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# Advances in AI-based image analysis for skeletal identification in veterolegal cases

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**Abstract**
This review study, conducted at the Department of Veterinary Anatomy & Histology, College of Veterinary Science and Animal Husbandry, OUAT, Bhubaneswar, India, from August to September 2024, explores the role of artificial intelligence (AI) in identifying bones in veterolegal cases, highlighting its potential to enhance diagnostic accuracy and streamline forensic investigations. AI technologies, such as artificial neural networks (ANNs) and deep learning, offer significant advantages in veterinary education by providing personalized learning experiences. These technologies enable students to engage deeply with complex anatomical concepts through virtual dissections and simulations, leading to improved retention of essential knowledge for their future practice. In forensic applications, AI plays a pivotal role in improving the identification and classification of skeletal remains, even in challenging cases involving substantial decomposition. By analyzing large anatomical datasets, AI enhances the efficiency and precision of forensic investigations, contributing to more accurate findings and aiding in the resolution of veterolegal cases. The successful integration of AI into veterinary curricula requires educators to possess a fundamental understanding of AI principles, ensuring that future veterinary professionals are well-prepared to use these technologies effectively. In conclusion, incorporating AI into veterinary education and practice is a vital step in advancing veterinary anatomy and enhancing the overall efficacy of veterinary medicine. By equipping professionals with AI knowledge and skills, the veterinary field can better address modern challenges in animal health and welfare.

**Keywords:** Anatomy, learning, computer-aided, technology, artificial intelligence, machine learning, veterinary

## 1. Introduction
Artificial Intelligence (AI) has emerged as a transformative discipline that focuses on developing algorithms capable of performing tasks traditionally associated with human intelligence. By leveraging advances in artificial neural networks (ANNs) and deep learning, AI has made significant strides in recent years, leading to its adoption across a wide range of sectors, including finance, automotive engineering, economics, medicine, and education (Russell & Norvig, 2021) [44]. Defined as machines exhibiting intelligent behavior, AI systems have the ability to perform tasks typically carried out by humans, thereby enhancing efficiency and accuracy in numerous applications. AI encompasses three primary domains: symbolic, logic-based, and knowledge-based; statistical methods, including probabilistic approaches and machine learning; and sub-symbolic methods, which focus on embodied intelligence and search algorithms. Each of these domains addresses different problem aspects, including perception, planning, reasoning, and communication (Mitchell, 2019) [38]. The versatility of AI enables it to be applied in tackling complex challenges across various fields, including veterinary medicine. Within veterinary science, precise anatomical knowledge is critical, and the integration of AI offers promising avenues for enhancing both educational and practical applications. AI's integration into veterinary education is particularly significant as it can support all facets of curriculum development, analysis, learning, and assessment. The growing interest in AI applications in veterinary education is demonstrated by the increasing number of publications and citations on this topic in recent years (Dawson *et al.*, 2022) [10].

AI technologies such as ANNs and deep learning provide personalized learning experiences that allow veterinary students to engage with complex anatomical concepts at their own pace (Gomez *et al.*, 2021) [14]. Virtual dissections and simulations, enabled by AI, allow students to visualize and manipulate anatomical structures without the ethical concerns and limitations associated with cadaver-based learning (Schneider *et al.*, 2020) [46]. This ultimately enhances the retention of critical anatomical knowledge, which is essential for students' future veterinary practice. In addition to improving veterinary education, AI also has significant potential in veterinary forensic investigations, where identifying skeletal remains and other visceral organs can be complex, especially in cases involving dismembered or significantly decomposed remains. The identification and classification of skeletal remains play an essential role in veterolegal cases, which often require detailed analysis to establish the identity and cause of death of an animal. Traditionally, such forensic examinations have been labor-intensive and time-consuming, often involving skilled professionals manually analyzing bones. However, the advent of AI technologies such as deep learning algorithms can revolutionize this process, improving the accuracy and speed of skeletal identification and forensic analysis (Chaurasia *et al*., 2024) [8].

