Forensic Science International 345 (2023) 111616

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

Next generation forensic taphonomy: Automation for experimental, field-based research

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A R T I C L E I N F O

Article history:
Received 19 August 2022
Received in revised form 22 October 2022
Accepted 25 February 2023
Available online 27 February 2023

Keywords:
Post-mortem interval
Decomposition
Experimental design
Methodology
Forensic taphonomy
Automation
South Africa

A B S T R A C T

Determining the post-mortem interval (PMI) is often a critical goal in forensic casework. Consequently, the discipline of forensic taphonomy has involved considerable research efforts towards achieving this goal, with substantial strides made in the past 40 years. Importantly, quantification of decompositional data (and the models derived from them) and standardisation in experimental protocols are being increasingly recognised as key components of this drive. However, despite the discipline's best efforts, significant challenges remain. Still lacking are standardisation of many core components of experimental design, forensic realism in experimental design, true quantitative measures of the progression of decay, and high-resolution data. Without these critical elements, large-scale, synthesised multi-biogeographically representative datasets – necessary for building comprehensive models of decay to precisely estimate PMI – remain elusive. To address these limitations, we propose the automation of taphonomic data collection. We present the world's first reported fully automated, remotely operable forensic taphonomic data collection system, inclusive of technical design details. Through laboratory testing and field deployments, the apparatus substantially reduced the cost of actualistic (field-based) forensic taphonomic data collection, improved data resolution, and provided for more forensically realistic experimental deployments and simultaneous multi-biogeographic experiments. We argue that this device represents a quantum leap in experimental methodology in this field, paving the way for the next generation of forensic taphonomic research and, we hope, attainment of the elusive goal of precise estimation of PMI.

1. Introduction

The overarching goal of the study of forensic taphonomy has remained unchanged from the discipline's inception in 1940: to unravel the complexities of the temporal and spatial relationship between the depositional environment and organic material deposited therein [16]. The shorter temporal applications of forensic taphonomy necessitate a comprehensive understanding of the decomposition ecosystem to assist in medicolegal death investigations [24] observed that "taphonomic models, approaches, and analyses in forensic contexts" may be used to "estimate the time since death, reconstruct the circumstances before and after deposition, and discriminate the products of human behaviour from those created by the earth's biological, physical, chemical, and geological subsystems." Such answers regularly prove pivotal for resolution of medicolegal death investigations. Contemporarily, forensic taphonomy requires little introduction to its researchers and practitioners, and their results have proven valuable and important in forensic practice time and again [59]. Proliferation of the discipline's research and its increasing transdisciplinary integration [59,62] bear testament to its pre-eminence in forensic science. In this paper, we present a vivid example of transdisciplinary enterprise to address the twin needs for forensic realism and robust, replicable experimental design in forensic taphonomic research, taking the form of a new fully automated system for recording forensic taphonomic field studies. However, before the new system is outlined, a brief reflection upon the discipline's history is required to contextualise and appreciate the extent of the technological leap proposed in this

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https://doi.org/10.1016/j.forsciint.2023.111616

article and its potential to propel forensic taphonomy into a new era of forensic actualism.

1.1. Background to estimating time-since-death: where are we today?

Estimation of time since death, otherwise known as the post-mortem interval (PMI), is reliant on the formulation of a decomposition model, which is in turn, based on understanding the decomposition ecosystem and carrion recycling [24,7]. Two approaches traditionally employed to assimilate data towards achieving this have been retrospective analysis of forensic casework, and experimental research. The former relies upon "a combination of inductive and deductive reasoning," while the latter generally employs "hypothetico-deductive reasoning and actualism" (Wescott, 2018:254). Experimental research – the focus here – has proven pivotal to the discipline, elucidating nuances of the decompositional process not captured when appraising a series of spatiotemporal snapshots of decomposition as derived from casework. Where casework has the edge, however, is in its capture of decompositional variation imbued through intrinsic inter-individual and extrinsic biogeographic differences. Experimental fieldwork has, traditionally, been confined to specific biogeographic regions, measuring decompositional patterns specific to microhabitat variations within those regions. Multi-habitat studies within regions are not uncommon, but the logistics involved in experimental research typically limit the scope of studies, confining them to specific regions, with rare exceptions (e.g., [43]). As such, this mode of study struggles to capture variability in decomposition between biogeographic regions due to difficulties in comparing geographically disparate research, as will be outlined below.

Experimental research was initially based on pure observation, exemplified by Reed's [48] trendsetting study, the design that became the template for subsequent research. He recognised the importance of: 1) replication (using carcass depositions in pairs, albeit in different habitats within the same biogeoclimatic area, and undertaking seasonal repetitions, at least as far as Northern Hemisphere spring was concerned); 2) standardisation of experimental units and methods (such as carcass size and time of data collection); 3) high resolution data (with data collection undertaken as frequently as thrice daily, and with 43 carcasses deposited over a full year); 4) avoiding carcass decompositional overlap (by ensuring no carcasses were decomposing in the same area at the same time); and 5) obtaining data on a wide variety of variables implicit in the decomposition ecosystem (meteorological variables, carcass and soil temperatures, soil pH, decomposition stages, and carrion entomofaunal assemblages). Payne [45] built on this model for forensic entomology and taphonomy, focusing on standardisation of experimental designs.

