FORENSIC INVESTIGATIONS WITH THE IDENTIFICATION OF HUMAN REMAINS WITH GROUND PENETRATING RADAR (GPR): A REVIEW

PESQUISAS FORENSES COM A IDENTIFICAÇÃO DE VESTÍGIOS HUMANOS COM O RADAR DE PENETRAÇÃO DO SOLO (GPR): UMA REVISÃO

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ABSTRACT

Forensic geophysics research using ground-penetrating radar (GPR) has the potential to non-destructively detect buried or hidden targets. A systematic literature review is a bibliographic technique that aims to answer a question objectively and impartially by evaluating a body of data from articles and other scientific documents. The question posed here was how GPR can assist in identifying bodies in different burial scenarios and where research on this topic is headed. The extracted articles were divided into two groups: controlled sites and uncontrolled sites. From the analysis of the results, it can be seen the most commonly used targets for research in controlled sites were pigs due to their anatomical similarity to humans. The articles reviewed involve the integration of more than one research method. As new scopes of investigations are a comparison of GPR image features for multiple burial scenarios, evaluation of the change in geophysical response of simulated mass graves over the years, and research about false-positive results which was discussed in only 2.1% of the reviewed articles.

Keywords: clandestine grave; uncontrolled and controlled research site; forensic Science; burials.

RESUMO

Pesquisas na área de geofísica forense com a utilização do radar de penetração no solo (GPR) têm o potencial de detectar de forma não destrutiva alvos enterrados ou ocultos. A revisão sistemática da literatura é uma técnica bibliográfica que se propõe a responder uma questão objetiva e imparcialmente avaliando um conjunto de dados oriundos de artigos e outros documentos científicos. A questão aqui posta foi saber como o GPR pode auxiliar na identificação de corpos em diferentes cenários de sepultamento e para onde pesquisas nesta temática estão se direcionando. Os artigos extraídos foram divididos em dois grupos: sítios controlados e sítios não controlados. Os alvos mais utilizados para pesquisas em sítios controlados são suínos devido à semelhança anatômica com os humanos. Como novos escopos de investigações estão a comparação de características de imagens de GPR para múltiplos cenários de sepultamento, avaliação da mudança na resposta geofísica de sepulturas clandestinas simuladas ao longo dos anos e pesquisas acerca de resultados falsos positivos que foi discutida em apenas 2,1% dos artigos revisados.

Palavras-chave: sepultamentos clandestinos; sítios controlados e não controlados; ciências forenses; sepulturas simuladas.

INTRODUCTION

Forensic research by searching for human remains associated with the use of the geophysical method, Ground Penetrating Radar (GPR), is advancing in various areas of the sciences being incorporated in different lines of research such as decomposition of organic material (Pringle *et al.*, 2020; Dick & Pringle, 2018; Schoor *et al.*, 2017; Schultz, *et al.*, 2016), in submerged areas (Ruffell *et al.*, 2017; Schultz et al., 2013; Parker *et al.*, 2010) controlled sites (Pringle et al., 2020; Cavalcanti *et al.*, 2018; Schoor *et al.*, 2017; Schultz *et al.*, 2016; Molina *et al.*, 2016a; Pringle *et al.*, 2016; Molina *et al.*, 2016b; Booth & Pringle, 2016; Salsarola *et al.*, 2015; Almeida *et al.*, 2015; Molina *et al.*, 2015; Almeida *et al.*, 2014; Lowe *et al.*, 2013; Pringle *et al.*, 2012a; Solla *et al.*, 2012; Schultz & Martin, 2012; González-Jorge *et al.*, 2012; Schultz & Martin, 2011; Parker *et al.*, 2010; Schultz, 2008; Schultz *et al.*, 2006; Powell, 2004; Schultz *et al*., 2002), use combined with other methods (Pringle *et al.*, 2020; Abate et al., 2019; Rubio-Melendi *et al.*, 2018; Cavalcanti et al., 2018; Molina et al., 2016a; Aziz *et al.*, 2016; Hansen & Pringle, 2013).

These forensic researches aided by geophysical methods are relatively recent and coincident with greater and better development of geophysical equipment, mainly, in this specific case, as happened with GPR in the mid-1990s. The increasing scientific development on the subject can be observed by the increase in the average publication of scientific articles that between 2000-2009 was 3.0 articles compared to the period 2010-2019 with an average of 6.9 according to data accessed on 03/15/2021 in the Web of Science.

In this context, the development of a Systematic Literature Review (SLR) is appropriate because it allows identifying both the evolution of scientific knowledge and evaluates it statistically. Thus, the present work had an as main objective: to analyze the advances obtained in forensic research of human remains identification with the help of the GPR geophysical method and, in a complementary way, to identify the common characteristics of the controlled sites, the limitations in the use of GPR and the real improvements in the use of complementary geophysical methods in this theme.

Systematic Review and Meta-Analysis

Systematic Literature Review (SLR) is a scientific research technique to gather, critically evaluate, and conducting a synthesis of the results of multiple primary studies (Benefield, 2003). It allows, within an area of knowledge, to identify, evaluate, and interpret the most relevant studies in a topic with the production of a critical synthesis of the main evidence, evolution, and highlights neglected themes that may indicate the proposition of future topics in the process for new research. SLR's concentrate on the identification of previous research, evaluating the results in a systematic way and with statistical resources employing synthesis. Its main features are a predefined set of objectives and eligibility criteria.