AI-based image analysis techniques for skeletal identification rely heavily on large datasets of anatomical information, allowing algorithms to recognize unique skeletal features and assist in classification. This application is particularly valuable in forensic cases, where identifying specific bones from fragmented remains can be challenging. AI's ability to analyze complex datasets enhances the efficiency and precision of forensic investigations, contributing to more accurate findings and aiding in the resolution of veterolegal cases (Fernandez *et al*., 2022) [12]. This includes the identification of bones and visceral organs, which is especially challenging when decomposition or damage makes visual inspection difficult.

In the context of trauma analysis, AI plays an important role in identifying distinct trauma signatures left on bones. For example, blunt force trauma, sharp force trauma, and gunshot wounds leave unique marks on skeletal structures that can be difficult to differentiate manually, particularly in cases of severe damage. AI algorithms, using techniques such as computer vision, can analyze bone damage patterns to classify the type of trauma and even estimate the force applied (Morris *et al*., 2023) [39]. This ability to analyze and interpret complex bone damage patterns enhances the reliability and accuracy of forensic investigations, thereby facilitating the resolution of veterolegal cases. Moreover, AI has shown great promise in automated bone matching, an essential aspect of forensic investigations involving dismembered remains. High-resolution image analysis, combined with machine learning models trained on extensive datasets, can be used to identify and match bone fragments, even when the fragments are incomplete or damaged (Fitzgerald *et al.*, 2022) [13]. AI can also assist in reconstructing the skeletal structure by analyzing the spatial relationships between matched fragments, helping forensic anthropologists visualize a complete skeleton. While the potential of AI in veterinary forensics is evident, its successful implementation depends on several factors, including the availability of quality data, advancements in AI algorithms, and the training of professionals to effectively utilize these technologies. Educators must possess a foundational understanding of AI principles to ensure that future veterinary professionals are equipped with the skills necessary to leverage AI in their practice (Gomez *et al*., 2021) [14]. This requires a comprehensive integration of AI into veterinary curricula, equipping students not only with theoretical knowledge but also with practical skills for using AI in diagnostic support, treatment planning, and forensic investigations. In conclusion, the application of AI in veterinary anatomy, particularly for skeletal identification in veterolegal cases, represents a significant advance in the field of veterinary medicine. The ability of AI to enhance diagnostic accuracy, improve educational outcomes, and streamline forensic investigations makes it an invaluable tool for modern veterinary practice. By embracing AI technologies and integrating them into both education and practice, veterinary professionals will be better prepared to meet the challenges of contemporary animal health and welfare. The integration of AI in this context is not merely an innovative approach but a crucial step towards advancing the effectiveness and efficiency of veterinary medicine and forensics.

## 2. Identification of bones using artificial intelligence

AI can play a crucial role in estimating age, gender, and ethnicity by analyzing the morphological features of bones. Age estimation is vital in veterinary forensic science and wildlife management for understanding population dynamics and health assessments.

### 2.1 Bone Growth and Degeneration Patterns

- **Bone Fusion:** In younger animals, the fusion of epiphyses in long bones is a key indicator of growth stages. For instance, the proximal and distal ends of the humerus and femur undergo epiphyseal fusion, which can be analyzed using AI algorithms to determine the age category. In older animals, AI can assist in examining the degree of wear and degeneration of articular surfaces and the presence of osteophytes, which typically increase with age. Research has shown that the use of AI in analyzing these patterns can yield high accuracy in age predictions (Al-Azzeh *et al.*, 2021) [1].
- **Cranial Suture Closure:** In adult animals, the fusion of cranial sutures serves as a significant indicator of age. The timing of suture closure varies among species, and AI algorithms can evaluate the degree of closure, thereby providing an estimate of the individual's age (Mansour *et al.*, 2020) [36]. Studies have shown that machine learning models can be trained to recognize suture patterns and their closure stages based on radiographic images.
- **Tooth Eruption and Wear:** In younger animals, tooth eruption patterns can be indicative of age. The development and timing of tooth emergence vary among species, and AI can analyze dental x-rays to determine these patterns accurately (Hussain *et al.*, 2023) [24]. In older animals, dental wear can provide insights into age. AI can quantify wear patterns and assess them against known standards to estimate age more precisely (Lindgren *et al.*, 2019) [32].
- **Deep Learning and Computer Vision:** AI models, particularly those employing deep learning and computer vision, are trained on extensive datasets of skeletal remains and dental features. These models learn to identify and correlate patterns associated with age, resulting in high accuracy in predictions (Liu *et al*., 2022) [34]. For example, convolutional neural networks (CNNs) have been effectively utilized to classify images of bones

and teeth, improving the reliability of age estimation methodologies.