Through time, experimental research focused on specific variables of the decay process. Mann, Bass and Meadows [34] synthesised the reported observations on variables involved in decay, stimulating research in the discipline that was increasingly honed to monitor specific variables such as temperature and rainfall – a reductionist research agenda. This approach facilitates evaluation of individual variables (in a regionally specific manner), but comes with the critical sacrifice of understanding the relationships *between* decomposition ecosystem variables. Whilst the sacrifice was not intentional, it was inevitable, and increasingly undermined forensic realism in research – ironically, the opposite of what Mann, Bass, and Meadows [34] advocated.

On the back of the [12,22]; Kumho Tire Co. v [31], the 1990's saw a revolution in forensic sciences. These precedents precipitated a large-scale and increasingly accelerated shift towards quantitative methodologies in forensic science. Henssge and Madea [25] eloquently articulated the underlying requirements as they pertain to taphonomic investigations directed towards informing or developing methods for PMI estimation, should the originators seek for the method to enter mainstream usage and prove viable in court. These requirements are: 1) quantitative measurement of the variables influencing decomposition (and, therefore, estimation of PMI); 2) mathematical description of the method (i.e., how it measures variables *and* the relationships between them); 3) joining points 1) and 2), taking into account influencing factors quantitatively; and 4) declaration of precision (requiring quantitative appraisal) *and* proof of precision on independent materials. Forensic taphonomy – like many forensic disciplines responding to the National Academy of Sciences' scathing 2009 review of forensic research and practice – moved swiftly towards objectivity and quantifiable methodologies. The 2005 work of Megyesi, Nawrocki and Haskell and 2011 work of Vass are, perhaps, the most famous examples of efforts to transition the discipline to more quantitative and standardised investigative approaches (both on-scene and in the research environment). For their merits, these methods unfortunately still fall short of meeting all of Henssge and Madea's criteria, notably criterion 4 [61], evidenced by the numerous reports of inaccuracies when the method is applied to decompositions in diverse biogeoclimatic circumstances (e.g. [9,35,47,57,61]). At best, these shortcomings indicate a need to revise the methods or innovate new ones; at worst, they have precipitated scrutiny of whether accurate *and* precise estimation of PMI is even attainable [5].

1.2. Challenges with existing methods for quantitative modelling of decomposition and estimation of PMI

The applicability of accumulated degree-days (ADD)/total body score (TBS)-based methods is undermined by four core issues. Firstly, and as was previously alluded to, the underlying datasets are limited to a single biogeographical area, meaning that the predictive model built by the respective authors is reflective of regionally specific decomposition. It is well-known that decomposition is biogeographically specific, with myriads of studies emphasising the importance of establishing regional baseline decompositional data (e.g., [20,21,41,57]). Secondly, the models are based on the influence of a single environmental variable: temperature. Though this variable is stated to capture most of the variation in decomposition (e.g., in Megyesi and colleagues' 2005 work, over 80% of the variation in decomposition was attributed to variations in temperature), uncertainty remains – often at unacceptably high levels for medico-legal purposes (e.g., the uncertainty in Megyesi and colleagues' work was 20% or more). Thirdly, the way decomposition is measured using TBS is not truly quantitative. It requires traditional qualitative descriptions of the morphological appearance of decomposition across three regions of the body be assigned a score (together comprising the TBS), which is then modelled against temperature. Given that the foundation of this system is the *qualitative* description of decay and (essentially arbitrary) assignment of scores, it still risks falling foul of bias, be it through inter-observer error (extensively studied, e.g. [11,42,47]), the impartation of bias by experienced users to new trainees (not yet explicitly studied), or a failure of the system to capture variations of decomposition from other biogeoclimatic regions (e.g., [57,61]). Fourthly, the entire concept of a qualitative description-based system for tracking progression of decomposition that relies on *sequential* change is flawed insofar as it ignores the fact that decomposition is not a linear process. Ironically, [37] recognised this (which is why decomposition is scored separately over three regions of the body), but the scores were still tied to seral stages of decomposition in the same way as Reed [48] had described it (Reed's system was, in turn, based on the much older concept introduced by Mégnin in 1894). The limitations of these frameworks have been recognised time and again, yet their use in forensic taphonomy persists, frequently justified as a common system whereby different decompositional circumstances may be compared (e.g. [2,34]).

However, as argued by Michaud, Schoenly and Moreau [39], this is unhelpful – even typological [46] – as it obfuscates the continuous nature of decomposition and impedes the “empirical testing of ecological mechanisms and models” ([39]:54) – it is, in fact, not forensically relevant or accurate.

