufderheide 2003b, 500-514; Panzer, Zink and Piombino-Mascali 2010, 1123-1132; Gitto 2015, 53-58; Suckling, Spradley and Godde 2016, 19-25; Ceciliason et al. 2018, 180-189). In medico-legal cases, human remains may be discovered in a variety of degrees of decomposition including a mummified or skeletonized state. Some bodies are concealed following a murder whereas the majority of cases are a result of neglect and social isolation due to extensive factors such as: drug addiction, physical illness, or previous traumatic events. Subsequently, extending post-mortem interval. Amenities such as automated systems for payment of bills may also delay discovery (Cacioppo and Hawkley 2003, 39-52; Hönigschnabl et al. 2003, 837-842; Archer et al. 2005, 259-265; Simoni-Wastila and Yang 2006, 380-394).

One, or a combination of variables, associated with the conditions and mechanisms of mummification stated above can promote mummification. These can be divided into three different categories: environmental, cultural and individual/case-specific. Environmental variables include biotic (caused by living organisms such as scavenging or insect activity) and abiotic (caused by non-living environmental forces including temperature and pH) (Rodriguez and Bass 1985, 836-852). Cultural variables are applied to the body peri- or post-mortem such as burial, clothing and trauma. Individual variables are those that a corpse contributes to the decomposition process such as weight, height and health of the deceased (Rhine and Dawson 1998, 145-159; Megyesi, Nawrocki and Haskell 2005, 618–626; Calce and Rogers 2007, 519-527; Wilson-Taylor 2012, 339-380; Forbes 2018, 24). Body mass index (BMI) is a controversial variable in decomposition studies. Researchers disagree on whether BMI has an effect on their studies (ummMann, Bass and Meadows 1990, 103–111; Simmons, Adlam and Moffatt 2010, 8-13; Spicka et al. 2011, 80-85; Matuszewski et al. 2014, 1039–1048).

A fundamental component of a forensic investigation with medicolegal significance is the estimation of the post-mortem interval (PMI) or time since death (TSD). Within the first 24 hours after death and during the early stages of decomposition, forensic pathologists and crime scene investigators conduct examinations where soft tissue is present (Byers 2017). Following this, when a corpse progresses to advanced decomposition, forensic anthropologists rely on subjective anecdotal evidence combined with decomposition stages and case study experience to make PMI estimations (Love and Marks 2003, 160-175). Forensic entomological methods are used throughout the decomposition process. From the moment of death, cellular breakdown releases chemicals that attract insects (LeBlanc and Logan 2010, 205-221). The Calliphoridae and Sacrophagidae with Musidae are insects used by forensic entomologists to establish the minimum post-mortem interval (Goff and Lord 1994, 51-57). Adult and larval Diptera do not concern themselves with skeletal remains (Tullis and Goff 1987, 332-339).

With the increase of taphonomic research, methods of estimating PMI are reported to be more accurate in the taphonomic literature (Leccia, Alunni and Quatrehomme 2018, 330.e1-330.e9; Zissler et al. 2018, 1349-1356). However, there is still a gap in translating this to practical use at crime scenes, and as such there are no reliable methods of PMI estimation routinely used at scenes of decomposition. Many decomposition sequences for present use are developed via cross-sectional data (Galloway et al. 1989, 607-616; Ceciliason et al. 2018, 180–189; Megyesi, Nawrocki and Haskell 2005, 618–26) as this type of research is more accessible to researchers in a multitude of geographic locations. A longitudinal study may be preferable but requires a large human body sample size and a facility that can be utilized consistently for observations over a long period of time (Rhine and Dawson 1998, 145-159). Experimental research conducted at research facilities in certain countries such as the Forensic Anthropological Research Facility (FARF) (“the Body Farm”) in Knoxville, Tennessee (Galloway et al. 1989, 607-616) and the Australian Facility for Taphonomic Experimental Research (AFTER) (Forbes 2018, 24) have helped to develop a further understanding of the processes and variables of human decomposition in different settings. However, predictive PMI models created in these countries rely on specific geographical and climatic variables when creating decomposition sequences (Suckling, Spradley and Godde 2016, 19-25). Countries where taphonomic research on human bodies has not been possible, renders them inapplicable globally and the large number of conflicting variables still require further research.

A valuable resource that is underappreciated are photographic archives held at police forces and Medical Examiner’s Offices. These archives may be used as a substitute in the absence of taphonomic research facilities as the photographs taken consist of scene of death and/or subsequent autopsy, recorded case notes consisting of variables surrounding the death and PMI if known. As these archives only depict the decomposition state that a body is found, an accurate sequence of events may not be achieved, leading to an incorrect PMI estimation (Suckling, Spradley and Godde 2016, 19-25). The first use of this archive as an academic resource was in 2005 (Megyesi, Nawrocki and Haskell 2005, 618–626). The method the authors devised has been used within experimental taphonomy to estimate PMI through variables including accumulated degree days (ADD). ADD is calculated by summing the daily maximum and minimum average temperature in the selected time range (Sorg, Haglund and Wren 2012, 477-498). Limitations of the use of photographic evidence must also be acknowledged. Images are not a complete alternative when considering inter-observer reliability and sensual recognition, e.g., touch and scent, a visual representation may cause errors when assigning a score (Suckling, Spradley and Godde 2016, 19-25).