It comprises three development stages (Planning, Execution, and Documentation). Planning begins with the definition of the protocol that specifies all the steps of the method that will be followed. The definition of the main question and other guiding parameters of the review ensures in advance that the methods employed will be standardized and the risk of bias reduced ("Systematic Reviews: CRD's guidance for undertaking reviews in health care", 2009). Execution objectively comprises the fulfillment of the protocol in its entirety, beginning with access to databases using keywords in advanced search processes utilizing strings. Documentation presents the product of the review that must have a minimum set of items (Checklist) comprising the final report document (Galvão *et al.*, 2015).

The steps involved are based on evidence-based searches and have as main steps (Porritt *et al.*, 2014): (i) Development of the review protocol that contains the formulation of the Main Question, Keywords, Inclusion/Exclusion Criteria and Selection of Databases; (ii) Search for the primary studies (articles) in the Databases; (iii) Selection of the primary studies (based on the inclusion/exclusion criteria); (iv) Data extraction using a summary sheet developed in parallel with the protocol; (v) Analysis and Synthesis of the extracted data focused on formulating the answer to the Main Question; (vi) Thematic suggestion for further research.

MATERIALS AND METHODS

For this research, the StArt (State of the Art) software (http://lapes.dc.ufscar.br/tools/start_tool), version 3.3 beta 03 (Lapes/UFSCar) was used. The steps performed in this research are: (i) defining the research protocol; (ii) importing the data from the articles obtained in the databases; (iii) selecting the articles; (iv) classifying the articles to be read; (v) summarizing using graphs with a statistical emphasis of the results. The searches were carried out in the Web of Science, Scopus, and Science Direct Databases considering the combination of keywords and the guiding delimiters (Table 1) that work as a first filtering process of the search.

As a result, a total of 890 articles were obtained: 651 in Science Direct, 201 in Scopus, and 38 in Web of Science. For each database, the searches containing the title, abstract, and keywords were exported in "bibtex" format and imported into StArt 3.0.3. After the selection 56 articles were accepted for the next step, 399 were rejected and 435 articles were duplicates. Initially, the stage of extraction of information from the articles occurs with the full-text search by accessing the Federated Academic Community (CAFe) (http://periodicos.capes.gov.br/). The summary table will not be displayed in this article due to the imposed page limit.

Table 1 - Protocol parameters defined for the research.

Parameters	Applied to the Systematic Review
Research Group Members	Reviewer A and Reviewer B.
Main Question	How can GPR assist in identifying bodies in different burial scenarios?
Keywords string structure	(("GPR" OR "ground penetrating radar") AND "forensic")) e ((("GPR" OR "ground penetrating radar") AND "forensic" AND ("burial" OR "burials" OR "buried") AND ("graves" OR "grave"))).
Database	Web of Science/Scopus/Science Direct.
Delimiters	Year of publication: 2000 to 2020. Publication type: Only articles available online. Language: English. Area of research: unrestricted.
Inclusion (I)/Exclusion (E) Criteria	(I) Forensic research using GPR. (I) Studies published and fully available in the scientific databases searched. (E) Does not address GPR applied to forensics. (E) Not in the selected language. (E) Full text not found. (E) Records without abstract. (E) Full text not accessible by the Capes Portal and/or without return of the authors by the Research Gate.

RESULTS

The visualization of co-authorship is presented in Fig. 1 for the period 1990-2021 with authorships being the unit of analysis. This relationship reflects how the networks of researchers are structured when considering at least 2 documents per author and at least 1 citation of the publication. In this graphic form, the size of the symbol reflects the number of publications belonging to the researcher clusters. The intensity of the relationships is reflected in the thickness of the lines and the proximity between the centers of the clusters (circles). Six clusters are identified that have their common core in researcher Pringle, J.K (Table 2). Cluster 1 (in green) is composed of 4 researchers and coordinated by Pringle, J.K., the most cited researcher when the topic is forensic research in the identification of human remains with the aid of geophysical methods. Clusters 2 (in dark blue), 3 (in purple), and 4 (in red) represent clusters with repetitive contributions to each other and Cluster 1, and with their network being structured, but with very tenuous relationships. The distance of the Cluster 5 (in yellow) to the others reflects a co-authorship association that occurred in previous years and was not continued with an increase in new publications. Cluster 6 (in turquoise blue) reflects a more recent association among researcher clusters, but already with relationships with researchers from Clusters 1, 2, 3, and 4.

The relations of association and intensity of coauthorship can be evaluated considering research institutes as the unit of analysis, but the corresponding graph will not be presented here. The largest concentration is in institutions in the United Kingdom with a minority presence of institutions from Colombia (South America) and Spain (Europe).

For the same period, the cocitation map (Fig. 2) was prepared to identify the relevant authors and/or articles in the theme from the selected documents. The unit of analysis considered was cocitation when an article cites two articles in common. The parameters used were a minimum of 25 cocitations on the reference and the weight of the relations being calculated for the number of these cocitations. In order not to filter out articles that may be citation references, the period used did not compute the beginning year, only the end, 2020.

The authors with the highest reference of publications with at least 25 citations, according to the Web of Science, are respectively: France et al., 1992 (47), Nobes *et al.*, 2001 (40), Schultz, 2007 (33), Schultz *et al*., 2006 (33), Schultz 2008 (29), Pringle *et al.*, 2008 (28), Ruffell *et al.*, 2005 (26), Owsley 1995 (26), Davenport, 2001 (26), Cheetham, 2005 (26), Pringle *et al.*, 2012 (25), Novo *et al.*, 2011 (25), and Bevan, 1991 (25). In addition to these 13 articles cited above another 43 articles that met the inclusion criteria outlined in the protocol were selected for full reading, extraction, and analysis. They were divided into 2 thematic groups, 48 articles, for a better presentation of the results: Controlled Sites (Table 3) and Non-Controlled Sites (Table 4).