1.3. The big challenge: overcoming the “5 hindrances” of forensic taphonomy

Based on the aforementioned, there is a clear need for continued innovation to improve the quality and precision models of decomposition for estimating the PMI, and these require high-resolution quantitative means of tracking decomposition processes. Quantification alone cannot resolve the problem, as demonstrated by [37] and Vass’ [60] systems, both of which – for their merits – fell short of *comprehensively* addressing a much more fundamental problem in forensic taphonomic research: a lack of standardisation in research design and data collection techniques. To wit, although standardisation of describing the progression of decomposition was part of the ambition of these attempts, no other aspects were standardised. The failures of validation of these techniques through independent studies may be partially ascribed to this deficit. The dearth of standardisation of data collection procedures and experimental design in forensic taphonomic research is surprising. Despite researchers emphasising the importance of standardisation in forensic taphonomic research, it remains conspicuously sparse [26,44,52,32,58,61]. Studies purporting to replicate others frequently fail to use equivalent carcass sizes, inter-carcass distances, sample sizes, data collection methodologies, or even the same carrion species. Thus, true biogeoclimatic replicates of experiments are rare. Without comparative and/or synthesised datasets representing decomposition in a diversity of biogeoclimatic circumstances that have data collected from standardised carrion in a standardised fashion across an array of standardised variables, the reductionist approach to understanding decomposition and constructing models of it for estimation of PMI is doomed to failure. Concerningly, the discipline has been aware of this problem since at least 1989 when Marshall described them as the "five hindrances of taphonomy". Little progress has been made towards resolving these issues despite subsequent reminders [24,50].

The net result of the above is impingement of *precision* in models used to estimate PMI, which comes down to data resolution – a perennial problem in experimental forensic taphonomy. The physical, in-person nature of conventional data collection in field-based experiments places it at disproportionate risk of being adversely impacted by resource constraints. If the researcher responsible for data collection is unable to do so for any reason, data for that day is lost. Repeated, irregular instances of this result in uneven gaps in the data collection record, which are difficult to address statistically, undermining analyses and conclusions. Remote photography is one way the discipline has sought to move away from this, for example, to monitor carcasses for the morphological progression of decomposition (e.g., [63]) or tracking scavenger activity (e.g., [55]). Another attempt has been remote monitoring of environmental variables using on-site weather stations and other data loggers, as regularly reported in the literature. Other promising quantitative means of measuring the progression of decomposition include tracking the evolution of volatile organic compounds (e.g., [15]), and succession of entomofauna (e.g., [14]) and bacterial communities (e.g, [38]) on carrion. Yet all these approaches still require on-site visitation; thus, the bottleneck imposed by manual data collection persists.

By what means can we overcome Marshall’s [28] persistent “Five Hindrances'' of taphonomy and achieve a truly quantifiable means of tracking the progression of decay, with simultaneous monitoring of diverse variables in the decomposition, across true spatiotemporal replicates (as opposed to the commonly-published simple pseudoreplicates, see [49]) such that we can produce comparative and/or synthesised datasets? Our proposal is a new era of automating the taphonomic data collection system [17].

Automation is not a novel concept to forensic sciences, but to the authors’ knowledge, an integrated system for collecting a diversity of data across an array of variables in forensic taphonomy research does not yet exist, and certainly not one that offers a truly quantifiable means of tracking the progression of decomposition. We have constructed such a system, first reported upon in 2020 [17], which we are continuously improving. In this paper, we share the technical details of the device, and its efficacy in field deployments to date, along with an open invitation to help us develop its capabilities much further.

2. Device and apparatus

Our autonomous system was initially conceived as a means for recording carcass weight loss at regular intervals remotely and autonomously, given that it is a truly quantifiable variable (based on empirical, impartial measures of mass) and offers a good proxy from carcass biomass removal via biotic and abiotic processes driving decomposition. Only a few studies have utilised weight loss over time as a quantitative measure of the progression of decomposition for one important reason: it is hard to do (e.g., [1,13,23,27,29,30,33,56,54]). It requires the erection of large, robust apparatuses to lift carcasses into the air (especially necessary for adult human cadavers or animal carcasses approximating adult human size) and is invariably manual in nature. Foul or dangerous weather, personnel absence or on-site injury, and apparatus malfunction may cause a failure of data collection. Moreover, without a dedicated apparatus per carcass and teams to operate all of them, simultaneous data collection of carcass mass at defined time points is impossible, rendering replicates never truly comparable. Given these issues, and considering that our goals include improved precision and resolution in data collection and capacity to benchmark a raft of other variables against carcass weight loss over time to understand how each contributes to weight loss (with reduction of temporal variation in sampling being a priority), automation was an obvious and necessary solution.

Our device is not only autonomous, but also remotely deployable for extended periods without on-site researcher interaction and/or intervention. This reduces research costs associated with travel to remote research sites and the time spent gathering data on site, and minimises disturbance – particularly relevant if vertebrate scavengers are under study. Thus, our data collection with this new system is more forensically accurate. To achieve these goals, the system needed to be weatherproof, robust, and have an independent power supply and control mechanism.