Leccia and colleagues (2018) repurposed the Wallace "rule of nine", a method commonly used to assess burn victims (Malic et al. 2007, 195-197), to calculate TBSA (total body surface area) of bodies with the presence of extensive to complete (50-100%) mummification within the Nice region of the south of France. A total of twenty photographs of forensic cases were used, fifteen of which found within the scientific literature (Leccia, Alunni and Quatrehomme 2018, 330.e1-330.e9). The appearance of major anatomical regions of the adult human body are divided into sections, each a multiple of nine (head, chest, abdomen, back, each limb, and genitalia) (Hettiaratchy and Papini 2004, 101-103). This method is a rapid yet rough estimate of TBSA. Therefore, this paper has two aims:

i) To improve Leccia, Alunni and Quatrehomme's (2018) model by visually assessing not only extensive to complete mummification but all degree and extent of mummification present within the metropolis of Pittsburgh, USA. Micozzi demonstrated the presence of mummification and skeletonization within the same body (Micozzi 1986, 953-961). Therefore, the presence of skeletonization will also be included in this assessment to ascertain whether certain variables cause a mummified body to conjointly skeletonize. This will be accomplished through analysing post-mortem photographs of 17 forensic cases between 2007-2015 in a secondary data analysis study (Giles 2014).

ii) To statistically analyse the results of this assessment in combination with each case's associated biological, intrinsic and environmental variables in order to quantitatively define the variables that have a positive influence on mummification and skeletonization.

Materials and Methods

Sample

This study used decomposition data and associated post-mortem photographs. A database of 2121 deceased adult forensic cases were previously examined during routine forensic post-mortem examinations, for all states of decomposition at Allegheny County Medical Examiner's Office in Pittsburgh (Giles 2014) between 2007–2016. Human remains that were deemed not to exhibit any signs of mummification on initial inspection by the Medical Examiner's Office were not included, resulting in a sample size of 53 cases. Of this sample, cases that did not have a known or reliable PMI were excluded as well as those with an unrecorded biological profile and demographic information such as age of the deceased, cause and manner of death, clothing worn, height and weight, and location the deceased was found. A total of 17 indoor and outdoor cases ranging from partially to fully mummified between 2007-2015 met the study criteria whilst 36 cases did not and so were excluded for the aforementioned reasons.

Case descriptive

The photographic forensic cases from Pittsburgh, USA (Table 3) within this study included 11 males and 6 females whose ages ranged from 18 to 84 years, with 10 cases falling within the broad age range set by Buikstra and Ubelaker (1994), Old Adult (50+ years). Using the ancestry[1] categories provided, 5 bodies were 'black', all of which were male, and 12 bodies were 'white' (6 males and 6 females). In 9 cases the body was located indoors (7 in different locations within residences, 2 in vehicles with garages) whilst 8 were located outside (1 buried, 1 on a road atop a bridge, 1 submerged, 5 surface deposition). The ante-mortem height and weights for all cases were unobtainable however the calculated post-mortem BMI of the cases ranged from 3.8-54.6. 11 of the bodies were fully clothed 2 in nightwear, 1 fully clothed and wrapped in a bin bag, 2 clothed above the waist, 2 unclothed, 1 unclothed and wrapped in a carpet.

Only cases where the reported time since death was known with a degree of confidence were included. These included a reported PMI derived from indirect evidence, e.g., dated missing person reports and dated suicide notes, recorded in 14 of the cases in this study, whereas 3 were direct evidence e.g., time and date that the death was witnessed, which is sufficient for the purpose of this study. Details of cause and manner of death are presented, (Table 1).

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[1] The USA classification used in the original database is referred to as 'race' however in the UK this terminology is a social construct rather than a biological representation.

Table 1. Cause and manner of death for 17 cases included in this paper.

There was 1 body found in a foetal position, 1 kneeling, 5 lying prone, 3 sitting, 1 lying laterally to the right, 2 lying supine, 2 lying vertically, and 2 with unrecorded positions. Figure 1 shows the PMI distribution of cases included in this study (n=17). The maximum recorded total PMI (in days) was 31 whilst the minimum was 3 PMI days, giving a mean of 12.9 PMI days and a mode of 19 PMI days.

Figure 1. Frequency distribution of cases by total PMI (days) (n=17)

Body mass index (BMI)

The height and weight of each body had been previously recorded during the post-mortem examinations. These recordings were taken and BMI was calculated by the researchers, body weight (kg) was divided by the square root of the body height (m^2) and expressed as kg/m^2. Within human decomposition studies, BMI is commonly calculated in longitudinal studies to determine whether this has an effect on rate of decomposition (Roberts, Spencer and Dabbs 2017, 1145-1150). The calculated BMI only reflects the state of the body post-mortem. No ante-mortem BMI were provided for any of the forensic cases, therefore, loss of mass comparisons were unattainable.

Calculation of post-mortem interval (PMI)

Through review of death investigation reports and circumstantial evidence provided with each case, PMI (in days) was calculated by subtracting the date of discovery from the date that they were last known to be alive. Within forensic practice, as opposed to experimental practice, the exact date that an individual died may not be obtainable due to concealment following a murder or as a result of neglect and social isolation.

The morgue time (in days) for each case was calculated by subtracting the date that the autopsy was conducted from the date of discovery. Total PMI (days) was calculated to include morgue time as no scene photographs were available to make a comparison to determine whether this had any impact. Only forensic cases where a known PMI could be assigned were included in this study as unknown PMIs would introduce too large a number of standard errors.

Decomposition scoring

With no clear consensus towards what constitutes extensive or partial mummification, a body part scoring system applicable to all extents of mummified human remains (0-100%) was first adapted from Leccia, Alunni and Quatrehomme's (2018) model through post-mortem photographs. This study implemented the Lund and Browder chart where anatomical regions were further divided, see (Table 2), rather than the Wallace "rule of nine" as the former is more representative of TBSA (Wachtel et al. 2000, 156-170; Yastı et al. 2015, 79-89). As many of the cases exhibited both skeletonization and mummification, the same system was used in conjunction. The body was first visually divided into sections and mummification for each section was given a percentage, see (Figure 2). Each section's percentage was first converted to a decimal by dividing by 100 and multiplied by the section's value (e.g., 15% of anterior left upper leg is 15÷100=0.15, 4x0.15=0.6). Once this had been completed for all body sections all values were summed giving the final TBSA. Skeletonization also followed this method, showing what percentage of a body had been affected by mummification, skeletonization, and what remained unaffected by these two post-mortem changes.