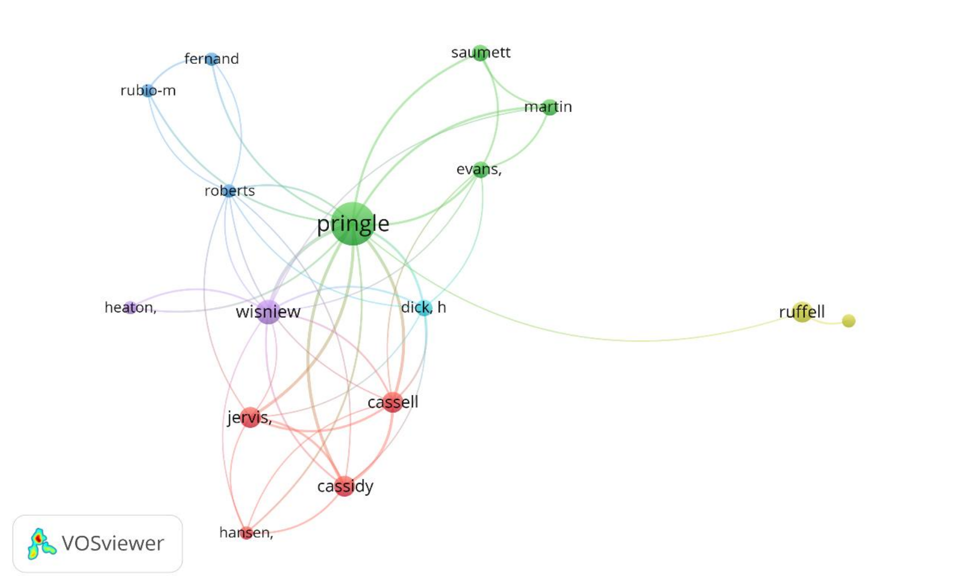

Figure 1 - Coauthorship network map between authors of the selected articles for the period 2000-2021 (Source: Web of Science). The most structured network is centered on the researcher with the most publications on the subject matter of this SLR. The thicker lines indicate direct citation and with greater intensity in the relationships of the researchers. The less thick lines indicate indirect citation and co-authorship.

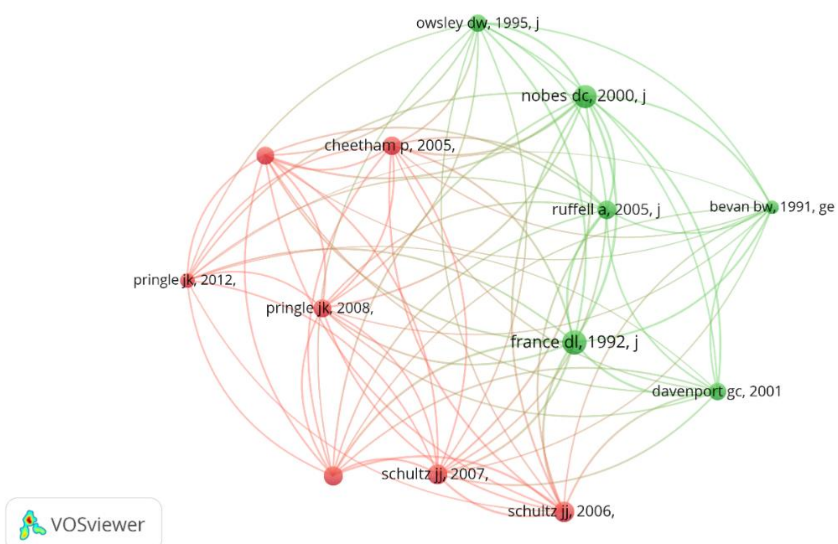

Figure 2 - The intensity of the cocitation network among the authors of the research on the topic in question (Source: Web of Science). In this figure, the network intensity from the core of the author Pringle, J.K. to other researchers is highlighted. Note: This analysis only considers the first author of each citation. This is a limitation of the data exported from the Web of Science.

Table 2 **-** Identification of associated researcher clusters to co-authorship.

Cluster	Researcher	Institution	Country
1	Pringle, J. K.	Keele University	United Kingdom
1	Evans, G. T.	Keele University	United Kingdom
1	Martin, M. C.	Universidad Nacional de Colômbia	Colombia
1	Saumet, M.	Universidad Nacional de Colômbia	Colombia
2	Cassela, J. P.	Keele University	United Kingdom
2	Cassidy, N. J.	Keele University	United Kingdom
2	Hansen, J. D.	Keele University	United Kingdom
2	Jervis, J. R.	Keele University	United Kingdom
3	Fernandez-Alvarez, J.	Universidad de Oviedo	Spain
3	Roberts, D.	Universidad de Oviedo	Spain
3	Rubio-Melendi, D.	Universidad de Oviedo	Spain
4	Heaton, V.	Keele University	United Kingdom
4	Wisniewiski, K. D.	Staffordshire University	United Kingdom
5	Ruffell, A.	Queen's University, Belfast	United Kingdom
5	Donnely, C.	Queen's University, Belfast	United Kingdom
6	Dick, H. C.	Keele University	United Kingdom

Controlled Sites

This group represents 62.5% of the total articles extracted in this SLR. The publications in this group occurred between the years 2000 and 2020. The general objectives of the surveys included: comparing different antenna frequencies, evaluating and demonstrating the effectiveness and the best methods and methodologies for grave detection, establishing an initial forensic research methodology, and evaluating the applicability of GPR.

