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Quantifying human post-mortem movement resultant from decomposition processes

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ABSTRACT

Background: Post-mortem movement is highly significant in unexplained death investigations, as body position or the position of remains helps to determine cause and manner of death, as well as potentially the circumstances surrounding death. Therefore, understanding post-mortem movement is of forensic relevance in death scene assessments.

Purpose: The aim of this study was to quantify post-mortem movement in anatomical structures of a human donor during decomposition in an Australian environment, an evaluation that has not previously been undertaken.

Methods: The aim was achieved using time-lapse images of a human donor decomposing in order to capture the post-mortem movement over a 16-month period. Megyesi et al.'s [1] total body score system was used to quantify the decomposition of the donor in each image to determine the decomposition stage. ImageJ software was used to determine the distance from static landmarks to anatomical structures of interest in each image to allow for quantification.

Results: Early decomposition progressed rapidly, and advanced decomposition plateaued at 41 post-mortem interval days with a total body score of 24. The results support the conclusion that post-mortem movement does occur in all limbs of the donor. The anatomical structure that produced the most movement was the right styloid process of the radius, moving a total distance of 51.65 cm. A surprising finding of the study was that most post-mortem movement occurs in the advanced decomposition stage, with the lower limbs being the most active.

Conclusion: This study supports that post-mortem movement can be quantified using time-lapse imagery, with results supporting movement in all limbs, a process that was active for the entire study period. An interesting finding was that the decomposition plateaued in the advanced stage with the donor remaining in mummification, and not reaching skeletonization after 16 months *in situ*. These findings are of significant importance to police in death scene assessments and forensic investigations.

1. Introduction

Post-Mortem Movement (PMM), or movement after death, can be an important factor to consider in unexplained death investigations. Scenes involving human remains can be complicated to process, especially where the remains are in an advanced stage of decomposition. An accurate assessment of the scene is vital to help identify the victim and/or perpetrator if a crime has been committed, as well as helping to determine cause and manner of death. Forensic anthropologists and pathologists are often called upon by law enforcement to apply their expertise to death investigations and contribute to an understanding of cause of death and how long the remains have been *in situ*. Both of these factors can be difficult to determine if the remains are in poor condition, or have moved from their original deposition site [2].

Post-Mortem Interval (PMI), or time since death, can be estimated by scoring human decomposition using published formulas, such as Megyesi et al.'s [1] Total Body Score (TBS). For unidentified

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remains these estimates can be entered into databases for comparison with dates when people have been reported missing, to help decrease the potential matches in missing person's lists [3]. PMI can help lead to identification of victims, ensuring the rights of the deceased and assist with the return of remains to their families [2].

Where an unexplained death has occurred, the police will map the crime scene, recording the arrangement of remains or a victim's body position, and all physical evidence found [4]. This mapping process can help police determine the cause of death and/or circumstances surrounding the death, for example if the death occurred as a result of natural causes or homicide. Incorrect assessment of the cause of death or misinterpretation of a crime scene can lead to perpetrators going free and lack of closure for victim's families, or innocent people being wrongly accused of a crime.

Decomposition processes along with physical disruption (for example scavenging by animals and insects) can affect a victim's body position or remains after death [5]. Other natural processes (including environmental conditions such as extreme heat or heavy rain, or the effects of gravity in a hanging death for example) can also change the condition or location of human remains [6]. The body position at time of death is crucial in death investigations, this can assist with establishing a cause of death and/or circumstances surrounding the death, therefore making any PMM of remains highly significant in forensic cases. No studies to date have mapped PMM that occurs as a result of the decomposition process. Research in decomposition studies primarily focus on PMI, clandestine grave site detection, grave soil ecology, effect of scavengers, and scene interpretation [7].

Wilson et al.'s [3] study used time-lapse cameras for the first time to capture the decomposition of a human donor in an Australian environment. The study found time-lapse imaging allowed for greater frequency of scoring decomposition [3]. Time-lapse imagery data can be used to better inform the police about potential PMM, reducing the likelihood of misinterpretations of a crime scene. Therefore, not taking advantage of time-lapse imaging to monitor post-mortem movement could result in misinterpretations of scenes and/or the cause of death in forensic investigations.

Very little is known about decompositional movement in the human body, and this lack of understanding could potentially mislead estimates of, for example cause of death, and result in criminal acts going unpunished. Data quantifying post-mortem movement would be of use to police when undertaking crime scene assessments and forensic investigations. As a result, a descriptive study was carried out using time-lapse imaging, with the aim to quantify post-mortem movement in anatomical structures of a human donor during decomposition. The study investigated the amount of PMM, at which stages of decomposition this occurs, and which parts of the body display PMM. The design allowed the study to answer the research questions: 1) How much PMM occurs in a human donor decomposing in an Australian bushland environment? 2) Does PMM occur in all parts of the human donor and which parts display the most movement? 3) At which decomposition stages does PMM occur in a human donor?

2. Materials and Methods

The sample population for this study consisted of one human body, donated to the Australian Facility for Taphonomic Experimental Research (known as AFTER), managed by University of Technology Sydney (UTS). Security measures, such as Closed-Circuit Television (CCTV) and swipe card access points, prevent non-authorised human entry, and fences stop land-dwelling scavengers from accessing the premises. It is located in a bushland environment in New South Wales, Australia. AFTER's body donation program is an invaluable willed-body donation program, managed by UTS, where donors wish to bequeath their bodies after death for the purpose of taphonomic research.

Within 24-hours of death, the donor was transported to AFTER. The donor was a non-autopsied mature male, who was recorded upon arrival at the facility as 1.82m tall. He died of natural causes and had no major penetrating injuries or trauma. Present on the donor's legs were minor scrape-type injuries that occurred perimortem, and which were unlikely to affect the natural decomposition process.

The donor was placed unclothed in a supine position outdoors at AFTER on the natural ground surface inside a cage (an ethical requirement for this study). The cage measured 4.35m high, by 2.40m wide, and 4.35m long (Table 1), and consisted of metal mesh grids to prevent any avian scavenger activity disturbing or removing the remains. The donor was placed *in situ* in February 2018 with his head to the east (cardinal direction), and 0.45m from the top of the cage, and his right shoulder 0.66m from the side of the cage (Fig. 1). The cage was fitted with a door to allow researchers full access to all sides of the donor whilst he remain *in situ* to prevent disturbance to the body, minimising any external effects on the decomposition process. (Due to ethical restrictions it is not possible to publish images of the donor).

2.1. Environment

The donor was exposed to the natural elements of the Australian bushland at AFTER, which is located at the base of the Blue Mountains in New South Wales. The environment consists of eucalypt bushland with temperatures reaching highs of 42 °C in the summer months and lows of less than 0 °C at night in winter.

Environmental conditions and descriptive statistics were calculated using data obtained directly from the AFTER weather station, but when unavailable, from the Richmond RAAF base weather station.

2.2. Time-lapse Cameras

Time-lapse photography was used to capture images that facilitated quantification of PMM in the human donor. This study facilitated visual observation of the decomposition processes of the donor using the time-lapse images taken between February 2018 and June 2019.

Five Brinno TLC 200 Pro time-lapse cameras with a resolution of

Table 1
Camera Placements, Cage Dimensions and Donor Placement.

Camera	Description	Measurement
A	Full top view of entire body	2.2m from ground surface
B	Directly above face	0.53m from ground surface
C	Directly above right hand	0.53m from ground surface
D	Directly above left hand	0.44m from ground surface
E	Profile view of body	0.25m from ground surface
Donor		
F	Donor	
	Height of donor	1.82m
	Inside cage to head of donor	0.45m
	Inside cage to right shoulder of donor	0.66m
Cage Dimensions		
	Height	4.35m
	Width	2.40m
	Length	4.35m

Note: m = metre.