2.1. Technical specifications

The device is showcased in Fig. 1, comprising a galvanized steel tripod with legs 3.5 m in length, with two free-standing feet and the third mounted to a large, 50 kg galvanized steel base plate. The steel baseplate serves as the mounting point for the lifting mechanism: a MAC-AFRIC 12 V ATV winch (Model: EWP 2500 A; rated line pull = 1134 kg @ 2.1 m, 591 kg @ 14 m) with a control box. The winch cable (Ø 4.8 mm × 14 m) is fed through a 2:1 pulley (Fig. 2A) mounted below the apex of the tripod and connects to a load cell (300 kg capacity in pictured setup; Fig. 2B): the means by which carcass weight is measured. The load cell bolts onto a sub-frame for holding the carcass.

The sub-frame comprises a galvanized steel grid of 10 mm steel rebar, spaced 10 cm apart in the x- and y-axes, welded to a frame. Four arms bolted to the grid frame support a galvanized steel plate positioned centrally overhead the grid. This plate serves two

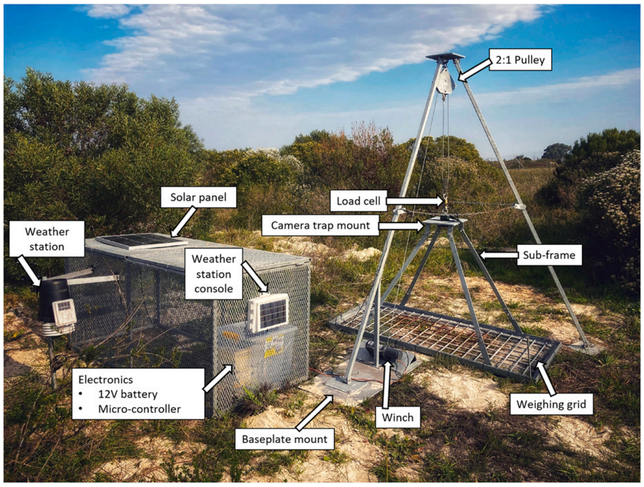

Fig. 1. : The complete autonomous data collection setup.

purposes: 1) it is the mounting point for carcass-monitoring camera (s) (a lens of 120° will capture the entire grid in view at the height pictured); 2) it is the connection point for the load cell.

A Raspberry Pi 3B+ (brand and model of a Single Board Computer [SBC]), which also accepts load cell data via a HX711 instrumentation amplifier, controls the winch. Weighing the carcass is not as simple as lifting and lowering the sub-frame for set times (e.g., 2 s). A simple symmetrical 2-second lift and lower was inappropriate as lowering was quicker due to the winch not needing to lift the carcass. To mitigate this, a simple algorithm was programmed for the weight lift protocol, visualised in Fig. 3. The code is available upon request. The Raspberry Pi also carries a GSM PiHat SIM7600 communication module connected to the internet. This affords the research team remote connection to and control of the device at any time, from any location, facilitating ad-hoc lifting, error-checking and troubleshooting, re-programming, customisable email alerts and, most importantly, remote pushing of data to the research team.

The entire system is powered by a 12 V sealed lead-acid (SLA) 100Ah deep-cycle battery, charged by a single 55 W photovoltaic panel. The remainder of the electronic setup includes relays for winch operation, and an analogue-to-digital controller module for measurement of voltage, current, and temperature of the electronics and load cell. A block diagram of the electrical components is presented in Fig. 4.

2.2. Additional capabilities

We initially measured weight loss to evaluate whether it was even possible to procure data from a process inherently difficult to monitor. Once it was clear we could, we turned our attention to expanding the array of variables to monitor. One of the advantages of the modular and off-the-shelf design of the Raspberry Pi's is their capacity to accept an array of inputs from myriad sensors. This may include thermometers measuring various carcass temperatures, pH sensors, cameras of all types, and custom sensors of your own construction. For example, our research team have developed, constructed, and implemented a custom sensor for monitoring full-thickness tissue moisture for quantifying regional- and whole-carcass desiccation over time [18]. The value of this approach cannot be overstated; indeed, it represents a real-world, affordable, and relatively easily implementable solution for simultaneous monitoring of diverse variables. Moreover, the data may be recorded at *any* resolution as dictated by the research design, and remotely so.

3. Discussion and Conclusion

The purpose of this research initiative was to develop a device/system that would: 1) reduce the cost of data collection; 2) improve data resolution; and 3) give the research team remote access to the data.