All of the articles had their controlled sites constructed in a natural area having clay soils as the one that appeared the most, at 36.6% (Cavalcanti *et al.*, 2018; Schoor *et al.*, 2017; Molina *et al.*, 2016a; Molina *et al.*, 2016b; Molina *et al*., 2015; Hansen & Pringle, 2013; Lowe *et al*., 2013; Pringle *et al*., 2008; Freeland *et al*., 2003; Miller *et al*., 2002; Freeland *et al.*, 2002) of the controlled sites, in second place the soil type that appeared most was clayey sandy, present in 23.3% (Pringle *et al.*, 2020; Pringle *et al.*, 2016; Booth & Pringle, 2016; Almeida *et al.*, 2014; Lowe *et al.*, 2013; Pringle *et al.*, 2012a; Schultz *et al.*, 2006) of the controlled sites, followed by sandy soil, present in 16.6% (Schultz *et al*., 2016; Pudova *et al.*, 2016; Pringle *et al.*, 2012b; Schultz & Martin, 2012; Schultz, 2008) of the controlled sites of the selected articles in this group.

Table 3 - Main parameters used in Controlled Sites research. ER= Electroresistivity; MS= Magnetic Susceptibility; MC= Magnetic Conductivity; MG= Magnetic Gradient; MT= Microwave Tomography; LMT= Linear Microwave Tomography; MD= Metal Detector; LS= Laser Scanning; RP= Rectified Photography.

Reference	Goals	Target dimensions (m)	Predominant soil type	Target type	Target depth (m)	Center frequency (MHz)	Complementary techniques	Main results
Pringle *et al.*, 2020	Evaluate the response of unmarked graves over ten years.	1,5x0,75x0,6	Clayey sandy	Pig	0,6	110, 225, 450, 900	ER	Target produced low resistivity anomalies for up to four years. GPR (110-900MHz) detected the target and the 225 MHz frequency was the most efficient.
Cavalcanti *et al.*, 2018	Observe the geophysical response to different burial scenarios.	1,8x1x1	Clayey	Pig	1	400	ER	Detection due to target contours. The Wenner-Schlumberger arrangement shows a better resolution of the grave boundaries.
Schoor *et al.*, 2017	Investigate the changes associated with shallow and clandestine burials.	2,2x1,2x0,75	Clayey	Pig	0,75	250	-	The grave anomalies are discernible as hyperbolic reflections in the unmigrated 2D radargrams and this changes over investigation time to lower resolution.
Schultz *et al.*, 2016	Determine the applicability of GPR to detect controlled burials.	1x1x1 / 1x1x0,5	Sandy	Pig	0,5 / 1	250, 500	-	The graves produced a more distinct response with clearer target reflections compared to bare carcasses. The imaging of the dominant 250 MHz frequency antenna was more favorable.
Molina *et al.*, 2016a	Evaluate whether the chosen methods can detect the simulated graves.	1,7x0,7x0,5	Clayey	Pig and Human Remains	0,5	250, 500	ER, MC and MS	The 250 MHz and 500 MHz frequencies showed good detection. MS, MC, and ER showed reduced detection of the simulated targets.
Pringle *et al.*, 2016	Determine the applicability of GPR to detect controlled graves.	1,5x0,75x0,6	Clayey sandy	Pig	0,6	110, 225, 450, 900	ER	The unwrapped pig shows low resistivity anomalies until the fourth year. The wrapped pig shows high resistivity anomalies. The frequencies (110 and 900 MHz) were good for the wrapped pig and low resolution for the bare pig.

Molina *et al.*, 2016b	Evaluate whether the chosen methods can detect the mock graves.	2x2x0,8 / 2x2x1,2	Clayey	Pigs and Human Remains	0,8 / 1,2	250, 500	ER, MC and MS	Good detection of wrapped targets in all periods with 250 MHz. Skeletons and decapitated and burned remains were poorly visualized.
Pudova *et al.*, 2016	Propose a protocol for field operations, data processing, and analysis.	6x8	Sandy	Metal and plastic objects, bones, concrete, wood trunk	0,4 to 1,2	400, 1200	-	Metal objects, concrete blocks, a plastic bottle filled with water, and a PVC bag filled with animal bones were picked up easily. Wood logs and empty plastic bottles were unclear.
Booth *et al.*, 2016	Develop a method to quantify the evaluation of a time-lapse file.	Not mentioned	Clayey sandy	Pig	0,5	110, 225, 450	-	Lower frequency antennas provided better results although the grave was detectable by all frequencies tested.
Salsarola *et al.*, 2015	Evaluate the effectiveness of the technique in two different burial environments.	2x1x0,9	Permeable and loose	Pig	0,8 to 0,9	500	-	GPR was useful in recognizing anomalies at burial depths. With slight anomalies of skeletal remains at 92 weeks from burial.
Almeida *et al.*, 2015	Analyze GPR reflections by a LMT approach.	2x1x1,1	Sandy clayey	Pig	1,1	270, 900	LMT	Anomalies are present in the position of the buried pig in both radargrams and tomographic images.
Molina *et al.*, 2015	Evaluate the best detection techniques for forensic geophysics.	2x2x0,8 / 2x2x1,2	Clayey	Pig and human remains	0,8 / 1,2	250	-	Anomalies are present in the position of the buried pig in both radargrams and CT images.
Almeida *et al.*, 2014	Apply microwave tomography with GPR.	2x1x1,1	Clayey sandy	Pig	1,1	270, 900	MT	GPR showed reasonable detection of the targets. Simulated burials using skeletonized human remains were not identified after 19 weeks.
Hansen *et al.*, 2013	Detail geophysical techniques for detecting surface buried objects.	5x5x0,15	Semi-urban; clay	Metal objects, bladed weapons, grenades, guns, ammunition, and bricks	0,15	450, 900	MS, MG, ER, MD and gradiometry Fluxgate	MT in conjunction with the 270 MHz GPR frequency improved target identification.
Lowe *et al.*, 2013	Investigate the applicability of GPR for forensic investigations	Not mentioned	Clayey sandy / silty clay / fine sand	Pig	0,76	500	-	MS: optimal for target detection; MD: did not detect all targets. GPR: optimal for target detection in the semi-urban environment. ER: good for target detection in the semi-urban environment.