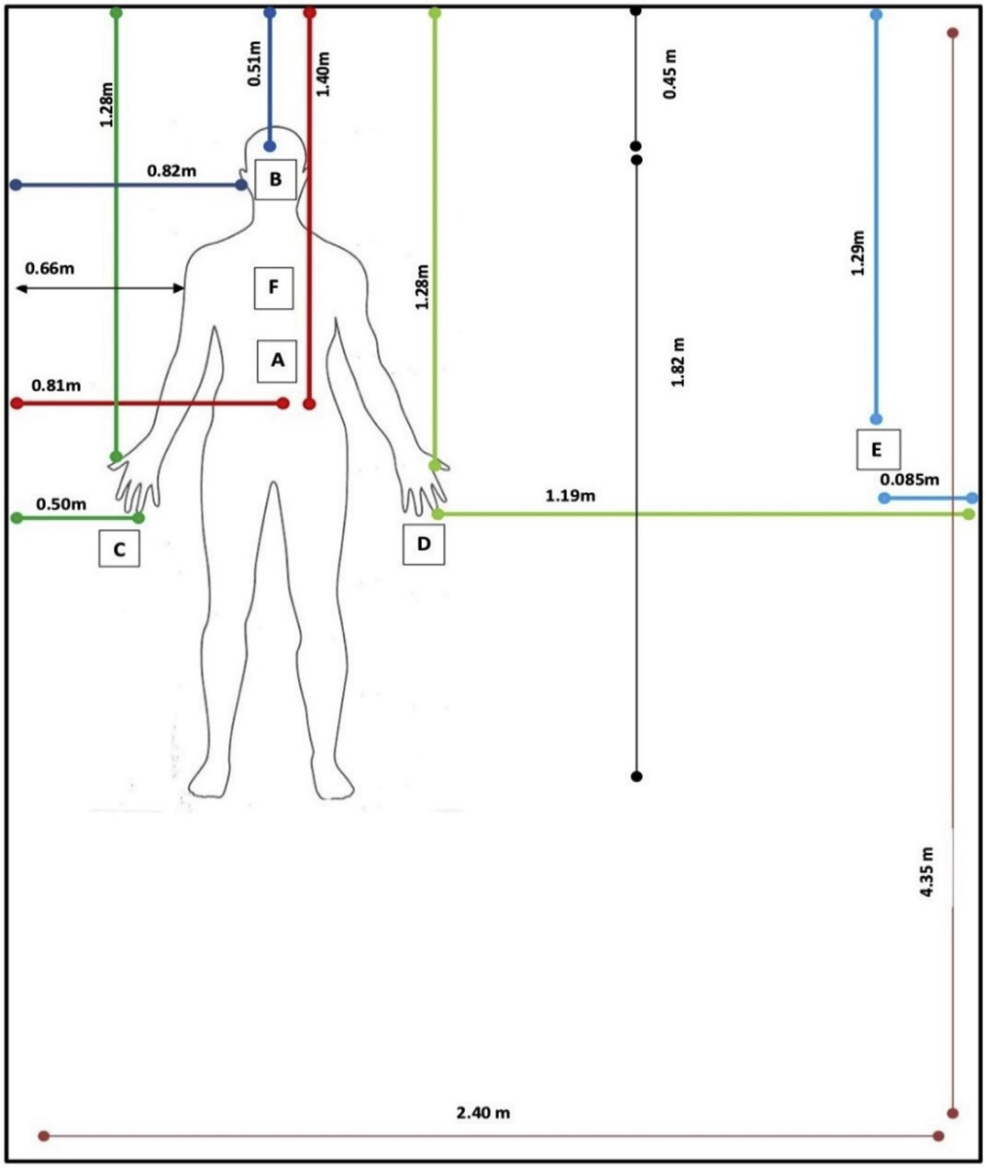

Fig. 1. Camera Placements, Cage Dimensions and Donor Placement.
Diagram not to scale.

1.3 mega-pixels were used to capture images of the decomposition process. The five cameras were fixed into position using steel support rods attached to the inside of the cage. Each of the five cameras were positioned above the face 0.53 m from the ground surface, the left hand 0.44 m from the ground surface, the right hand 0.53 m from the ground surface, as well as a top view 2.2 m, and a profile view of the entire body 0.25 m from the ground surface (Fig. 1 and Table 1). Time-lapse cameras were set to capture images every 30 min during daylight hours which was initiated within 2 hours of the donor arriving on site. Recording was only briefly stopped to change batteries in the cameras and download images from the Secure Digital (SD) memory cards to a secure laptop for approximately 1–2 minutes once every month. The top view camera A provided a full anterior view of the entire body (Table 1), it produced the best images to quantify the PMM and was used as the main data source for this study. Photographs were taken every 30 minutes of daylight hours over the 16-month period of decomposition. This is recognised as a limitation of the study as it was not possible to observe the PMM during the night.

From Camera A, one image captured at 15:00 hours every 24 hours of the 16-month study period, was selected to assess the decomposition process and quantify the PMM in the donor. This 15:00 hour timestamp was selected as the 24-hour observation time for this study as it is recorded as the hottest time of the day in Australia.

2.3. *Post-Mortem Interval*

The Post-Mortem Interval for the donor used in this study was known. In forensic cases where remains are found and a PMI is not known it can be estimated using published formulas such as Megyesi et al.'s [1] method, Total Body Score system (TBS) and Accumulated Degree Days (ADD). Wilson et al.'s study [3] tested Megyesi et al.'s [1] formulas in Australia on a human donor to estimate PMI using time-lapse images. The study produced results that correlated closely with the donors date of death, which indicated that Megyesi et al.'s [1] model does accurately predict PMI in the New South Wales environment of Australia.

Decomposition stages were observed and recorded for each image for this study using Megyesi's et al.'s [1] categories and stages of decomposition (Table 2). Megyesi et al.'s [1] TBS system involves ranking visual observations of decomposition using points to score three independent parts of the body; the head, torso, and limbs (Table 2). The scores for the three independent parts are added together to produce a total body score to represent the overall decomposition.

2.4. Static and Anatomical Landmark Points

Anthropometric landmarks were used to identify anatomical structures of the donor's body to allow for a direct comparison with static landmarks to quantify the PMM. Static landmarks and

Table 2
Categories and Stages of Decomposition (from Megyesi et al., 2005).

Categories and stages of decomposition for the head and neck
A Fresh - (1 pt) Fresh, no discoloration.
B Early decomposition - (2 pts) Pink-white appearance with skin slippage and some hair loss. - (3 pts) Gray to green discoloration: some flesh still relatively fresh. - (4 pts) Discoloration and/or brownish shades particularly at edges, drying of nose, ears and lips. - (5 pts) Purging of decompositional fluids out of eyes, ears, nose, mouth, some bloating of neck and face may be present. - (6 pts) Brown to black discoloration of flesh.
C Advanced decomposition - (7 pts) Caving in of flesh and tissues of eyes and throat. - (8 pts) Moist decomposition with bone exposure less than one half of that area being scored. - (9 pts) Mummification with bone exposure less than one half of that area being scored.
D Skeletonization - (10 pts) Bone exposure of more than half of the area being scored with greasy substances and decomposed tissue. - (11 pts) Bone exposure of more than half the area being scored with desiccated or mummified tissue. - (12 pts) Bones largely dry but retaining some grease. - (13 pts) Dry bone.
Categories and stages of decomposition for the torso
A Fresh - (1 pt) Fresh, no discoloration.
B Early decomposition - (2 pts) Pink-white appearance with skin slippage and marbling present. - (3 pts) Gray to green discoloration: some flesh relatively fresh. - (4 pts) Bloating with green discoloration and purging of decompositional fluids. - (5 pts) Post-bloating following release of the abdominal gases, with discoloration changing from green to black.
C Advanced decomposition - (6 pts) Decomposition of tissue producing sagging of flesh: caving in of abdominal cavity. - (7 pts) Moist decomposition with bone exposure less than one half that of the area being scored. - (8 pts) Mummification with bone exposure of less than one half that of the area being scored.
D Skeletonization - (9 pts) Bones with decomposed tissue, sometimes with body fluids and grease still present. - (10 pts) Bones with desiccated or mummified tissue covering less than one half of the area being scored. - (11 pts) Bones largely dry but retaining some grease. - (12 pts) Dry bone.
Categories and stages of decomposition for the limbs
A Fresh - (1 pt) Fresh, no discoloration.
B Early decomposition - (2 pts) Pink-white appearance with skin slippage of hands and/or feet. - (3 pts) Gray to green discoloration: marbling; some flesh still relatively fresh. - (4 pts) Discoloration and/or brownish shades particularly at edges, drying of fingers, toes, and other projecting extremities. - (5 pts) Brown to black discoloration, skin having a leathery appearance.
C Advanced decomposition - (6 pts) Moist decomposition with bone exposure less than one half that of the area being scored. - (7 pts) Mummification with bone exposure of less than one half that of the area being scored.
D Skeletonization - (8 pts) Bone exposure over one half the area being scored, some decomposed tissue and body fluids remaining. - (9 pts) Bones largely dry but retaining some grease. - (10 pts) Dry bone.

Take each point value and sum them to find the total body score (TBS).
For example: 5 (head) + 5 (torso) + 5 (limbs) = 15 TBS.
If an area of body has differential decomposition or different features (such as brown to black discoloration on relatively fresh skin on the torso) record both numbers. For the total body score, average the two numbers before totalling the body score.
Total body score is supposed to represent overall decomposition, so if you're unsure about where to fit a section of the body into a category either go for the lowest score or an average score.

anatomical landmarks were chosen to apply to each image as points to perform measurements of the post-mortem movement of the donor (Table 3). Static points acted as stationary points in all images to allow for a valid reference to measure from. For the upper limbs, the static point chosen was the umbilicus (US), (belly button) of the donor as it was present in all images, and the donor did not reach full skeletonization, with decomposition stopping at the mummification stage.