Figure 2. Visual diagram of an adult human body divided into sections. Anterior and posterior foot is 1.75% so that the sum total is 100%. (Yastı et al. 2015, 79-89.

Table 2. Modified Lund and Browder chart to calculate total body surface area in adult mummified remains. Each value equates to percentage of an adult human body totalling 100% (adapted from Yastı et al. (Yastı et al. 2015, 79-89)).

Statistical analysis

In this study there are multiple variables, body sections and individual characteristics such as age, ancestry, sex, BMI. The number of variables were minimised by calculating the correlations between them using principal component analysis (PCA). This helped to identify the mummified and skeletonized body sections with high correlation co-efficients, those that will mummify and/or skeletonize at the same time with high confidence. Secondly, PCA helped to indicate the best individual characteristics to use in the regression. This statistical method uses an orthogonal transformation which converts a correlated set of observations to an uncorrelated set of components (Wright 1985, 35-38). By using this method, the correlation coefficients matrix table was calculated, and thus which variables are mostly related to each other was established. Regression analysis was used to find out the relationship between the dependent (PMI days) and independent variables (age, sex, ancestry, BMI, body position, and body location). Statistical procedures were conducted through IBM SPSS 25.0.0.0 for Macintosh and Microsoft Excel 16.16.5 for Macintosh.

Results

Decomposition scoring

Many of the forensic cases within this study displayed both mummification and skeletonization, and active decomposition simultaneously. The seasonal breakdown of discovery exhibited 2 in spring, 9 in summer, 4 in autumn, and 2 in winter. The months of May-October are warm and humid in Pittsburgh, the results show that over half of cases (n=13) were discovered during this time period with the majority during the month of August (n=5) suggesting that discovery of a body is more likely during these months. No deaths were recorded in January, March, October or December.

As observed in Figure 3, approx. half of the cases exhibited a combination of mummification and skeletonization to varying degrees (n=8) and no cases were reported as fully skeletonized or without mummification. Cases that displayed mummification had a TBSA that ranged from 0.5-86.94 with a mean of 35.83 whilst those showing skeletonization had a TBSA that ranged from 0-30.52 with a mean of 6.56. Overall, no correlation between TBSA and PMI was noted without the inclusion of intrinsic and extrinsic variables.

Figure 3. Distribution of Mummification TBSA and Skeletonization TBSA by total PMI (days)

Table 3. Seventeen forensic cases included in this study displaying mummification and skeletonization

Table 3. (Continued)

Factor analysis of body part scores

Individual body part scores were used in PCA to determine any covariance between the scores without losing the data values (Wright 1985, 35-38). The results of which illustrate the body parts with a high correlation co-efficient, of which mummification or skeletonization co-existed in >0.95 of cases. These values indicate a high confidence that they will co-exist on a decomposing body. Values below this would not be appropriate for combination due to variation. There was no missing data and the correlation matrix table was generated (Appendix 1). There were many body parts, only those with high correlation value (i.e., 0.95 or greater) can be found in (Table 4) whilst the original table can be found in (Appendix 1). As illustrated in the original table (Appendix 1), anterior left lower leg mummification has a high correlation with anterior right lower leg mummification, 0.97, and thus can be combined with greater confidence than anterior left hand mummification and posterior right upper arm mummification which had a correlation co-efficient of 0.55. Despite the high correlation between body parts with 0.95-0.99, such as anterior left hand skeletonization and posterior left hand skeletonization, caution should be noted as in 1% of cases these two may not coexist. Under controlled conditions, the correlation co-efficient would be 1.00, indicating that in all 17 cases two body parts would become mummified or skeletonized without uncertainty.

Table 4. Mummification and skeletonization correlation matrix table of individual body scores

Table 4. (Continued)

Factor analysis of intrinsic and extrinsic variables

Individual characteristics included in the PCA calculation were intrinsic (age, ancestry, sex[2], height and weight (combined to calculate BMI) and extrinsic (body location and body position) variables, see (Table 3) for full details. As seen in (Table 5), there were no missing observations in the data. Age and BMI display the greatest mean and standard deviation, suggesting a wide range of values included in the dataset.

Table 5. Descriptive statistics of the 17 cases, 4 intrinsic and 2 extrinsic variables being analysed

The correlation matrix (Appendix 2, Table 6) of all 6 variables showed low correlations, none of the variables correlated higher than 0.29. The determinant score of the correlation matrix is 0.252, which is significantly different from zero indicating an issue with multicollinearity, in that there is a lack of it. In order to resolve this, the variable causing the issue, body position, needs to be removed (Whitley and Kite 2013, 342).

A KMO and Bartlett test (Kaiser-Meyer-Olkin Measure of Sampling Adequacy and Bartlett's Test of Sphericity) (Appendix 2, Table 7) showed that the KMO test value was (0.474) with a p-value of (0.255), the variables were not statistically significant.

The components of the total variance table (Appendix 2, Table 8) are the 6 intrinsic and extrinsic variables of the 17 cases used throughout this paper. The amount of variance in these variables is known as the eigenvalue, shown in the total columns. The sum of the initial eigenvalue total is 6, confirming that there are 6 components. Eigenvalues greater than 1 are extracted, the first 2 components are used. There was a break after two components and the 'Cumulative %' column of (Appendix 2, Table 8) shows that 61% of total variance has been explained by the first two components.