Pringle *et al.*, 2012a	Determine the applicability of GPR to detect controlled graves.	1,5x0,75x0,6	Clayey sandy	Pig	0,6	110, 225, 450, 900	ER	GPR was successful in identifying clandestine graves in clayey loamy and fine sandy loamy soils.
Pringle *et al.*, 2012b	Establish methodologies for forensic research in coastal areas.	1x0,4x0,5	Sandy	Mannequin	0,5	225, 450, 900	MD, ER and MS	The unwrapped pig presents low resistivity anomalies. The wrapped pig shows high resistivity anomalies. Frequencies (110 and 900 MHz) are good for identifying the wrapped pig.
Solla *et al.*, 2012	Analyze the effectiveness of GPR in forensics.	Not mentioned	Sandy clayey	Pig and objects	0,5 / 1	500	Photogrammetry	450 MHz frequency was successful, but bad data was due to saltwater. ER and MS were successful.
Schultz *et al.*, 2012	Monitor empty and filled control graves.	1x1x0,5 / 1x1x1	Sandy	Pig	0,5 / 1	250, 500	-	GPR was successful in identifying buried remains such as mock hideouts, drug caches, weapons, clothing, and personal effects.
González-Jorge *et al.*, 2012	Compare terrestrial laser scanning, rectified photographs, and 3D GPR.	2x1,2x0,7 / 2,1x1x0,5	Not mentioned	Pig and human bones	0,5 / 0,7	500	LS and RP	The frequency of 250 MHz was the best for deep grave detection and 500 MHz for shallow grave detection.
Schultz *et al.*, 2011	Compare GPR reflection profiles of a control grave.	1x1x1	Spodosol	Pig	1	250, 500	-	The result obtained with terrestrial laser scanning coincides with real data. GPR data detected the target accurately.
Pringle *et al.*,2008	Determine the best forensic geophysical techniques.	2x0,5x0,6	Clayey	Plastic Resin	0,6	225, 450, 900	ER, MC, MG and MS	With the frequencies of 250 and 500 MHz, the grave was detected with the 6-month-old pig target.
Schultz 2008	Test GPR to detect small pig cadavers.	Not mentioned	Sandy	Pig	0,5 to 0,6 / 1 to 1,1	500	-	ER located the grave. MG did not locate the grave. MS did not show the grave. GPR provided varied responses.
Schultz *et al.*, 2006	Test GPR to detect large pig carcasses.	Not mentioned	Clayey sandy	Pig	0,5 to 0,6 / 1 to 1,1	500	-	Target produced low resistivity anomalies for up to four years. GPR (110-900MHz) detected the target and the 225 MHz frequency was the most efficient.
Powell 2004	Detect graves in forensic investigations.	1x1x0,5 / 1x1x1	Limestone	Pig, kangaroo, human cadaver	0,5 / 1	200	ER	Detection due to target contours. The Wenner-Schlumberger arrangement shows a better resolution of the grave boundaries.
Freeland *et al.*, 2003	Compare raw data operating on buried corpses.	2,4x1,8x0,6	Clayey	Human cadavers	0,6	400, 900	-	The grave anomalies are discernible as hyperbolic reflections in the unmigrated 2D

								radargrams and this changes over investigation time to lower resolution.
Miller *et al*., 2002	Evaluate GPR integration and anthropological data of decomposition rates.	~2,4x1,8	Clayey	Human cadavers	~0,45	Not mentioned	-	The graves produced a more distinct response with clearer target reflections compared to bare carcasses. The imaging of the dominant 250 MHz frequency antenna was more favorable.
Schultz *et al.*, 2002	Test the applicability of GPR to detect buried bodies.	Not mentioned	Sandy	Pig	0,5 to 0,6 / 1 to 1,1	500, 900	-	The 250 MHz and 500 MHz frequencies showed good detection. MS, MC, and ER showed reduced detection of the simulated targets.
Freeland *et al.*, 2002	Evaluate the use of GPR over buried corpses.	~2,4x1,8	Clayey	Human cadavers	~0,6	400, 900	-	The unwrapped pig shows low resistivity anomalies until the fourth year. The wrapped pig shows high resistivity anomalies. The frequencies (110 and 900 MHz) were good for the wrapped pig and low resolution for the bare pig.
Hammon III *et al.*, 2000	Perform 2.5D finite-difference simulations in the time domain of GPR responses.	Not mentioned	Dry sandy and clay	Human cadavers	0,4 / 0,9	450, 900, 1200	-	Good detection of wrapped targets in all periods with 250 MHz. Skeletons and decapitated and burned remains were poorly visualized.