The static point for the lower limbs was the corner of a fixed camera rod (CRS) which was situated to the right of the donor and was present in each image (Fig. 2). The anatomical landmarks chosen were bony structures of the donor that were visually identifiable in each of the images. The upper limb anatomical landmarks consisted of the medial epicondyle of the humerus (MEH) for both the right and left sides to mark the elbow of the donor, the styloid process of the radius (SPR) for both the right and left hand sides marked the wrist of the donor (Fig. 2). The lower limb anatomical landmarks consisted of the medial epicondyle of the femur (MEF) for both the right and left hand sides to mark the knee of the donor, and the medial malleolus of the tibia (MMT) for both the right and left hand sides to mark the ankle of the donor (Fig. 2). Movements of the anatomical landmarks were then quantified by direct comparison with the static points in each image.

2.5. ImageJ Software

ImageJ software was used to analyse the images of the donor to determine the distances from the static landmark to the anatomical landmark of interest. For the upper limbs of the body the distance of the movement was calculated through comparison of the anatomical structures; SPR (wrist), and the MEH (elbow), with the static anatomical landmark US (Table 3). For the lower limbs of the body the distance of the movement was determined through comparison of the MEF (knee), and MMT (ankle), to the corner of static camera rod (CRS). The distance between the anatomical and static landmarks was determined in ImageJ using the x and y co-ordinates of each anatomical landmark, as represented in Fig. 2.

ImageJ line tool was used to draw a line between the static landmarks and the anatomical landmarks of interest in each image to produce *x* and *y* coordinates (Fig. 2). These *x* and *y* coordinates for both the static points and anatomical structures of interest were recorded in every image and used for data analysis.

2.6. Pythagoras' Theorem

Pythagoras' theorem was used to find the length of the hypotenuse (Fig. 3) to calculate the distance between the static and anatomical landmarks. These pairs of coordinates (static landmark *x*, and static landmark *y*) and (anatomical landmark *x*, and anatomical landmark *y*) were applied to Pythagoras' theorem $a^2 + b^2 = c^2$ to calculate the distance in pixels between the static and anatomical landmarks. The *c* value (distance) was then converted into the actual distance in centimetres (cm). This was achieved by measuring the pixel height of the donor in the images then dividing by the actual known donor height (pixel height 568/donor height 182 cm) producing a result of 3.120879 pixels, therefore 3.120879 pixels = 1 cm. Analysing images with ImageJ and applying its coordinates to Pythagoras' theorem facilitated the quantifications of PMM.

Table 3
Static Landmark Points and Anatomical Landmark Points.

Static Landmark	Landmark Site	Abbreviation
1	Umbilicus	(US)
2	Camera Rod	(CRS)
Anatomical Landmark		
3	Right Medial Epicondyle of the Humerus	(RMEH)
4	Left Medial Epicondyle of the Humerus	(LMEH)
5	Right Styloid Process of the Radius	(RSPR)
6	Left Styloid Process of the Radius	(LSPR)
7	Right Medial Epicondyle of the Femur	(RMEF)
8	Left Medial Epicondyle of the Femur	(LMEF)
9	Right Medial Malleolus of the Tibia	(RMMT)
10	Left Medial Malleolus of the Tibia	(LMMT)

2.7. Statistical Analysis

Statistical analysis for this study was limited due to the sample size of one donor. The study required multiple measurements from the donor, therefore this multivariate data required results to be displayed as scatterplots, line graphs or bar graphs in order to determine relationships between the variables.

3. Results

3.1. Decomposition Stages Using Total Body Score (TBS)

Megyesi et al.'s [1] categories and stages of decomposition model (Table 2) was used to score the decomposition of the donor in each image. The TBS result determined which decomposition stage the donor had reached. The donor was entering early decomposition measuring a TBS of 6 points upon initiation of image capture (approximately 2 hours after arriving at the facility) (Fig. 4). The donor progressed through early decomposition, displaying discolouration of the skin, bloating with green discolouration, purging of decompositional fluids, along with the release of abdominal gases (known as post-bloating), and black discolouration as per Megyesi et al.'s [1] model (Table 2). The donor entered advanced decomposition when the TBS reached 19 at 18 days PMI (Fig. 4). Advanced decomposition plateaued at 41 days PMI with a TBS of 24.

At the end of the study period the TBS score remained 24 at 485 days PMI (Fig. 4), the donor was still in advanced decomposition presenting with mummification, and minimal bone exposure. An interesting finding of this study was that the donor had not yet reached the final stage of decomposition (skeletonization) represented by a TBS of 27 as seen in Fig. 4.

3.2. Post-mortem Movement in Anatomical Landmarks of Upper Limbs

The distance of movement for the anatomical landmarks of the upper limbs (LMEH and RMEH), and (LSPR and RSPR), of the donor were plotted against the total PMI days as seen in Fig. 5. The results (Fig. 5) show there was an initial spike in movement for all upper limb anatomical landmarks (MEH and SPR) at 9 PMI days during the early decomposition stage. PMM of the donor's upper limbs continued throughout all 485 PMI days. The right upper limb achieved the most motion for the upper limbs with the RSPR landmark moving a total distance of 51.65 cm (Fig. 5). The LSPR produced the least amount of activity for the upper limbs moving a total distance of 23.46 cm.

The results in Fig. 5 show continuous movement of the donor across the 485 PMI days. At 135 PMI days during the advanced decomposition stage there was another spike in movement in all upper limb landmarks except the LSPR. Furthermore, in the advanced decomposition stage the RMEH had a noticeably larger spike in movement (Figs. 5 and 6) at day 450 PMI. Fig. 6 shows the

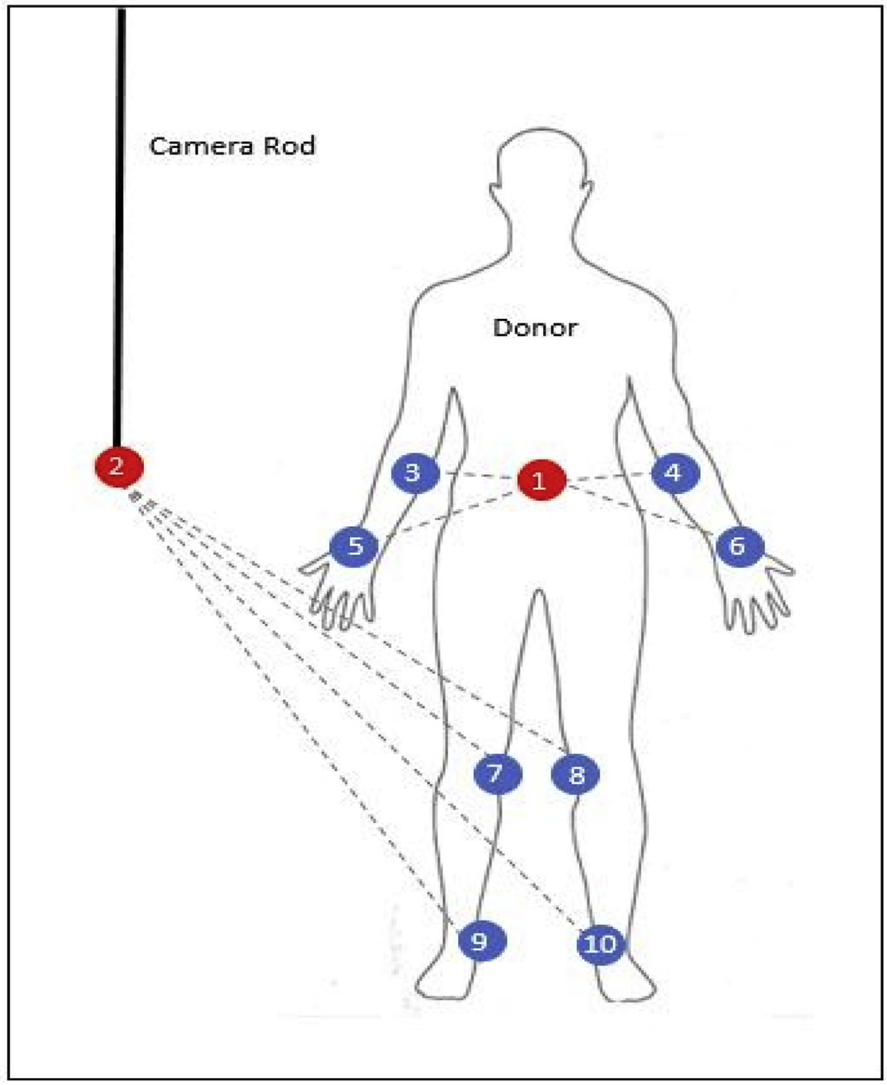

Fig. 2. Static Landmark Points and Anatomical Landmark Points.
Demonstrating x and y coordinates of each landmark point to measure the distance between the two points.

most weekly activity in the upper limb landmarks occurred in the first week of the donor arriving at the facility during the early decomposition stage. The RSPR achieved a maximum weekly distance of 41.27 cm in the first week of arrival, including a total of 16.18 cm in just 24 hours between 8 and 9 PMI days (Fig. 6).