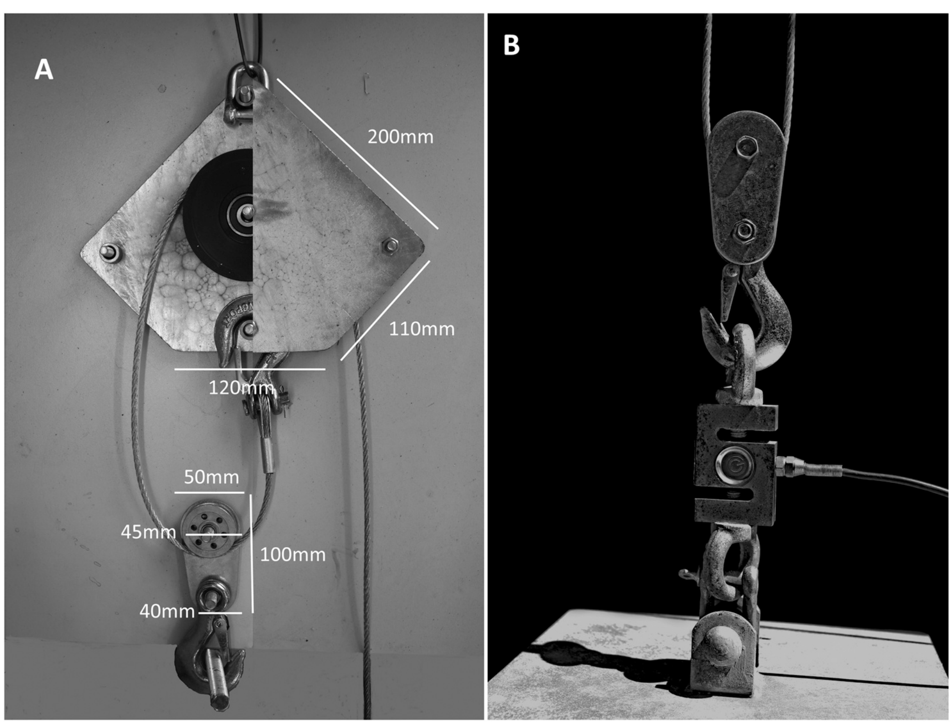

Fig. 2. : A – The 2:1 pulley with cut-out view to show inner mechanics and measurements. B – The load cell attachment setup (load cell is the "S"-shaped device with a wire protruding to the right).

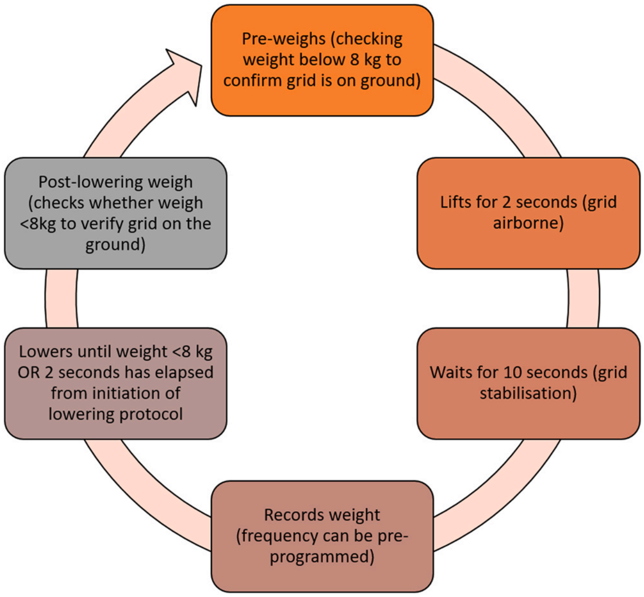

Fig. 3. : Algorithmic flowchart of the coded weight loss protocol. Code available upon request. **Step 1 (top):** the device conducts a pre-weight assessment that checks whether the weight is below a pre-defined value (e.g. 8 kg) by way of confirming that the sub-frame is on the ground. This serves two purposes: it provides a baseline for the weight measure to follow, and it serves a safety check to ensure the winch does not lift the sub-frame too high (which would cause impact between the load cell and the 2:1 pulley). **Step 2:** the device turns on the winch for 2 s (time is programmable) to ensure the sub-frame and grid are off the ground. **Step 3:** the device waits 10 s before recording any data to allow the airborne sub-frame and grid to stabilise in the air. **Step 4:** the weight is recorded (frequency is programmable; we sample at 50 Hz). **Step 5:** the device turns on the winch to lower the sub-frame and grid. Weight is continuously measured at this point, with the Raspberry Pi watching for the weight to drop below 8 kg (the pre-defined minimum indicates that the sub-frame and grid are back on the ground) OR 2 s has elapsed from initiating the lowering protocol. The latter ensures no unspooling of the winch cable occurs which would compromise subsequent weighing operations. **Step 6:** as a safeguard, the system undertakes a post-lowering weigh check (against the pre-defined benchmark) to ensure the sub-frame and grid are, in fact, on the ground.

Table 1
Weather parameter ranges observed in Cape Town, South Africa where the automated weight loss measurement device has been tested and successfully performed.

Weather parameters	
Temp. range	15.1–32.8 °C
Hum. range	21–96%
Max. rain rate	33.6 mm/h
Max. solar radiation	978 W/m^2
Max. wind gust	51.5 km/h
TSHW Index range	13.5–37.6 °C

In terms of cost reduction, the device cost the research team approximately US$1000 to construct (materials only). By comparison, a single 77-day warm season decomposition cycle costs between US$400 and US$500 in fuel alone to visit our original research site just over 20 miles from the University (of Cape Town). A single 142-day cool season decomposition cycle costs nearly US$900. Thus, the cost of a single device is already met within just half a year of data collection. The devices are robust and have been deployed in the field on multiple occasions since 2019, representing seven seasonal decomposition cycles, without any signs of corrosion. We know the device is operable in a minimum range of environmental parameters as experienced during field testing in Cape Town, South Africa (see Table 1). The cost of constructing an apparatus will vary depending on the technical expertise available to the research team in question, but given the longevity of each device, it is likely that implementation will still reduce the overall cost of data collection over time. This is especially true when considering the device's remote capabilities (which reduce the cost of in-situ labour, not just financially, but in terms of time as well) and the capacity of the device to monitor multiple variables simultaneously which becomes increasingly difficult and/or cumbersome when undertaken manually as the number of measured variables increases.