In 73.3% of the articles in the controlled sites theme group the targets analyzed were pigs (Pringle *et al.*, 2020; Cavalcanti et al., 2018; Schoor *et al.*, 2017; Schultz *et al.*, 2016; Molina *et al.*, 2016a; Pringle *et al.*, 2016; Molina et al., 2016b; Booth & Pringle, 2016; Salsarola *et al.*, 2015; Almeida et al, 2015; Almeida *et al.*, 2014; Lowe *et al.*, 2013; Pringle *et al.*, 2012a; Solla *et al.*, 2012; Schultz & Martin, 2012; González-Jorge et al., 2012; Schultz & Martin, 2011; Schultz, 2008; Schultz *et al.*, 2006; Powell, 2004; Schultz *et al.*, 2002), but the use of kangaroos (Powell, 2004), human remains (Molina *et al.*, 2016a; Molina *et al.,* 2016b; Molina *et al.*, 2015; González-Jorge *et al.*, 2012; Powell, 2004; Freeland *et al.*, 2003; Miller *et al.*, 2002; Freeland *et al.*, 2002; Hammon *et al.*, 2000), objects such as sheet metal, iron pipe, bag with animal bones, concrete block, wooden log, metal barrels (Pudova *et al.*, 2016), water bottles (Pudova *et al.*, 2016), clothing and personal effects (Solla *et al.*, 2012), rifle and pistol simulacrum (Solla *et al.*, 2012), cell phones and bullet casings (Solla *et al.*, 2012), bricks, screws, knives, grenades (Hansen & Pringle, 2013), plastic resin human skeleton (Pringle *et al.*, 2008), and fiberglass mannequins (Pringle *et al.*, 2012b). Depths studied ranged from 0.15 m representing shallow graves to 1.2 m representing deep graves. Targets at only one depth were the option chosen in 60% of the articles.

The center frequencies used ranged from 110 MHz to 1200 MHz. The most commonly used frequencies were 500 MHz (Schultz *et al.*, 2016; Molina *et al.*, 2016a; Molina et al., 2016b; Salsarola *et al.*, 2015; Lowe *et al.*, 2013; Solla *et al.*, 2012; Schultz & Martin, 2012; González-Jorge *et al.*, 2012; Schultz & Martin, 2011; Schultz, 2008; Schultz *et al.*, 2006; Schultz *et al.*, 2002) and 900 MHz (Pringle *et al.*, 2020; Pringle et al., 2016; Almeida *et al.*, 2015; Almeida *et al.*, 2014; Hansen & Pringle, 2013; Pringle *et al.*, 2012a; Pringle *et al.*, 2012b; Pringle *et al.*, 2008; Freeland *et al.*, 2003; Schultz *et al.*, 2002; Freeland *et al.*, 2002; Hammon *et al.*, 2000), both employed in 40% of the controlled sites. The 500 MHz frequency appears most often associated with sandy soils, while the 900 MHz frequency was most often associated with clay and sandy-clay soils. The 500 MHz frequency provided good results in tracking the evolution of decomposition with a satisfactory resolution to depth ratio.

Of the 30 articles analyzed, in 53.3% the choice was to use only GPR for the target analyses. In the remaining 46.7% the GPR appeared associated with other geophysical techniques such as electroresistivity (Pringle et al., 2020; Cavalcanti *et al.*, 2018; Molina *et al.*, 2016a; Pringle *et al.*, 2016; Molina *et al.*, 2016b; Hansen & Pringle, 2013; Pringle *et al.*, 2012a; Pringle *et al.*, 2012b; Pringle *et al.*, 2008; Powell, 2004), magnetic susceptibility (Molina *et al.*, 2016a; Molina *et al.*, 2016b; Hansen & Pringle, 2013; Pringle *et al.*, 2012b; Pringle *et al.*, 2008), microwave tomography (Almeida *et al.*, 2014), terrestrial laser scanning (González-Jorge *et al.*, 2012), and magnetic gradiometry (Hansen & Pringle, 2013; Pringle *et al.*, 2008).

Uncontrolled Sites

This group represents 37.5% of the total SLR articles and their publications occurred between the years 2007 and 2019. The main objectives included: highlighting the importance of geophysical methods by reporting their results, proposing general requirements for field operations, presenting research results and documenting investiga-tions, assisting in locating human remains and determining the location of unmarked graves.

The most frequently investiga-ted site type in this thematic group was cemetery (Damiata *et al*., 2017; Aziz *et al*., 2016; Barone et al., 2016; Hansen *et al*., 2014; Büyüksaraç et al., 2013; Doolittle & Bellantoni, 2010; Fiedler *et al.*, 2009) which was present in 38.8% of the reviewed articles, but investigations of clandestine graves were also frequent (Wisniewski *et al.*, 2019; Abate *et al.*, 2019; Novo *et al.*, 2011; Ruffell *et al*., 2009b) present in 22.2% of the reviewed articles. The soil types that were most present in this group were clay soils (Rubio-Melendi *et al*., 2018; Aziz *et al*., 2016; Hansen *et al*., 2014; Billinger, 2009; Ruffell *et al*., 2009a; Fiedler et al., 2009; Ruffell *et al.*, 2009b) found in 38.8% of articles and sandy (Wisniewski et al., 2019; Abate et al., 2019; Rubio-Melendi *et al*., 2018; Aziz *et al*., 2016; Hansen *et al*., 2014; Forbes *et al*., 2013), which appeared in 33.3% of articles.