The LMEH moved the least, with a distance of 11.50 cm in the first week after the donor was placed *in situ*. It did, however, peak between 450 and 457 PMI days at a distance of 8.50 cm for that week which was an unusual spike compared to the other anatomical landmarks. Fig. 6 shows continual peaks of activity in the upper limbs over the duration of the study during both early decomposition, and advanced decomposition stages. This reinforces the finding that PMM did occur in this donor and continued 16-months after death.

3.3. Post-mortem Movement in Anatomical Landmarks of Lower Limbs

The distances moved by the anatomical landmarks in the lower limbs (MEF and MMT) were plotted against PMI days to quantify the amount of movement. The left lower limb displayed the most activity with the LMMT traveling a total distance of 36.13 cm, and the LMEF moving a total distance of 31.57 cm, whilst the RMEF produced the least activity, moving 14.27 cm (Fig. 7). The movement for the left lower limb spiked during early decomposition whilst the right lower limb did not spike until 51 PMI days in the advanced decomposition stage (Fig. 7). The results in Fig. 7- show that right lower limb movement plateaued at 107 PMI days, whilst the distance covered by the left lower limb continued to increase for the remainder of the study period.

Results in Fig. 8 show the weekly movement of the anatomical landmarks in the lower limbs. The RMMT moved a weekly distance of 8.87 cm at 58 PMI days during the advanced decomposition stage, which was the maximum amount of movement for of all lower limb anatomical landmarks (Fig. 8). The left lower limb had the most spikes in movement and was more active during the advanced decomposition stage compared to the right lower limb (Fig. 8). These results further demonstrate how PMM of the donor actively continued throughout the duration of the study.

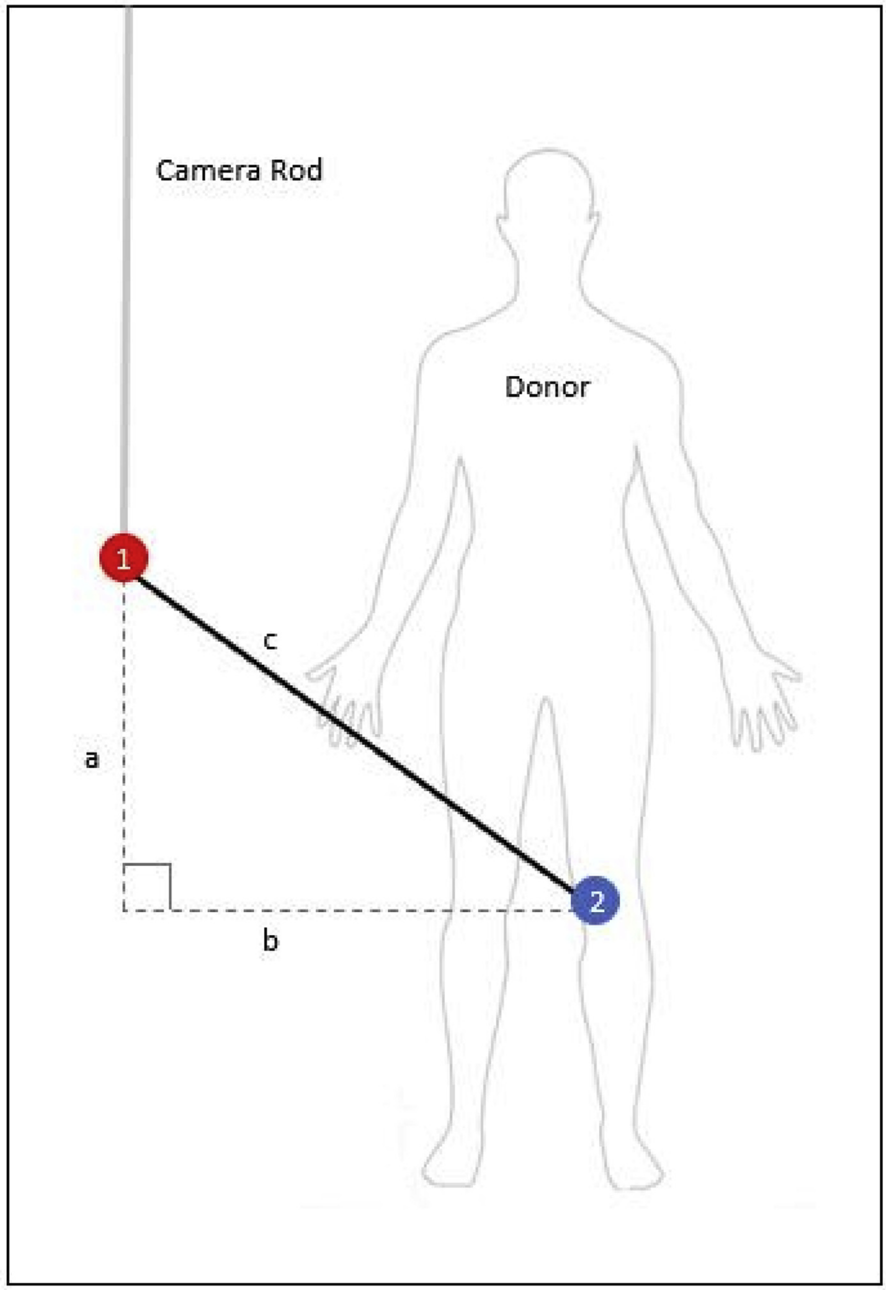

Fig. 3. Pythagoras' Theorem and Landmarks.
Demonstrating the use of Pythagoras' Theorem ($a^2 + b^2 = c^2$) to find the distance between **1.** Static and **2.** Anatomical Landmarks in each image.

3.4. Total Post-mortem Movement in Anatomical Landmarks and Decomposition Stages

The total distances each anatomical structure of the donor moved for the 16-month study period is displayed in Fig. 9. The results show the anatomical landmark SPR of the right upper limb was most mobile achieving a distance of 51.65 cm, whilst the MEF of the right lower limb was the least active, moving a distance of 14.27 cm. The right upper limb moved the furthest out of all limbs of the donor, whilst the least overall distance was recorded from the right lower limb. The results show all anatomical landmarks of the donor moved a considerable distance post-mortem during the decomposition process.

Total post-mortem movement for each anatomical landmark was plotted against the decomposition stages, shown in Fig. 10. These results determined at which decomposition stage anatomical landmarks of interest were most mobile. The results showed that PMM occurs in both the early decomposition and the advanced decomposition stage (Table 2). For the upper limbs the RSPR and RMEH produced the most movement in the early decomposition stage, whilst the LSPR achieved the most movement in early decomposition, however the LMEH was most active in the advanced decomposition stage. An interesting finding was that all anatomical structures of the lower limbs were more active in the advanced as opposed to early decomposition stage. These results indicate that PMM occurs in both early and advanced decomposition stages.

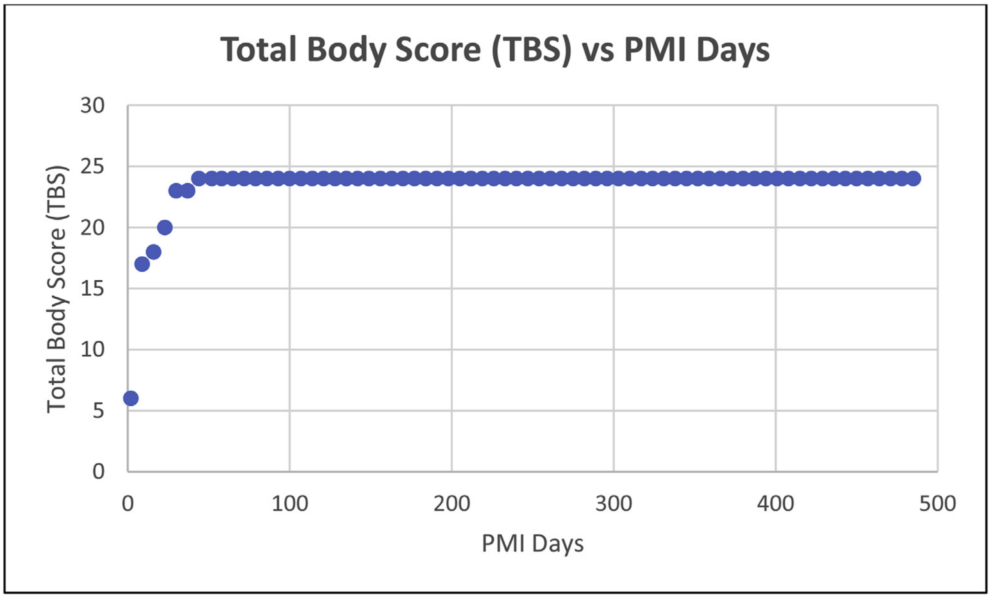

Fig. 4. Total Body Score (TBS) and Post-mortem Interval (PMI) days scatterplot.