Of course, not all forensic taphonomic research takes place in remote circumstances, so, such a dramatic reduction in research cost as we measured may not be realised where research is undertaken in close proximity to the research base. In such circumstances, however, we would argue that the value gained through improved data

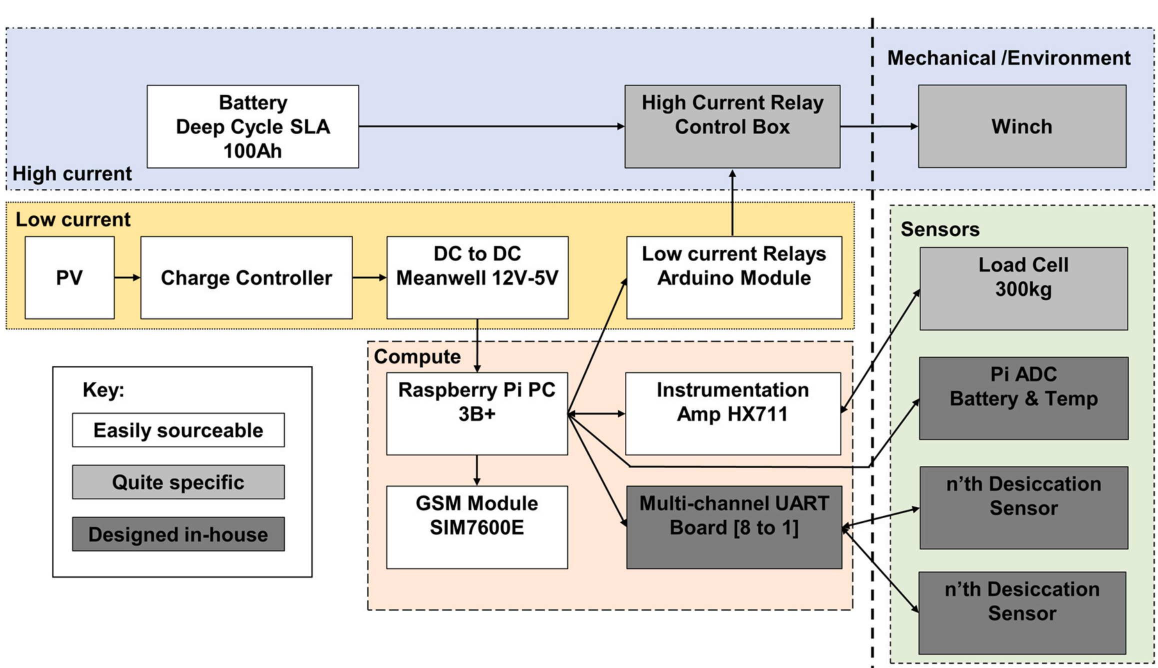

Fig. 4. : Block diagram of the electrical components comprising the device, showing high/low current and compute portions, and mechanical/environment interface and sensor components. The relative ease of procurement of each component is indicated in the key on the bottom left.

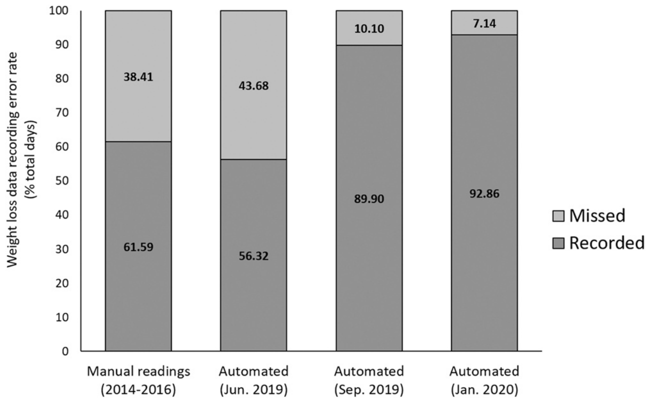

Fig. 5. : Stacked bar plot indicating proportions of missing weight loss data for four sets of decomposition-monitoring cycles: 2014–2016 (manual readings), June-August 2019 (autonomous readings), September-December 2019 (autonomous readings), and January-March 2020 (autonomous readings). The numbers within the bars indicate actual values based on the y-axis scale.

resolution and diversity of variables monitored (and simultaneously so, as discussed below) is well-worth the investment. We also recognise that scaling up the number of carcasses could reverse the cost benefit, making the research cost-prohibitive where deployment of large numbers of carcasses is necessitated by the chosen experimental design. We would, however, argue that this device is not intended for such research; quite the contrary, it is intended to pave the way for mitigating the significant problem of simple pseudo-replication that typically accompanies such experimental designs [49], along with the invariable changes in carrion ecology that accompany the creation of what is, essentially, a mass fatality incident. Such is explained further in the “Next Steps” section below.