In 94.4% of the articles in this group the targets sought were human bodies (Wisniewski *et al*., 2019; Abate *et al*., 2019; Barone & Di Maggio, 2019; Rubio-Melendi *et al*., 2018; Damiata *et al*., 2017; Aziz *et al*., 2016; Fernández-Álvarez *et al*., 2016; Barone *et al.*, 2016; Hansen et al, 2014; Büyüksaraç *et al*., 2013; Novo *et al.*, 2011; Doolittle & Bellantoni, 2010; Billinger, 2009; Ruffell *et al*., 2009a; Fiedler *et al*., 2009; Ruffell et al., 2009b; Schultz, 2007), whether in recent crime burials or in cemeteries where bodies have already been buried for years. In 5.5% of articles the searched target was the grave of a buried dog (Forbes et al., 2013).

The center frequencies used in GPR surveys ranged from 100 MHz to 500 MHz. The most commonly used frequencies were 500 MHz (Barone & Di Maggio, 2019; Rubio-Melendi *et al.*, 2018; Damiata *et al.*, 2017; Fernández-Álvarez *et al.*, 2016; Barone *et al.*, 2016; Forbes *et al.*, 2013) employed in 33.3% of target investigations and the 250 MHz (Wisniewski *et al.*, 2019; Rubio-Melendi *et al*., 2018; Aziz *et al*., 2016; Büyüksaraç *et al*., 2013; Novo *et al*., 2011) used in 27.7% of articles. The 500 MHz frequency appears most often associated with sandy soils while the 250 MHz frequency appears most often associated with sandy and clay soils.

In 50% of the articles, the choice was to use GPR associated with other complementary tech-niques which were quite varied and included: conductivity and magnetic susceptibility (Wisniewski *et al*., 2019), metal detector (Wisniewski et al., 2019; Ruffell *et al*., 2009a; Ruffell *et al*., 2009b), aerial photography (Abate *et al*., 2019; Ruffell *et al*., 2009a), unmanned aerial vehicles (Abate et al, 2019), time-domain reflectometry (Damiata *et al*., 2017), terrestrial laser scanning (Aziz et al., 2016), electroresistivity (Hansen *et al*., 2014), victim recovery dogs (Ruffell *et al*., 2009b) and geographic profiling (Ruffel *et al*., 2009b) while in the other 50% of the articles only the GPR method was used for the target analys.

Table 4 - Main parameters used in the Uncontrolled Site surveys. ER= Electroresistivity; ERT= Electrical Tomography; MS= Magnetic Susceptibility; MC= Magnetic Conductivity; TDR= Time Domain Reflectometry; MD= Metal Detector; TLS= Terrestrial Laser Scanning; UAV= Unmanned Aerial Vehicle; GIS= Geographic Information System; VRD= Victim Recovery Dogs.

Reference	Goals	Site Type	Predominant soil type	Target type	Center frequency (MHz)	Complementary techniques	Main results
Wisniewski *et al.*, 2019	Document investigations and discuss how geoscience can assist law enforcement in future archived searches.	Clandestine grave	Sandy	Murder Victim	250	MS, MC and MD	Geophysical anomalies were identified and the most promising ones were investigated in a detailed manner.
Abate *et al.*, 2019	Locate mass graves and mass graves and increase the excavation recovery rate of the Missing Persons Committee in Cyprus.	Unmarked graves	Site 1: sandy; site 2: not mentioned	Missing Persons	400	Continuous aerial photography, UAV and GIS	There was the effectiveness of the techniques in defining the search parameters for potential burial sites.
Barone *et al.*, 2019	Highlight non-destructive geophysical techniques to help find missing persons.	Natural cave	Volcanic tuff	Missing person	500	-	The results accurately located and defined the searched target.
Rubio-Melendi *et al.*, 2018	Detail a non-invasive study at the El Salvador Cemetery in the city of Oviedo, northern Spain.	Mass grave	Sandy and clayey horizons	Unmarked graves	250, 500	ERT	The results established the boundaries of the mass grave, as well as extending the knowledge about the internal structure of the grave.
Damiata *et al.*, 2017	Report results of a survey using GPR on a Viking Age Christian cemetery.	Cemetery	Andosol	25 graves	500	TDR	All the profiles collected on the skeletons have hyperbolae to some degree.
Aziz *et al.*, 2016	Use GPR and TLS to locate and characterize unmarked graves in the Mueschke Cemetery in Houston, Texas.	Cemetery	Sandy / clayey Sandy / clayey	Graves	250	TLS	GPR surveys produced anomalies that were consistent with gravestones and cemetery records.
Fernández-Álvarez *et al.*, 2016	Detail the geoforensic search for a Spanish Civil War mass grave.	Mass grave	Silty matrix	Human cadavers	500	-	Clear geophysical anomalies in 2D GPR profiles and remains were successfully discovered.
Barone *et al.*, 2016	Present partial results of a GPR search conducted at the Non-Catholic Cemetery in Rome (Italy).	Cemetery	Not mentioned	Gravestone s	500	-	The GPR survey was able to discern several anomalies beneath the surface of the Ancient Cemetery.
Hansen *et al.*, 2014	To identify the locations of unmarked graves in cemeteries.	Cemetery	Clayey / sandy / alluvium	Unmarked graves	225, 450	ER	The targets were identified effectively using 2D GPR and ER profiles.
Büyüksaraç *et al.*, 2013	Determine whether it is possible to use geophysical imaging methods to locate unmarked graves.	Cemetery	Not mentioned	Lost graves	250	ERT and magnetic imaging surveys	The results showed that the methods used are suitable for delineating buried historic sites.