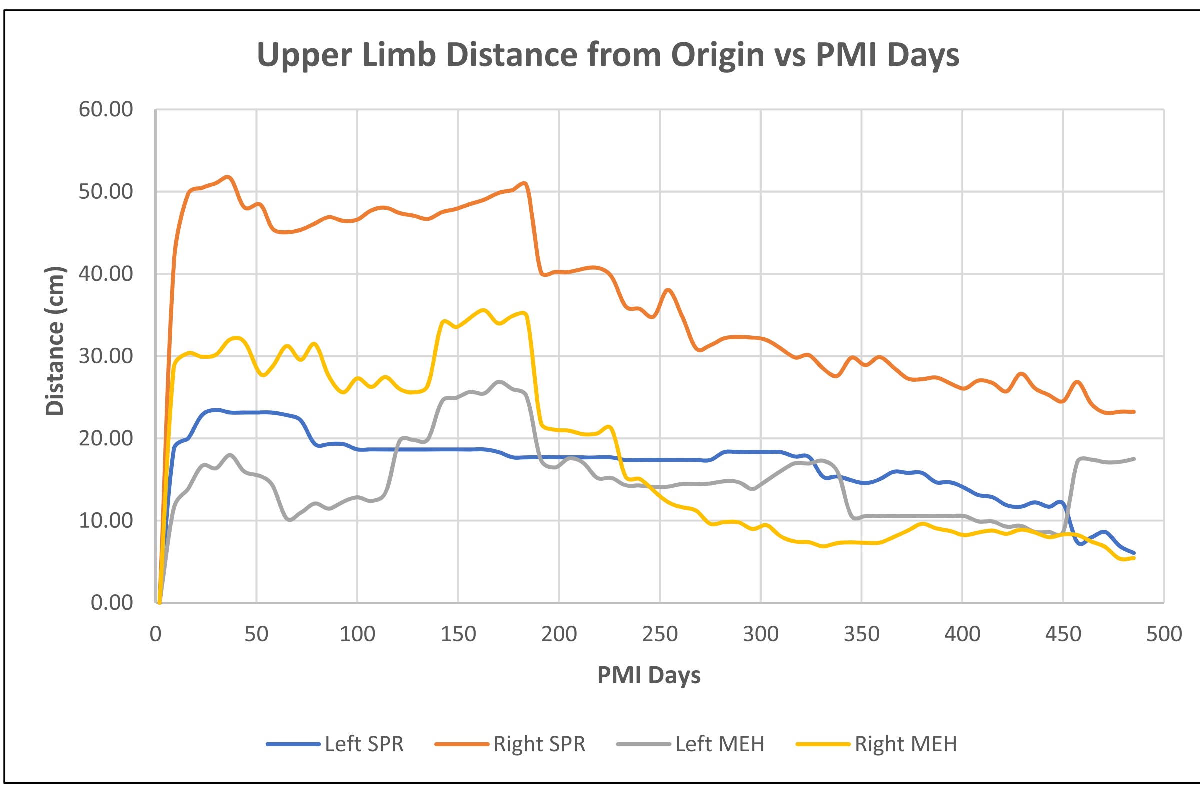

Fig. 5. Upper Limb Distance from Origin Compared to PMI days.

3.5. Environmental Conditions

Data obtained from AFTER and Richmond RAAF weather stations allowed for the calculation of the daily averages for temperature, rainfall, relative humidity (RH), and wind speed, to determine if these factors had a significant impact on when, and how much post-mortem movement occurs.

Averages were calculated for each day of the 16-month study period. The average daily temperature was 19.2 °C, average rainfall 1.1 mm, average RH 66%, and the average wind speed was 0.07 m/s. The average daily temperatures were plotted against PMI days to determine if the temperature may have had an impact on PMM (Fig. 11). These results assisted with comparing temperatures to PMI days to determine whether significant movement is caused by temperature variations. The highest average temperature for the study period was 43.2 °C at 345 days PMI.

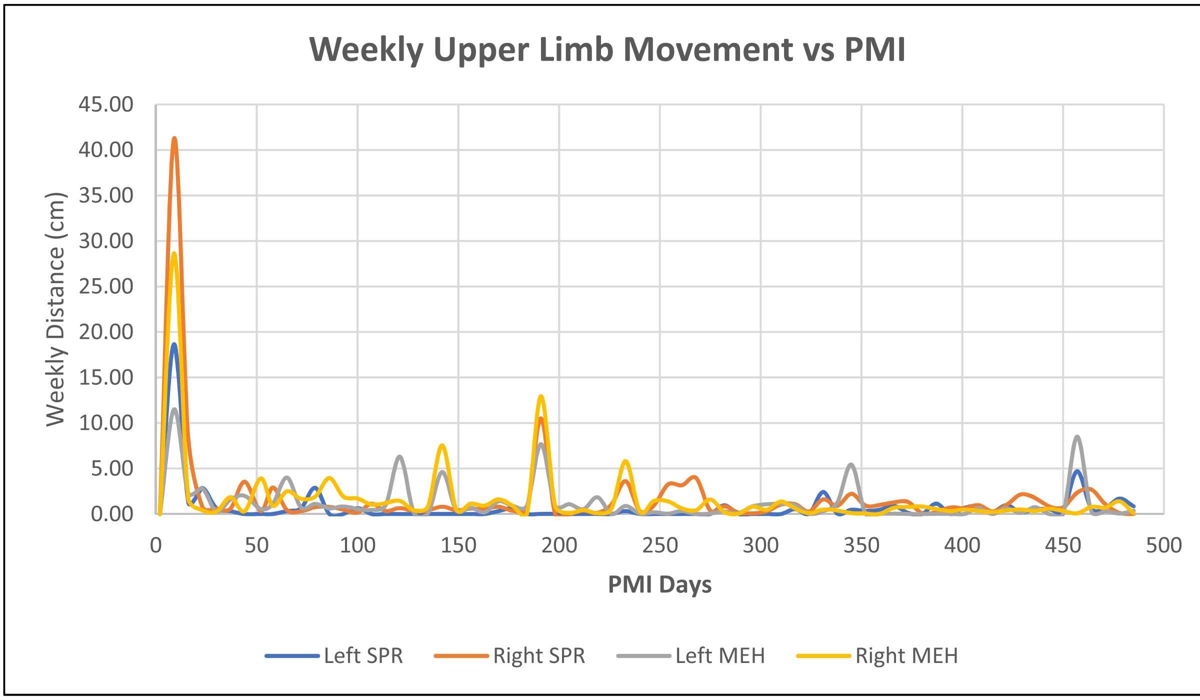

Fig. 6. Weekly Distance of Upper Limb Movement Compared to PMI days.

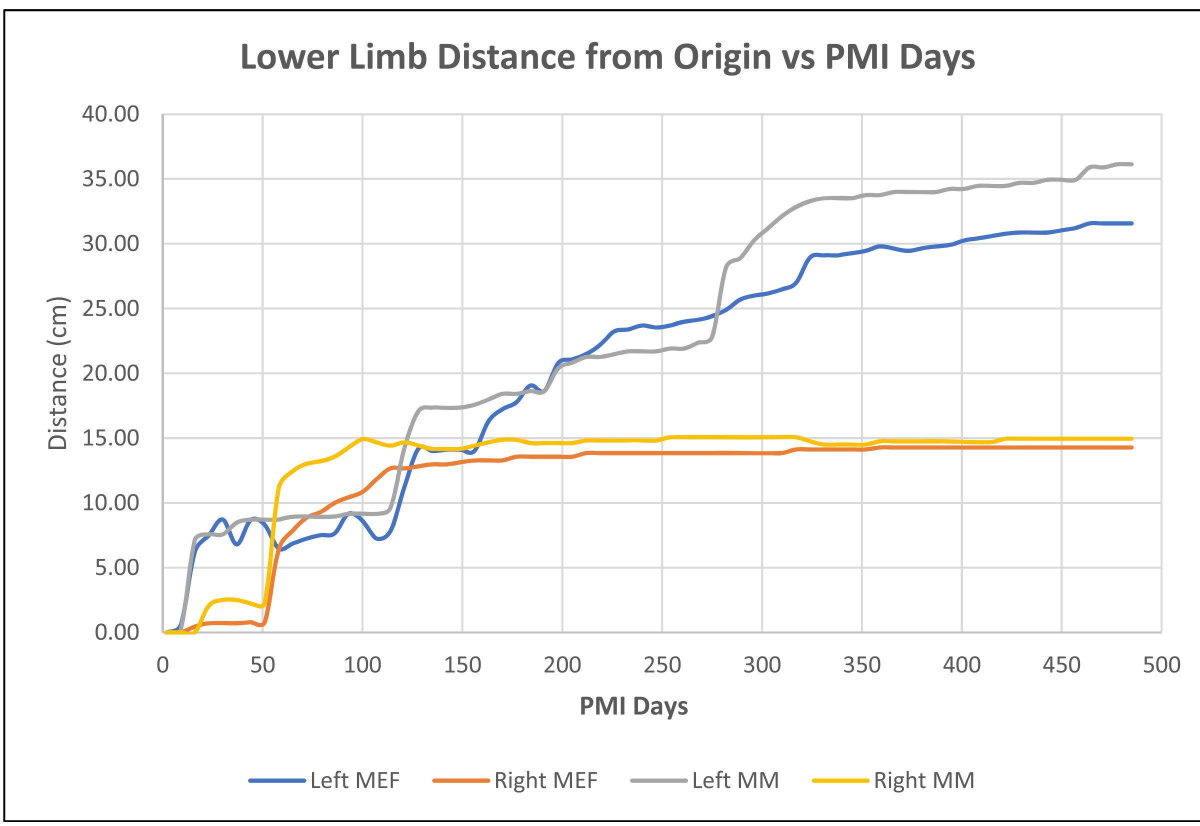

Fig. 7. Lower Limb Distance from Origin Compared to PMI days.