Evaluation of attainment of improved data resolution is visualised in Fig. 5. Using our research programme as the illustration (covered by UCT Faculty of Health Sciences’ Animal Ethics Committee Approval 018_023), weight loss data obtained manually between 2014 and 2016 resulted in an apparent data loss rate of almost 40% (if every day of deployment required at least one measurement of carcass weight). This was ostensibly due to resource-constraint driven study design, and incapacitations on the part of the single researcher (see [10]). The first iteration of our device was not an improvement (as is expected with prototyping), but debugging and electromechanical refinement of the device have ensured that the second and third iterations have greatly improved upon the quality of data, with a missing data rate of just over 7% as of January 2020. It is important to note that these values represent weight loss measured just once per day, but the device has the capacity to measure weight at any frequency.

As it pertains to remote access to on-site data, the device remains fully accessible to the research team remotely, and data are received remotely via email once per day. Occasionally, emails bounce or are not sent due to random coding execution errors, but the data are also retained on the device locally for redundancy and are downloaded during bi-monthly site visits.

Challenges remain and the device is not infallible. There are numerous potential sources of error due to the number of working parts; we have experienced data loss due to malfunction of the load cell (the cause undetermined but suspected to be failure of weatherproofing), malfunction of the load cell amplifier, failure of the battery recharging system due to malfunction of the PV charge regulator, and malfunction of the code on the Raspberry Pi. However, these still represent a minority of incidents as evidenced by the improved quality of the data record (Fig. 5). As issues are encountered, solutions are developed and the device refined, and we have not yet encountered an issue we could not overcome.

3.1. Significance of the device and next steps

The potential value of this device lies in its ability to facilitate forensically realistic field-based experimental taphonomic research. Forensic realism is about replication of taphonomic scenarios that reflect actual forensic cases. To illustrate, in our local context, our cases comprise single clothed individuals and, on rare occasions, a pair of persons [3]. The carrion biomass load in such cases is an important consideration when designing experiments to develop data that will underpin models of decomposition used to estimate PMI for such cases. Whilst carcass mass has been explored as a potential confounder in the design of field-based experimental forensic taphonomic research (see [36] for detailed discussion), carrion biomass load in the experimental environment has not been considered. Variations in carrion biomass load are known to affect the activity of vertebrate scavengers via processes such as scavenger swamping [4,51,53]. Such is particularly true of small facultative scavengers that are not wide-ranging or long-lived, which typify many urban and peri-urban landscapes [19,40,64]. The Cape grey mongoose (*Herpetes pulverulentus*) is a prime example in our local context, identified through our previous research (Spies et al., 2018a,b, 2020). Multiple, closely-spaced carcasses have also been shown to alter invertebrate utilisation of carrion, leading to a recommendation for inter-carcass distances of at least 50 m [36]. Ergo, there is an experimental design imperative in our local context to limit the sample size to ensure greater congruence between experimental and forensic settings with respect to carrion ecological parameters. Our device provides a means to mitigate the sacrifice in statistical robusticity that might be experienced with such a setup, by providing for the continuous, simultaneous monitoring of carcasses deployed in multiple, true habitat replicates. The latter, in turn, provides mitigation against the issues of simple pseudo-replication which have pervaded experimental design in forensic taphonomy research [49].

The precision and accuracy of a PMI estimate relies on the data underpinning the model in use having been captured at regular, *frequent* intervals. Traditionally, this has been achieved through physical disruptions to the ecosystem (and, by extension, all aspects relevant to creating an accurate PMI estimate) through manual data collection. Our automated approach considerably reduces on site disruption to the taphonomic ecological processes involved in decomposition. As a specific example, the device weighs carcasses for just 10 s at midnight – a time our previous research in this biogeographic region has demonstrated to have the least vertebrate and invertebrate scavenger activity (identified via high-sensitivity remote camera trap photography and videography). Thus, the results of our studies employing this system are more forensically realistic in terms of carcass disturbance, potentially improving PMI estimates derived from such data.

The next phase of development for this automated apparatus has two foci - 1) developing a cloud-based data repository and automated data processing capabilities, and 2) expanding the array of variables monitored simultaneously.