Forbes *et al.*, 2013	Use GPR to locate the remains of a dog buried in Canada.	In natural área	Sandy	Buried dog's grave	500	-	The GPR survey was able to accurately identify the location of the investigated grave.
Novo *et al.*, 2011	Assisting police investigations.	Clandestine burial	Massive limestone	Murder victim and pickaxe	250	-	The 250 MHz antenna allowed a good fit between target detection, dense acquisition grid, and an extensive survey area.
Doolittle *et al.*, 2010	Identify clandestine and unmarked graves.	Cemeteries	Not mentioned	Unmarked graves	400	-	GPR brought improvements to the identification of unmarked graves in Connecticut.
Billinger 2009	Assist an investigation conducted by the Edmonton Police Service in Alberta, Canada.	The basement of a house	(Clay below basement)	Human cadavers	Not mentioned	-	Positive results were obtained from the GPR analysis, but the excavation was not successful.
Ruffell *et al.*, 2009a	Confirm the location of a cemetery, assess the number of burials and depth by geophysical survey and measurement.	Mass grave	Clayey	Graves	100, 200, 400	Aerial photography, MD, magnetometric and electromagnetic survey	About 170 anomalies compatible with burials were identified in 200 MHz GPR data, 84 of which coincided with surface collapses.
Fiedler *et al.*, 2009	Determine the location of unmarked graves in cemeteries.	Cemetery	Clayey	95 graves	400	-	GPR proved reliable in determining the exact location of the investigated targets.
Ruffell *et al.*, 2009b	Investigate an area of depressed ground with features consistent with a clandestine burial.	Clandestine burial	Clayey	Homicide victim	225	VRD, MD and geographic profiles	GPR showed a hyperbolic anomaly. The investigation showed no evidence of excavation for burial purposes.
Schultz 2007	Provide a discussion of GPR methodology and implementation of this technology by law enforcement agencies.	Burial under a cement slab	Not applicable	Two buried bodies	Not mentioned	-	The results indicated a large disturbance and a skeleton was located in the area studied.

DISCUSSION

Thematically the reviewed papers cover a wide range of scenarios encountered in forensic studies. New scopes of investigations include the comparison of GPR image features for multiple burial scenarios and evaluation of the changing geophysical response of simulated mass graves over the years.

Research generally involves the integration of more than one method. While the use of electroresistivity, susceptibility, and magnetic conductivity have been common methods used for locating grave targets and objects, integration with other indirect methods such as metal detectors can be important in initiating searches for metallic objects such as weapons or even belts that are wearing the grave victims. The application of geophysical methods is gaining popularity and GPR has become a common geophysical option for forensic investigations because, besides being effective in locating buried targets, it can be integrated with other methods as part of a protocol for forensic target search. A major advantage of using GPR for buried target searches is the speed with which the method is employed and returns results for interpretation.

A common goal raised in the articles was the demand to adopt a protocol proposal with requirements for field operations, establishing methodologies for forensic search, processing, and analysis of collected data. Thus determining general requirements such as equipment configuration and how the processing of the data obtained in the field should be managed when searching for forensic targets. Prerequisites for using GPR include analysis of the type of soil being studied, as well as the depth and type of target.

From the articles reviewed, the timing of this research reflects strong experimentation with new technologies with the potential for integration with GPR, although, in parallel, there is still a search to understand the advantages and disadvantages that these techniques can imprint on forensic research.

One of the advantages of GPR is that it can be used to search for forensic targets under asphalt and concrete without the need for excavation. Thus GPR is used to determine the location of possible burials under concrete and under these conditions, there was discussion about false-positive results through analysis of GPR data in only 2.1% of the articles. The results of GPR analysis can only be properly interpreted by individuals with significant experience. The presence of a signature on radargrams can lead to misinterpretations of targets buried under the concrete which highlights the importance of experienced interpreters and the use of complementary techniques.

CONCLUSIONS

The main objective of this SLR was to analyze the advances in forensic research in the identification of bodies in different burial scenarios with the help of the GPR geophysical method, and this objective was achieved as can be seen in the results. In a complementary way, it was aimed to indicate the common characteristics of the controlled sites, the limitations in the use of GPR, and which are the real improvements in the use of complementary geophysical methods in this thematic as it was evidenced in the results and discussions mentioned above.

Geophysical methods play an important role in the non-destructive detection of buried or hidden targets. The non-invasive nature of geophysical methods is of particular value in forensic geophysics and can provide quick answers in criminal investigations, for example.

This review article highlights the most promising areas and presents a basis for the scientific development of forensic geophysics. Recommendations for further research should include the nature of the environment, the influence of physical parameters on the identification of human evidence in forensic investigations using GPR, and the determination of gas concentration variations related to the decomposition of organic material from forensic targets, being the current object of the authors' research that will rely on the laboratory analysis of soil samples for moisture monitoring, GPR imaging for analysis of soil moisture variation, evaluation of the influence of clay content on target detection using GPR imaging, and measurement of the variation of CH_4 and CO_2 concentration associated with decomposition of organic target tissues.

Using all possible techniques and devices although comprehensive can be expensive and time-consuming a good approach is to use a combination of two methods which can be helpful in a possible ambiguity in data interpretation. Surveys with the integration of GPR with magnetic susceptibility are indicated when the targets include small metal objects. Electroresistivity is another complementary technique with potential as it has a fast collection time, good detection rates, and simpler data processing than GPR. The 500MHz frequency, one of the most widely used, brought better results in tracking the evolution of decomposition with a satisfactory resolution to depth ratio. From the analysis of the results, we conclude that the research on the use of GPR in forensic geophysics is seeking to highlight the ability of the method to identify targets in multiple burial scenarios with different sizes and depths and burials in various circumstances. Such as covered bodies by different materials, e.g. rubble, wrapped in plastic, with and without clothing, and to understand its limitations.

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