3.6. Qualitative Visual Observations of Images

Some time-lapse images captured movement of the donor that was unquantifiable due to the camera angles not capturing a static point to measure from in the images, or the cameras being moved when batteries were changed. It is recognised as a limitation of the study that not all cameras could be used to quantify the post-mortem movement, however a qualitative description of the

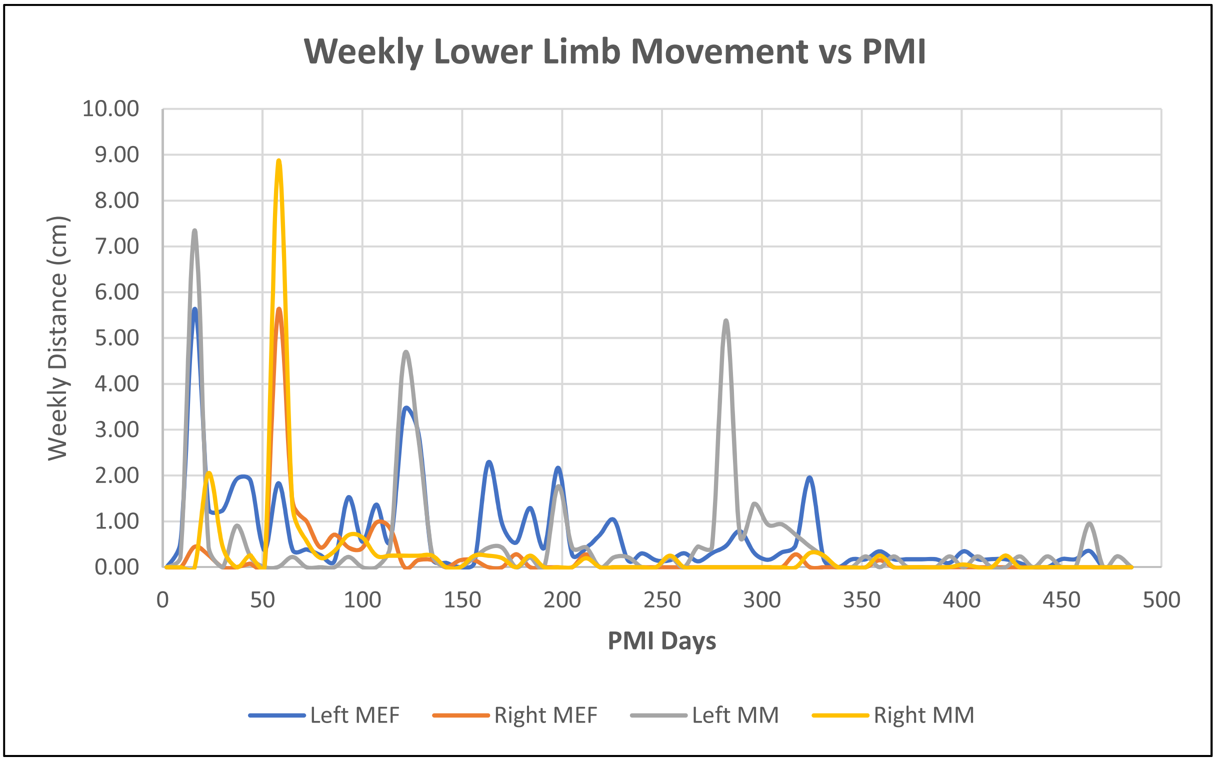

Fig. 8. Weekly Distance of Lower Limb Movement Compared to PMI days.

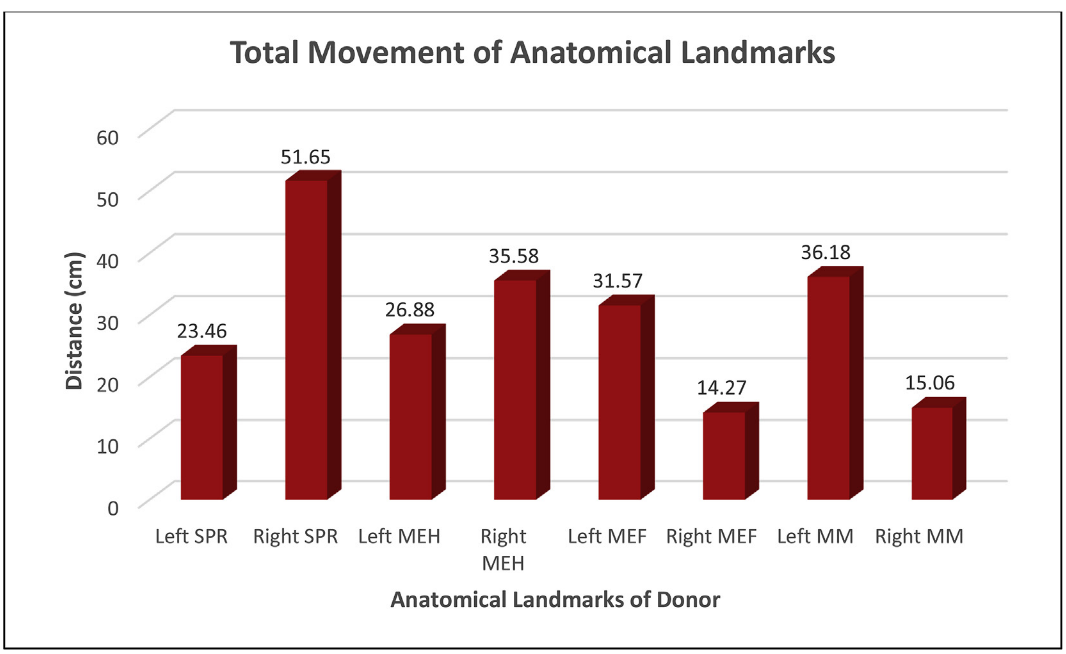

Fig. 9. Total Post-mortem Movement of Anatomical Landmarks of the Donor.

decompositional movement was recorded to mitigate some of the effects of this.

The donor was in a supine position with upper limbs down alongside the body at the commencement of the study (Fig. 12). Observations of the images showed that during early decomposition, the upper limbs displayed abduction (moving away) from the sides of the torso, whilst the lower limbs produced minimal movement with knees flexing (bending) slightly.

Visual observations of the decomposition process in the time-lapse images from camera B above the face (Fig. 1) showed the lateral flexion of the donor's head to the left side at 13 PMI days during early decomposition. The cranium, mandible and teeth remained intact due to the mummification process of the donor, therefore movement of these anatomical structures remained in