The results of the correlation matrix and total variance (Appendix 2, Table 6 and 8) were taken and a rotated component matrix (Appendix 2, Table 9) using varimax rotation with Kaiser normalization was computed as all factor correlations were low. The rotated component matrix illustrates that all the variable's values were strong with body position having weaker values than others.

Factor Analysis excluding variable 'body position'

Factor analysis was run whilst keeping the same individual characteristics included in the PCA calculation. The KMO and Bartlett test value was 0.514, greater than the previous KMO and Bartlett test value however, there was a lower significance value than previously seen of 0.15. Excluding body position resulted in almost 69% of total variance being explained by the first 2 components.

The final rotated component matrix (Table 10) shows that the majority of variables had a strong value, i.e. values that are large in magnitude, those that are positively or negatively farthest from zero, suggesting that no more variables need to be excluded from

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[2] The USA classification used in the original database is referred to as 'gender' however in the UK this terminology is seen as an identity rather than a genetic difference.

factor analysis, and the second analysis was the best PCA. Excluding body position from the factor analysis resolved the issue with multicollinearity. Age, sex, ancestry, BMI and body location in the dataset are the most effective variables with the strongest values.

Table 10. Rotated component matrix excluding body position, varimax rotation with Kaiser Normalization rotation converged in 3 iterations

Regression analysis

The materials and methods section of this paper explains that total PMI (days) is the dependent variable, as this variable needs to be predicted in various situations. PCA analysis indicated that the independent variables are age, sex, ancestry, BMI, and body location as these variables have the greatest effect on the dataset. Regression analysis was conducted using these parameters.

Simple linear regression was first used to determine the association between the dependant variable and each independent variable, these yielded low R squared values, see (Table 11).

Table 11. Simple linear regression results

Multiple regression analysis combined the dependant variable and the 5 independent variables. (Table 12) shows the model summary of the data using the predictors constant, body location, sex, age, BMI, and ancestry. The multiple R value, 0.661, was greater than any of the simple linear regressions indicating that 66% of the variance has been explained.

Table 12. Overall model fit

Unstandardized predicted values were derived from the regression equations based on the intercept (constant) and unstandardized (independent variable) slopes, these predicted values were used to predict the dependant variable. The relationship between the predicted value and the dependant value corresponds to R (Figure 4). When comparing the prediction error around the line of best fit, there is a greater amount in the individual simple regression models than the multiple regression model. The R square value, 0.437, shows that 43.7% of the total variation in the dependant variable (total PMI days) can be explained by the independent variables (age, sex, ancestry, BMI, body location) in combination. This value is not high suggesting that there is a low goodness of fit. Despite the low standard error, adjusted R square decreased this value to 18.1% confirming that many of the independent variables are a poor fit for the model.

Figure 4. Multiple regression scatter plot

Analysis of variance (ANOVA) was used to determine whether the model or the mean of the independent variables was better at predicting the outcome and calculates the independent variable's predictive power. The F statistic (regression mean square divided by residual mean square) is not significantly above 1 (1.709), on their own each variable is not predictive enough to be statistically significant. The F statistic is not significant.

As shown in (Table 13), the B values are the regression values used to predict the dependant value in the multiple regression analysis. The coefficients are not significant at 1% or 5% level of significance. Based on the PCA, the variables are expected to be highly significant.

Table 13. Parameter estimates of the dependant variable against the independent variables. The dependant variable is total PMI in days

Discussion

This study aimed to explore the intrinsic and extrinsic variables that promote mummification and skeletonization on the decomposing body by utilizing a dataset of 17 indoor and outdoor cases within the metropolis of Pittsburgh, USA. The data collected from the selected cases was statistically analysed to quantitatively define these variables for use in forensic investigations.

One of the key aims of this research was to quantitatively define any intrinsic or extrinsic variables (Table 3) that positively influence mummification through the use of a secondary analysis of a dataset from Pittsburgh, USA (Giles 2014). Papers written by Galloway et al. (1969) and Pinheiro (2006) include skeletonization, 'hence skeletonization was included.

TBSA of each forensic case (n=17) was recorded using a modified Lund and Browder chart and graphically depicted against total PMI (days). Positive results were not seen with no connection between TBSA and total PMI (days). This may have been due to the lack of bodies included in the analysis. In order to resolve this, PCA was conducted using 4 different intrinsic (age, ancestry, sex, BMI) and 2 extrinsic variables (body location and body position). KMO and Bartlett test showed inadequacies within the sample and the rotated component matrix suggested a second analysis be conducted with the removal of body location. The second PCA found that 69% of total variance was explained by age, sex, ancestry, BMI and body location making them the most influential variables. However, multiple regression analysis found that due to the limited sample size, significance was not found until the 10% level. It is recognised that a significance level of 5% (0.05) is generally accepted. However, an observable effect can be seen from the p>0.10 of this preliminary study, the 90% confidence level stipulates further study (Zar 2013, 71-102; Nuzzo 2014, 150-152). Despite this, age was found to have the most influence on the dataset. The influence that age has on mummification and skeletonization has not been specifically investigated however some researchers have included this in their decomposition studies. It should be noted that these studies involved the use of both child and adult bodies. Janaway (1996) concluded that in both archaeological and forensic cases, mummification of children is more common than in adults of the same environments (Janaway 1996, 70).