Our next ambition is to create a cloud-based data repository where data can be pushed directly. This repository would include automated processes for screening and cleaning incoming data (including automatically flagging missing data) and producing simple graphics and descriptive statistics. Having a cloud-based data repository would make it easier for our own research team to work with the data, but also provides a convenient and standardised means for sharing the data with other teams, and simultaneously acts as a data back-up. Additionally, and importantly, it provides a foundation for the creation of a framework within which biogeographically disparate teams of researchers could *simultaneously* collect the *same* data from carcasses in a *standardised* format, establishing the long-called for comparative and/or synthesised datasets [50]. The same will help individual research teams avoid the aforementioned simple pseudo-replication in experimental design by facilitating deployments of single carcasses across true habitat replicates, land resources permitting [49]. At the time of writing this manuscript, we know this approach is possible, our device having provided for the completion of two simultaneous multi-biogeographic decomposition sequences wherein we successfully recorded simultaneous carcass weight loss, scavenging, and weather variables at two locations 34 km apart. To the best of our knowledge, this represents only the third truly simultaneous monitoring of different decompositional circumstances (the other two being related to monitoring scavenger activity, see [6] and [43]), and the first to document quantitative description of the progression of decomposition in such circumstances.

At present, our typical decompositional monitoring setup records carcass weight loss, visual changes in carcass appearance overtime (via static overhead camera), scavenger activity (via independent camera traps), and 33 weather variables (via an on-site weather station). The latter three sets of data currently require some manual data collection; ideally, we aim to integrate all aspects of carcass monitoring in the future. Moreover, we seek to obtain a wider range of measures of the carcass, including a range of carcass temperatures, tissue moisture, and carcass and soil pH. The former two are obtainable using our custom carcass desiccation sensors; the latter would be a new addition. The monitoring of in-carcass pH in real time has recently been reported by [8] in laboratory conditions for palaeontological study. Their setup is precisely what could be incorporated into an autonomous, remotely operable centralised data collection system like the one we have built, and deployed in outdoor field settings as the next step. But why stop there? What about simple autonomous robotics for sample collection (e.g., swabs of carcass-based bacteria, headspace gas samples for VOC analysis, entomological specimens)? What about artificial intelligence (AI)-driven videographic monitoring for coding and quantifying scavenger interaction with the carrion? AI algorithms such as YOLO (You Only Look Once) v2 could be used to identify specific scavenger species, and more advanced algorithms such as DeepLabCut™ by Mathis Laboratory can be used to track specific behaviours defined by changes in posture or body part movement/placement. These algorithms are compatible with Raspberry Pi technology. Provided sufficient plug-in storage was included in the setup, recorded videographic footage could, in theory, be analysed in-situ at the deployment site. The integration of multiple sensing modalities on individual carcasses would also have the positive effect of supporting the 3 R's in animal-based research, these being Reduction, Refinement, and Responsibility.

Automation represents a completely new and vast horizon waiting to be explored by forensic taphonomists. The approach we have outlined above has never before been attempted, and we do not yet know if it will work. Further work is needed to determine whether higher resolution datasets comprising a wider range of variables will, indeed, improve the precision of our estimates of PMI. Specifically, the device needs to be rolled out in additional biogeographic areas and new models of decomposition constructed from the derived data, whereafter the models can be evaluated for predictive accuracy. But given the multiplicity of benefits of the automated approach as explored in this manuscript, is it not worth a try? We believe the approach could give us – as a discipline – the capacity to overcome the "Five Hindrances" and step fully into a new age of transdisciplinary, quantitative data-driven taphonomic science underpinned by forensic realism in experimental design. We stand to gain greater medicolegal legitimacy and, therefore, practical forensic relevance, and potentially even achieve our elusive goal of *precise* estimation of the PMI. Thus, this new generation of automation moves us closer than ever before to achieving the core goals of experimental, field-based forensic taphonomic research.

Funding sources

This work was supported by the South African National Research Foundation [Grant 115357], and the University of Cape Town [Research Development Grant, Research Contracts and IP Office's Explorer Grant, and the Faculty of Health Science's Discretionary Research Grant].

CRediT authorship contribution statement

Devin Finaughty: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Justin Pead:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation. **Maximilian Spies:** Validation, Formal analysis, Investigation, Data curation, Writing – review & editing. **Victoria Gibbon:** Conceptualization, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Conflict of Interest

The authors declare that they have no conflict of interest.

Acknowledgements

We would like to thank the following people for their contributions towards the development and field testing of our automated taphonomic data collection apparatus: Mr John Morris (Farm Manager: Mariendahl Experimental Farm, Stellenbosch University) for providing the pig carcass used for this research; the South African Medical Research Council for granting access to the facilities at the their Animal Unit in Cape Town, South Africa to conduct the research; Mr Charles Harris (Principle Technical Officer: Mechanical Workshop and Operations, Department of Human Biology, UCT), Mr Tyrone De Wet (Mechanical Workshop/Laboratory assistant: Department of Human Biology, UCT), and Mr Abdul Samuels (Laboratory assistant: Department of Human Biology, UCT) for their assistance with construction and assembly of the mechanical components of the automated system in both laboratory and field conditions, as well as transporting experimental carcasses; Noelene Le Cordier (University of Cape Town), Dr Tim Low (University of Cape Town), and Professor Sure Mataramvura (University of Cape Town) for granting access to UCT land to conduct the research; and Dr Trevor McIntyre (School of Agriculture and Life Sciences, University of South Africa) for the provision of camera traps for monitoring our experimental carcasses. The financial assistance of the South African National Research Foundation (NRF) towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the authors and not necessarily to be attributed to the NRF.

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