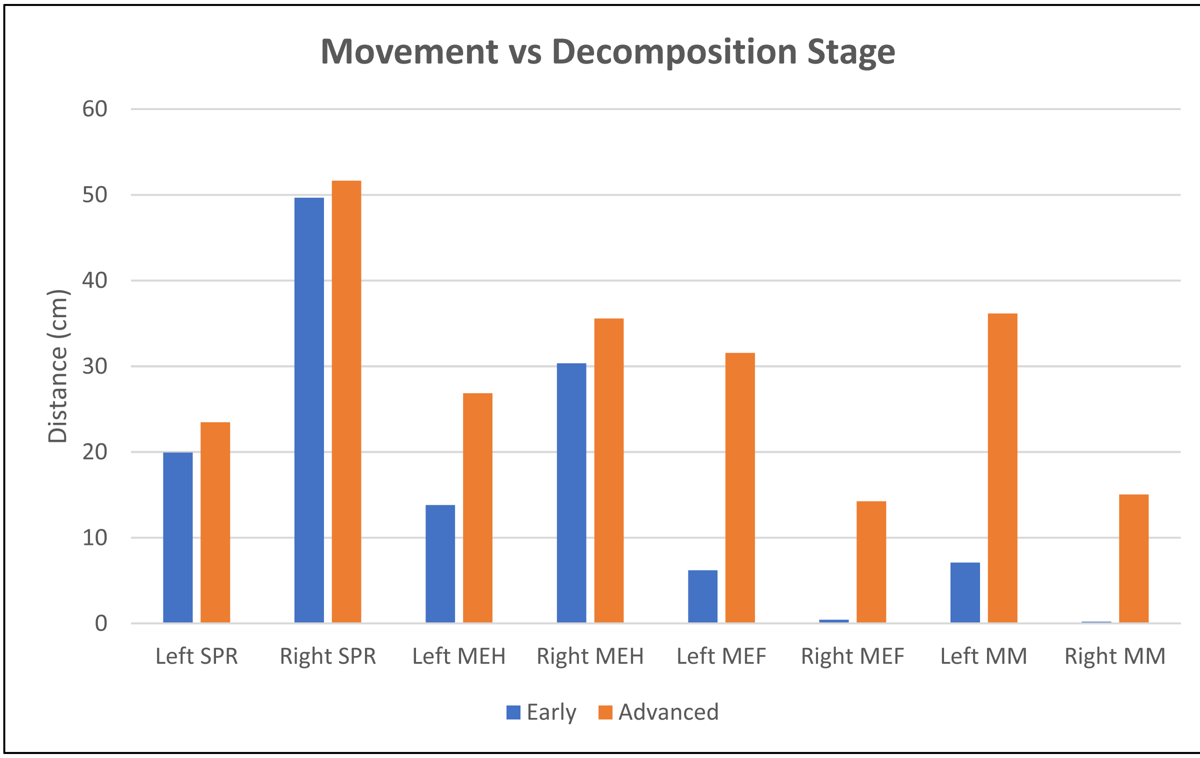

Fig. 10. Post-mortem Movement Compared with Decomposition stage.

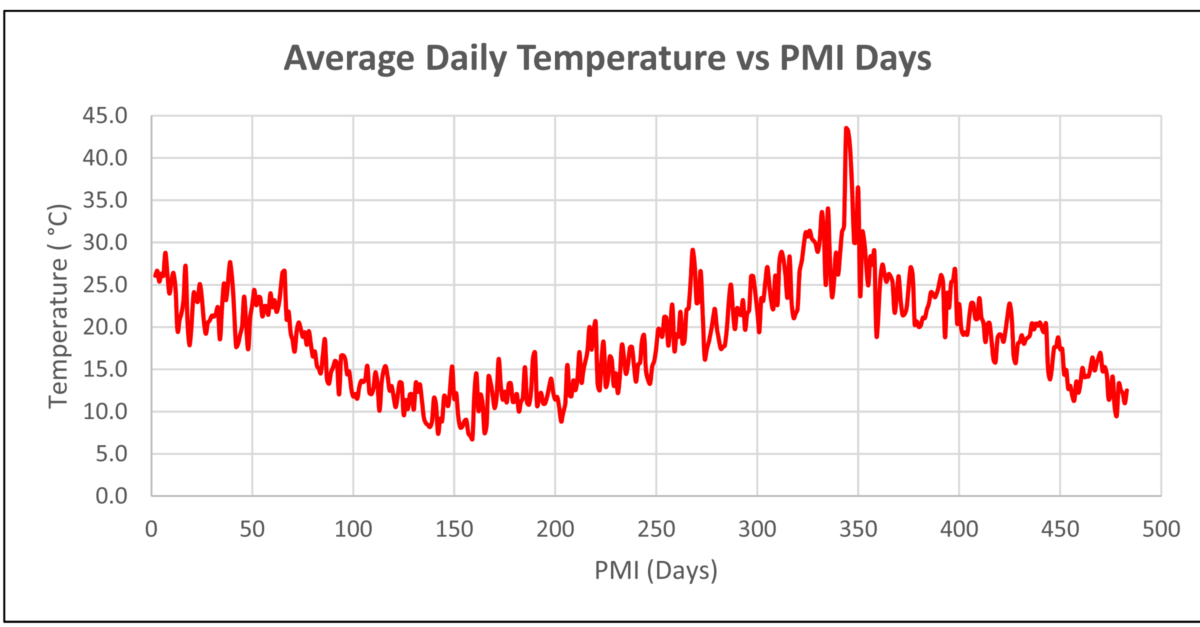

Fig. 11. Average Daily Temperature (°C) Compared to (PMI) days.

the same position for the duration of the study period (Fig. 12). Weather data at 13 PMI days (Table 4) showed no extreme weather, but the images captured high rates of insect activity including fly larvae and ants. However, insect activity in early decomposition is a normal process that could have contributed to the movement, along with the muscles in the neck relaxing and breaking down, as a result of the decomposition process.

The upper limbs moved continuously throughout the study (Fig. 12), which can be seen from the top view camera A, as well as those above the right and left hands, and camera E that provided a profile view of the body (Fig. 1). The abduction of the right upper limb from the torso occurred in early decomposition (Fig. 12).

The time-lapse images from the profile camera E (Fig. 1) unexpectedly captured flexion (upward movement) and extension (downward movement) of the left upper limb migrating from the ground's surface, that commenced from 275 PMI days (advanced

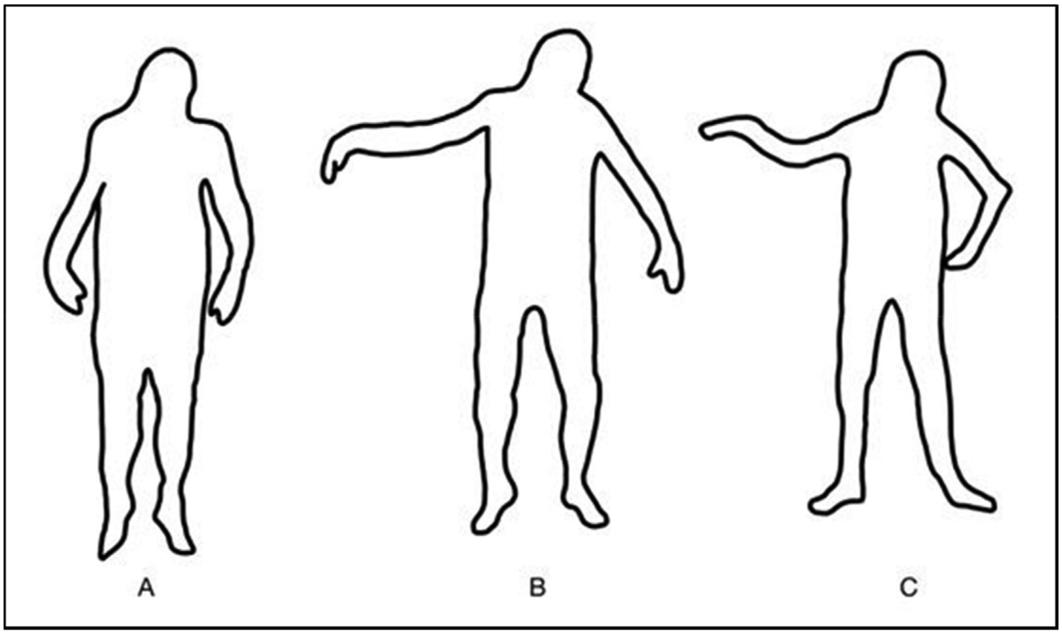

Fig. 12. Donor Body Positions During Decomposition.
Body Positions: Image outlines of; **A.** Donor body position at 2 PMI days, initial starting position. B. Donor body position at 16 PMI days. **C.** Donor body position at 485 PMI days, study end position. Diagram not to scale.

Table 4
Environmental Conditions and PMI Days. Environmental conditions and PMI days where spikes in movement occurred. All weather data is the daily average.

PMI (Days)	Season	Temperature (°C)	RH %	Rainfall (mm)	Wind m/s	Insect Activity
9	Summer	26	56	0	0	High
13	Summer	21.6	65	0	0	High
51	Autumn	24.3	72	0	0	Low
107	Autumn	15	70	0	0	Nil
135	Winter	13.2	78	0	0	Nil
275	Summer	17.3	62	0	0	Nil
331	Summer	29.8	70	0	0	Nil
450	Autumn	17	97	4.8	0	Nil

decomposition). At this stage, the donor was in mummification with no bone exposure and there was no insect activity observed in the images. This movement of the left lower limb continued for the remainder of the study over the Australian summer, autumn, and winter periods, suggesting that weather was not a factor contributing to this movement.

At 331 PMI days the metacarpal of the 1st digit disarticulated from the left hand, expelling itself onto the ground's surface. At this time, the donor was still in mummification, with minimal bone exposure. The weather data for 331 PMI showed the daily average temperature was 29.8 °C with a RH of 70% and no rainfall or wind (Table 4), this was within the normal range for the summer season in this region of Australia. The left upper limb continued to move for the remainder of the study, with adduction (moving towards) the torso, and away from the expelled metacarpal of the 1st digit.