Another of this study's aims was to improve on Leccia, Alunni and Quatrehomme's model that calculated TBSA in forensic cases that presented with >50% mummification by assessing all degree and extent of mummification. A modified Lund and Browder chart was able to further achieve this by giving a greater representation of mummification and skeletonization in relation to TBSA. This model attempted to illustrate that an accurate PMI could be estimated using intrinsic and extrinsic variables with mummification and skeletonization TBSA. PCA was also used with individual body part scores to determine the mummified or skeletonized body parts that would most likely co-exist on a decomposed human body, (Table 4) shows these body parts. Within the body parts of the 17 cases, there was no indication of mummification and skeletonization co-existing in >0.95 of cases. There was, however, evidence of co-existence with lower confidence, e.g., mummification of the anterior head and skeletonization of the posterior torso which had a correlation co-efficient of 0.54. These two states of decomposition are not a common occurrence however, partial mummification and skeletonization have been found to co-exist on a body in forensic contexts (Pinheiro 2006, 85-116). Evidence of separate mummification and skeletonization co-existence was found (e.g., mummification of the anterior left hand and posterior left hand, skeletonization of the anterior right lower arm and posterior right lower arm). This is congruent with the findings of Janaway, who found that mummification of hand and arm tissue is commonly found (Janaway 1996, 70). This is reinforced forensically by a case study where only the right hand and arm were held vertically and became mummified. (Verhoff, Schütz and Lasczkowski 2003, 185-188). Aturaliya and Lukasewycz demonstrate, through experimental conditions, that vertical versus horizontal body position has an influence on speed of desiccation (Aturaliya and Lukasewycz 1999, 893-896).

Caution should be given towards the use of the scoring method in this paper as it has only been used experimentally however, a future consideration would be to test this constraint under experimental conditions to further its validity before use in forensic practice. Only complete, adult human remains are acceptable for this model due to the findings of other academics. Adults and children have been found to have different decompositional changes relating to body size and surface-to-volume ratios (Morton and Lord 2002, 151-171). An adult body is larger in size with a smaller surface-to volume ratio, they do not succumb to post-mortem effects as quickly as children as their weight largely consists of water (Lyman 1994; Aufderheide 2011, 75–80; Blau and Forbes 2016, 227-235). Bone mineral density (BMD) decreases as organic material is lost in the post-mortem environment but can also result from starvation in children (Ross and Abel 2011; Hale and Ross 2018, 1-19), it is lower in children than adults even before death. This reduced amount of mineralized bone combined with the smaller size likely explains the difference in decomposition rates (Manifold 2012, 51–69). Bodies presenting with some form of mummification and/or skeletonization should be included as this study focused predominantly on these two states of decomposition.

It is advised that this method be used with the body in question present, multiple good quality photographs of all aspects of the body are a suitable alternative (Ribéreau-Gayon et al. 2018, 167-176). Experimental field studies with a greater number of bodies may also be useful as this study has shown n=17 subjects to produce limited results. The small number of observations per case (n=17) can often result in results not being as representative as larger sample sizes. Control over certain variables such as temperature, age, indirect/direct sunlight, indoor/outdoor, BMI, etc. could lead to important conclusions being made to support this study's findings. Should significant results be seen, research into different climates worldwide may produce significantly different environmental differences. With regionally specific variables, e.g., temperature, humidity, soil pH, being diverse, globally different researchers are encouraged to utilize this method as a way of differentiating variables for greater forensic application worldwide (Cockle and Bell 2015, 136.e1-136.e9).

The relatively small dataset of this study has shed light onto the forensic importance that bodies displaying mummification and skeletonization have concerning medico-legal investigations. PMI estimations may be achieved with a larger dataset and further investigation.

About the authors

Chloe Jackson-Mitchell graduated from Cranfield University in 2019 with a MSc in Forensic Archaeology and Anthropology, before which obtaining a BSc honours in Archaeology from University of Reading. Her research interests include human decomposition and the encompassing taphonomic processes. Currently she is a member of British Association for Biological Anthropology and Osteoarchaeology and a team member of Cranfield Recovery and Identification of Conflict Casualties team.

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Table 1. Cause and manner of death for 17 cases included in this paper.

Cause of death	**Manner of death**
Blunt force trauma	Accidental
Blunt force trauma	Homicide
Blunt force trauma	Homicide
Undetermined	Homicide
Natural	Natural
Natural	Natural
Atherosclerotic Cardiovascular Disease	Natural
Atherosclerotic Cardiovascular Disease	Natural
Blunt force trauma	Suicide
Asphyxiation	Suicide
Asphyxiation	Suicide
Asphyxiation	Suicide
Undetermined	Undetermined
Undetermined	Undetermined
Undetermined	Undetermined
Asphyxiation	Undetermined
Drugs and/or poison	Undetermined

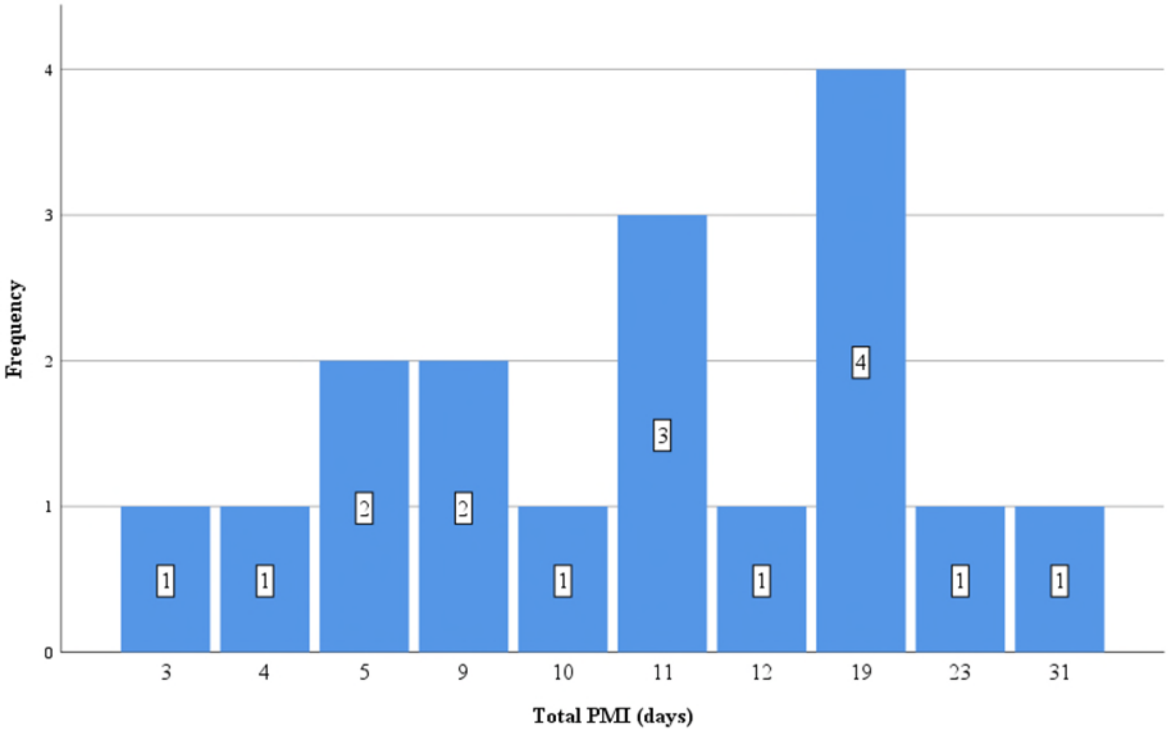

Figure 1. Frequency distribution of cases by total PMI (days) (n=17)

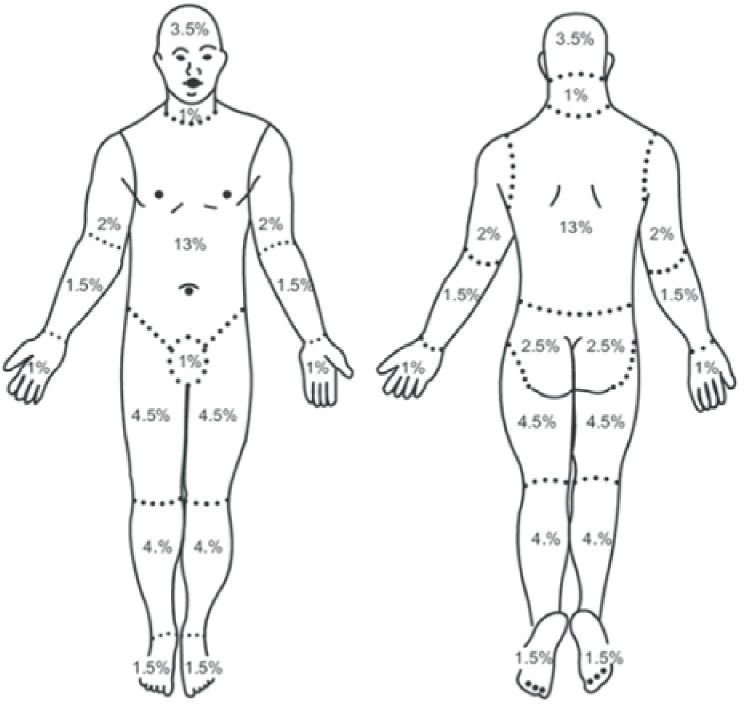

Figure 2. Visual diagram of an adult human body divided into sections. Anterior and posterior foot is 1.75% so that the sum total is 100%. (Yastı et al. 2015, 79-89.

Table 2. Modified Lund and Browder chart to calculate total body surface area in adult mummified remains. Each value equates to percentage of an adult human body totalling 100% (adapted from Yastı et al. (Yastı et al. 2015, 79-89)).

	Anterior	Posterior
Head	3.5%	3.5%
Neck	1%	1%
L. Upper Arm	2%	2%
R. Upper Arm	2%	2%
L. Lower Arm	1.5%	1.5%
R. Lower Arm	1.5%	1.5%
L. Hand	1%	1%
R. Hand	1%	1%
Torso	13%	13%
Anterior genitalia and perineum/ Posterior L. and R. buttocks	1%	2.5%
		2.5%
L. Upper Leg	4.5%	4.5%
R. Upper Leg	4.5%	4.5%
L. Lower Leg	4%	4%
R. Lower Leg	4%	4%
L. Foot	1.75%	1.75%
R. Foot	1.75%	1.75%