Visual observations from the top view camera A (Fig. 1) showed the lower limbs displayed minimal movement in the early decomposition stage with knees flexing slightly outwards. The observations in the advanced decomposition stage illustrated the lower limbs moving, specifically the left lower limb, where abduction had occurred (Fig. 12).

The study demonstrated how the body position can change substantially from initial placement throughout the post-mortem process, as seen in Fig. 12. The donor's final body position presented as if they had their left hand on their hip with the right upper limb remaining at a 180° angle away from the body.

4. Discussion

The aim of this study was to quantify post-mortem movement in anatomical structures of a human donor during decomposition in an Australian environment. This was achieved by using time-lapse images to capture post-mortem movement over a 16-month period. The study quantified the amount of post-mortem movement, noting, which anatomical landmarks demonstrated the most movement, and at which decomposition stages the activity happened.

The human donor decomposed outdoors in a bushland environment in New South Wales, Australia. Megyesi et al.'s [1] TBS method was used to score the decomposition in each image. The donor was in early decomposition when image capture was initiated with a TBS of 6, and advanced decomposition commenced when the TBS reached 19 at 18 PMI days (Fig. 4). Interestingly, advanced decomposition plateaued with a TBS of 24 at 41 PMI days, and at the end of this study the donor had not yet reached skeletonization, (the final stage of decomposition).

In each image, the distances between the static landmark and each anatomical landmark were determined using ImageJ software, which allowed quantification of the PMM. The results showed significant PMM in the upper limbs (Fig. 5) and lower limbs of the donor (Fig. 7). The anatomical structure that produced the most PMM was the RSPR of the upper limb with a total distance of 51.65 cm (Fig. 9). This result could have been influenced from the donor being right hand dominant, for example due to muscles on the right side possibly being bigger/stronger (because they are used more) and having greater moisture content, therefore when moisture is lost and the muscles and ligaments start to contract the movement is more pronounced on that side. This is an interesting theory however further research is required to determine if handedness is a factor in the amount of PMM of a limb. The handedness of the donor in this study is unknown.

The least amount of PMM occurred in the right MEF of the lower limb which moved a total distance of 14.27 cm (Fig. 9). A potential explanation is that the lower limbs having greater muscle mass than the upper limbs, therefore having higher moisture content. As a result, moisture loss is slower in the lower limbs due to the larger muscle mass. During the decomposition process, moisture would be lost more quickly from the upper limbs causing rapid and large amounts of movement.

The upper limbs had a spike in movement at 9 PMI days in the early decomposition stage, with the RSPR reaching a distance 41.27 cm in the first week (Fig. 6). Upper limbs continued to move throughout the study duration with a spike in movement occurring in all anatomical structures except the LSPR at 135 PMI days (Fig. 5).

Weather data at 135 PMI days was analysed to see if any contributing factors such as extreme heat or cold could explain the spike in movement. The daily averages for day 135 PMI were 13.2 °C for temperature, RH was 78%, wind speed was 0 m/s, and there was no rain (Table 4). Therefore, no extreme conditions could have contributed to the spike in movement. A further spike in PMM occurred between PMI 450–457 days from the LMEH of the upper limb (Figs. 5 and 6). The weather data recorded for the 450–457 PMI period showed averages for these days, temperature was 17 °C, RH of 97%, rain 4.8 mm and wind 0 m/s (Table 4). Although the temperatures were not extreme for this period compared to other times over the course of the study (Fig. 11), the RH of 97% was high and when combined with 4.8 mm of rain, may have contributed to the spike in movement. However, it would be expected that other anatomical landmarks would have also displayed this same increase in movement. When viewing the time-lapse images during the LMEH spike in movement, the left limb lifted off the ground with the elbow of the donor shifting to a 90° angle, and the phalanges (fingers) of the left hand nearly touching the torso (Fig. 12).

The most movement for the lower limbs was recorded on the left side with the MMT traveling 36.13 cm, and MEF 31.57 cm (Fig. 9). Left lower limb movement spiked at 9 PMI days in early decomposition, and the right lower limb did not display a spike in movement until 51 PMI days whilst in advanced decomposition (Fig. 7). A comparison of the right and left side of the lower limbs showed movement in the right side plateaued at 107 PMI days, whilst the left lower limb continued to move the entire 485 PMI days (Figs. 7 and 8). The results show the left lower limbs had significant peaks of movement throughout the entire study (Fig. 8) and when weather data was analysed for the PMI days where peaks in movement occurred, there were no unusual weather changes (Table 4).

As there was no physical disruption to the donor, such as avian scavenging, alternative natural processes such as weather were considered as a factor that could have contributed to this movement. The study found that weather did not determine when significant movement in the anatomical landmarks of the donor occurred, suggesting PMM is part of the natural decomposition process. Fig. 10 shows the decomposition stages, and in which stage the anatomical structures of the donor moved the most. This study found that for this donor all anatomical landmarks but the LMEH of the upper limbs displayed most movement in the early decomposition stages. The LMEH of the upper limb along with all anatomical landmarks of the lower limbs achieved most movement in the advanced decomposition stage. Due to the donor plateauing with a TBS of 24 from 41 PMI days and remaining in advanced decomposition, but not reaching skeletonization, the final stage of decomposition could suggest a likely contributing factor to the movement.

The mummification process that occurs during advanced decomposition (Table 2) results in the body being reduced to skin, cartilage, and bone [8]. Once remains have lost moisture, muscles contract and ligaments dry out [9]. This causes the joints to shrink and contract, which seems the likely cause of the movement occurring in advanced decomposition. Environmental conditions can facilitate mummification, for example the rate at which water is evaporated from remains can favour desiccation and mummification [10]. Rainfall is known to rehydrate mummified remains [11], however in this study the remains did not rehydrate because there was no significant heavy rainfall, therefore remaining mummified (rather than reaching skeletonization) until the end of the study. This is an interesting finding that could potentially be unique to this region of Australia.

An explanation for movement occurring during the early decomposition stage, particularly the spike in movement at 9 PMI days (Figs. 5 and 7), would be the effects of gas build up in the stomach, resulting in bloating in the abdomen. This may have contributed to movement of the limbs prior to bloating being reduced through the purging of decompositional fluids. The qualitative visual observations and the change in body positions displayed in Fig. 12 also support that PMM occurs long after death.

5. Conclusion

Establishing whether PMM has occurred is highly significant in unexplained death investigations, and understanding PMM in a human donor resulting from the decomposition process is important for police, forensic anthropologists and pathologists when assessing the body position. This knowledge can assist with determining the cause of death and/or circumstances surrounding the death, decreasing the potential for misinterpretation of a death scene.

The findings demonstrated that time-lapse imaging can be used to capture and assist with the quantification of PMM during decomposition of a human donor. The results in this study revealed which anatomical structure of the donor displayed the most movement, and at which decomposition stages the movement occurred. These findings have significant forensic relevance and should be taken into consideration when assessing an unexplained death scene.

An expected outcome of the study was that PMM occurred in early decomposition when the body's gases built up resulting in distention of the abdomen (bloating). Unexpectedly, PMM continued throughout the entire study with most movement occurring during the advanced decomposition stage. A further finding was that the upper limbs produce more movement in early decomposition, whilst the lower limbs are most active during advanced decomposition. The visual observations recorded from the images that could not be quantified also supported PMM of the donor.

A unique visual observation when viewing the time-lapse from camera E (Table 1), was the left upper limb lifting completely up off the ground with the elbow of the donor shifting to a 90-degree angle with the digits of the left hand nearly touching the torso.

The study found that weather conditions did not have a significant influence on spikes in movement, therefore indicating that PMM is a natural process of decomposition regardless of weather conditions. As this was a descriptive study that documents the movement, statistics were limited due to $n = 1$, although regression analysis demonstrated the linear relationship between sustained movement over time, and some anatomical structures (such as LMEF).

One limitation of this study was that PMM was only captured during daylight hours. A further limitation was all five cameras could not be used to quantify PMM due to slight movement of some cameras during battery changes, or having no static structures in the images to use as landmarks. Future studies should implement the use of night vision cameras to capture PMM during the hours of darkness, allowing researchers to compare this data to movement in daylight hours. Positions should be considered when securing cameras and selecting angles, to ensure a stable and static point of reference for later analyses.

To have human donors is a valuable gift that allows forensic researchers to augment our understanding of the decomposition process. The population size of one donor for this study was a limitation, however access to human donors is very limited, a situation that applies to all studies undertaken at taphonomic facilities around the world. However, future research needs to be carried out on multiple donors to establish if there is a distinct pattern of PMM, and if the results found in this research could be replicated. It would also be useful to undertake comparative studies at the forensic taphonomy facilities in the United States and the new facility opening in Quebec, Canada in 2020. The findings presented here begin to address the gap in knowledge of human PMM however, further research is required.

Declaration of Competing Interest

The authors have no conflict of interest that are directly relevant to the content of this manuscript.

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