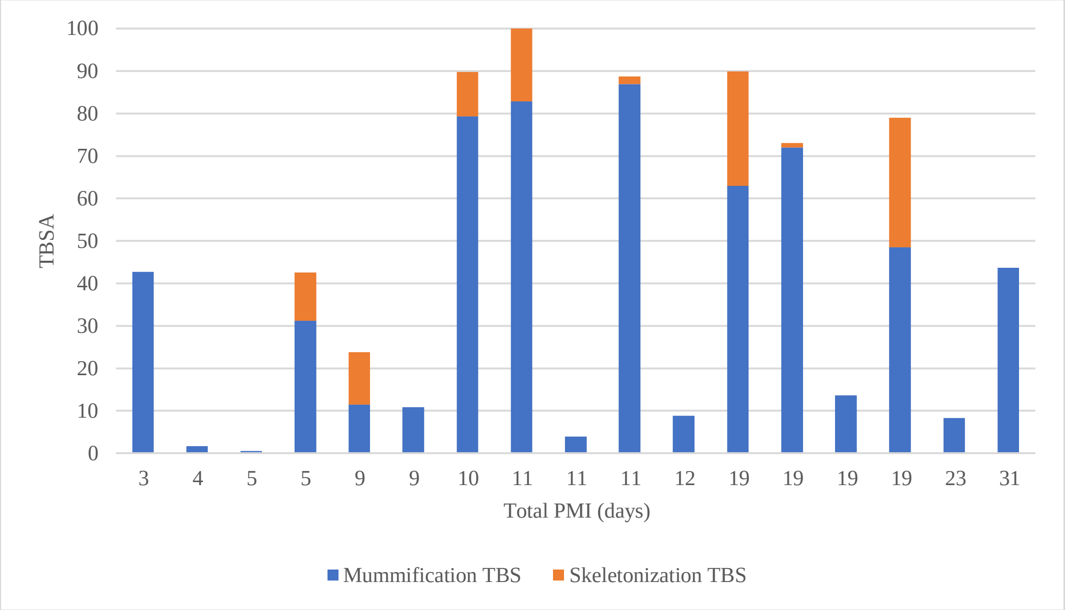

Figure 3. Distribution of Mummification TBSA and Skeletonization TBSA by total PMI (days)

Table 3. Seventeen forensic cases included in this study displaying mummification and skeletonization

	Age*, race, sex	**BMI**	**Body Location**	**Body Position**	**Clothing**	**Cause of Death**	**Manner of Death**	**LKA† evidence**	**PMI (days)**	**Morgue Time (days)**	**Total PMI (days)**	**Mummification TBSA**	**Skeletonization TBSA**
1	52 - OA, white, male	3.8	Indoors	Sitting	None	Undetermined	Undetermined	Witnessed	10	1	11	82.88	17.12
2	66 - OA, white female	54.6	Indoors	Sitting	Upper	Natural	Natural	Witnessed	3	1	4	1.6	0
3	36 - MA, white, female	8.0	Outside	Prone	None, rolled up in a carpet	Undetermined	Homicide	Missing person report	18	1	19	62.99	26.94
4	57 - OA, white, female	14.1	Outside	Unknown	Full (Upper and Lower)	Blunt force trauma	Suicide	Missing person report and suicide note	9	1	10	79.31	10.45
5	50 - MA, white, male	24.5	Outside	Vertical	Full (Upper and Lower)	Asphyxiation	Suicide	Missing person report and car sighting	18	1	19	71.98	1.05
6	38 - MA, black, male	26.2	Indoors	Vertical	Full (Upper and Lower)	Asphyxiation	Suicide	Dated suicide note	4	1	5	0.5	0
7	62 - OA, black, male	20.1	Indoors	Right lateral	Full (Upper and Lower)	Asphyxiation	Undetermined	Missing person report	10	1	11	3.88	0
8	57 - OA, white, female	28.0	Indoors	Prone	Upper	Atherosclerotic Cardiovascular Disease	Natural	Missing person report	8	1	9	11.41	12.41

Table 3. (Continued)

9	50 - MA, white, female	18.8	Outside	Prone	None	Blunt force trauma	Homicide	Missing person report	5	0	5	31.21	11.35
10	53 - OA, white, male	19.3	Outside	Supine	Full (Upper and Lower)	Drugs and/or poison	Undetermined	Missing person report	8	3	11	86.94	1.76
11	18 - YA, black, male	21.4	Outside	Prone	Full (Upper and Lower)	Undetermined	Undetermined	Missing person report	23	0	23	8.23	0
12	52 - OA, white, male	28.1	Indoors	Kneeling	Full (Upper and Lower)	Asphyxiation	Suicide	Missing person report and CCTV	19	0	19	13.63	0
13	44 - MA, black, male	27.2	Indoors	Sitting	Full (Upper and Lower)	Atherosclerotic Cardiovascular Disease	Natural	Missing person report and CCTV	30	1	31	43.7	0
14	36 - MA, white, male	5.8	Outside	Prone	Full (Upper and Lower)	Undetermined	Undetermined	Missing person report	16	3	19	48.51	30.52
15	84 - OA, black, male	17.7	Indoors	Unknown	Nightwear	Natural	Natural	Witnessed and delayed report	2	1	3	42.73	0
16	60 - OA, white, female	17.9	Outside	Foetal	Upper and lower + bin bag and tape	Blunt force trauma	Homicide	Missing person report	12	0	12	8.76	0
17	63 - OA, white, male	28.1	Indoors	Supine	Nightwear	Blunt force trauma	Accidental	CCTV and recorded key swipe	8	1	9	10.77	0

⁎ “OA” indicates older adult (50+), “MA” indicates middle adult (35-50), “YA” indicates young adult (18-35)
† “LKA” indicates last known alive

Table 4. Mummification and skeletonization correlation matrix table of individual body scores

Mummification combined body parts	Correlation co-efficient	Skeletonization combined body parts	Correlation co-efficient
Anterior left upper arm Posterior left upper arm	0.98	Anterior left upper arm Posterior left upper arm	0.95
Anterior right upper arm Posterior right upper arm	0.97	Anterior right upper arm Posterior neck	0.96
Anterior right lower arm Posterior right lower arm	0.99	Anterior right upper arm Posterior right upper arm	0.98
Anterior left hand Posterior left hand	0.99	Anterior right upper arm Posterior right buttocks	0.97
Anterior right hand Posterior right hand	0.98	Anterior right lower arm Posterior right lower arm	0.98
Anterior left lower leg Anterior right lower leg	0.97	Anterior left hand Posterior left hand	0.99
Anterior left lower leg Posterior right lower leg	0.95	Anterior left upper leg Anterior right foot	0.96
Anterior right lower leg Posterior right lower leg	0.97	Anterior left upper leg Posterior left lower leg	0.99
Anterior left foot Anterior right foot	0.99	Anterior right lower leg Posterior right lower leg	0.96
Anterior left foot Posterior right foot	0.99	Anterior left foot Posterior right foot	0.99
Anterior right foot Posterior left foot	0.99	Anterior right foot Posterior left lower leg	0.96
Anterior right foot Posterior right foot	0.99	Anterior right foot Posterior left foot	0.98
Posterior left buttocks Posterior right buttocks	0.99	Anterior right foot Posterior right foot	0.99
Posterior left foot Anterior right foot	0.99	Posterior neck Posterior right upper arm	0.95
Posterior left foot Posterior right foot	0.99	Posterior neck Posterior right foot	0.95
		Posterior left foot Anterior right foot	0.98
		Posterior left foot Posterior right foot	0.99

Table 5. Descriptive statistics of the 17 cases, 4 intrinsic and 2 extrinsic variables being analysed

	Mean	Std. Deviation	Analysis N
Age	51.65	14.769	17
Race	1.29	.470	17
Gender	1.35	.493	17
BMI	21.388	11.5289	17
Body Location	1.47	.514	17
Body Position	4.65	2.120	17

Table 6. Rotated component matrix excluding body position, varimax rotation with Kaiser Normalization rotation converged in 3 iterations

	Component	
	1	2
Body Location	-.767	.476
Age	.762	.184
BMI	.750	.033
Gender	.120	.850
Race	.064	-.840

Table 7. Simple linear regression results

Dependant variable	Independent variable	R squared value
Total PMI (days)	Age	0.383
Total PMI (days)	Sex	0.096
Total PMI (days)	Ancestry	0.021
Total PMI (days)	BMI	0.038
Total PMI (days)	Body location	0.053

Table 8. Overall model fit

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.661	.437	.181	6.901

Table 9. Parameter estimates of the dependant variable against the independent variables. The dependant variable is total PMI in days

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	32.376	16.134		2.007	.070
	Age	-.291	.140	-.563	-2.082	.061
	Race	-.374	4.421	-.023	-.085	.934
	Gender	-4.081	4.307	-.264	-.948	.364
	BMI	.013	.175	.019	.072	.944
	Body Location	.902	4.731	.061	.191	.852

Table 10. Rotated component matrix excluding body position, varimax rotation with Kaiser Normalization rotation converged in 3 iterations

	Component	
	1	2
Body Location	-.767	.476
Age	.762	.184
BMI	.750	.033
Gender	.120	.850
Race	.064	-.840

Table 11. Simple linear regression results

Dependant variable	Independent variable	R squared value
Total PMI	Age	0.383
Total PMI	Sex	0.096
Total PMI	Ancestry	0.021
Total PMI	BMI	0.038
Total PMI	Body location	0.053

Table 12. Overall model fit

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.661	.437	.181	6.901

Figure 4. Multiple regression scatter plot

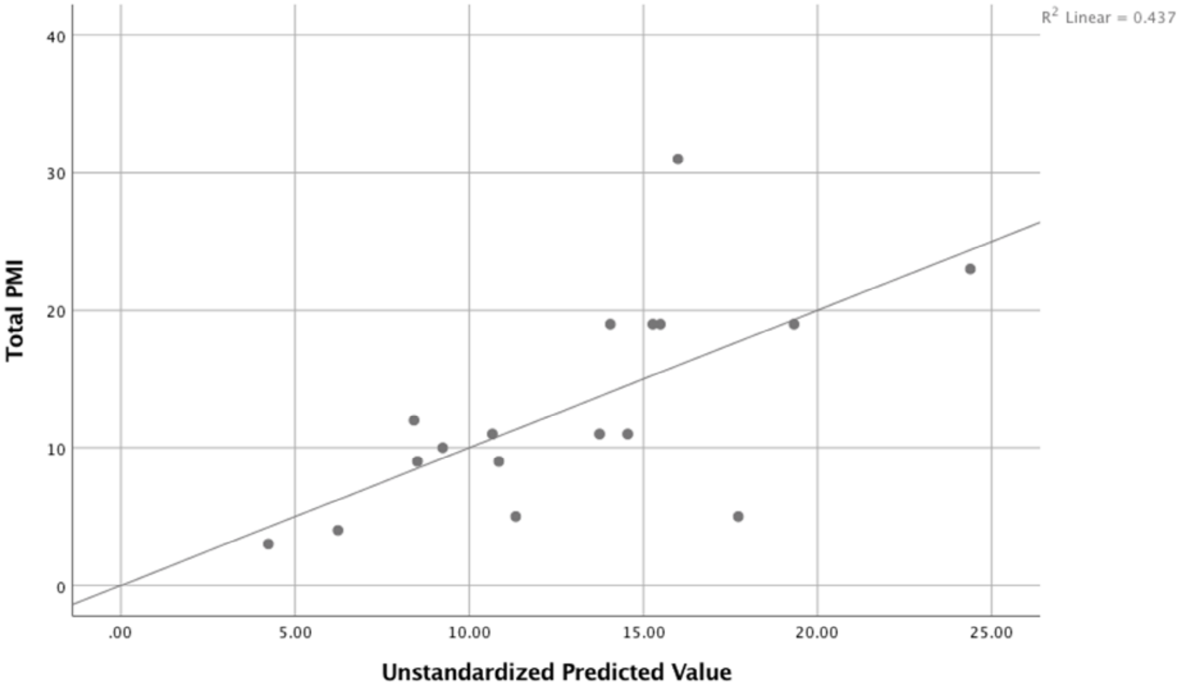

Table 13. Parameter estimates of the dependant variable against the independent variables. The dependant variable is total PMI in days

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	32.376	16.134		2.007	.070
	Age	-.291	.140	-.563	-2.082	.061
	Race	-.374	4.421	-.023	-.085	.934
	Gender	-4.081	4.307	-.264	-.948	.364
	BMI	.013	.175	.019	.072	.944
	Body Location	.902	4.731	.061	.191	.852