- **Benefits of AI in Age Estimation:** AI algorithms can process and analyze large datasets much faster than human experts, reducing the time required for age estimation. The use of AI minimizes subjective bias in assessments, leading to more consistent and reproducible results. AI systems can serve as educational tools, allowing students and professionals to better understand age-related changes in skeletal morphology through interactive learning modules.

### 2.2 Gender Estimation
Gender estimation is a critical aspect of forensic veterinary medicine, particularly when dealing with skeletal remains. The most reliable skeletal indicator for determining gender is pelvic morphology, which exhibits notable sexual dimorphism and provides essential information for identifying the sex of an individual.

- **Size:** The pelvic cavities of female animals are generally larger and wider than those of male animals. This size difference is primarily due to adaptations required for childbirth in females, allowing for the passage of offspring. In species such as dogs and cats, studies have demonstrated that the size and shape of the pelvis correlate closely with reproductive capabilities (Krogman & Iscan, 1986; Niskanen *et al.,* 2015) [29, 40].
- **Shape**: The pelvic inlet of a female is typically rounder and oval-shaped compared to the pelvic inlet of a male, which tends to be more heart-shaped. This morphological distinction is particularly evident in species like horses and cattle, where the pelvic shape significantly impacts parturition (Davis & Maki, 1998; Slauterbeck *et al.,* 2019) [9, 49].
- **Subpubic Angle**: The angle between the inferior pubic rami, known as the subpubic angle, serves as another critical indicator. In males, this angle measures approximately 70°, whereas, in females, it ranges from 90° to 100°. This variation reflects the broader pelvic cavity in females, a characteristic essential for reproductive functions (Huang *et al.,* 2019; Roberts, 2010) [23, 43].
- **Sacrum**: The sacrum in males is typically longer, narrower, and straighter than in females. The differences in sacral morphology contribute to the overall shape and function of the pelvis, making this feature a vital parameter in gender estimation (Koch *et al.,* 2020; Hamada *et al.,* 2018) [27, 18].
- **Iliac Crests**: In males, the iliac crests are generally higher than in females. This height difference is significant for determining sex, especially when examining skeletal remains where the pelvis is intact (Henderson *et al*., 2022; Ousley & Jantz, 2005) [20, 41].
- **Greater Sciatic Notch**: The greater sciatic notch is usually narrower and deeper in males compared to females. This characteristic can be assessed visually or through precise measurements, providing additional support for gender determination (Halcrow & Tayles, 2008; Schmitt *et al*., 2002) [17, 45].

### 2.3 Skull Features
The analysis of skull morphology is vital in gender estimation, as certain cranial characteristics exhibit sexual dimorphism. Artificial intelligence (AI) can effectively analyze these features, enhancing the accuracy of forensic assessments. Key skull features pertinent to gender determination include:

- **Size of the Mastoid Process**: The mastoid process is a bony prominence located on the temporal bone, and it typically exhibits sexual dimorphism. In males, the mastoid process tends to be larger and more robust than in females. This size difference is attributed to greater muscle attachment in males, as they generally have more developed neck muscles for physical activities (Keenan *et al.,* 2016; Bhat & Prabhu, 2020) [25, 4]. Measurements of the mastoid process can provide crucial information in forensic contexts, helping to estimate gender with improved accuracy.
- **Brow Ridge**: The brow ridge, or supraorbital ridge, is the bony prominence located above the eye socket. In males, this feature is usually more pronounced and prominent than in females. This sexual dimorphism is linked to evolutionary factors, where males exhibit stronger brow ridges as a result of greater testosterone levels (Henderson *et al.,* 2020) [19]. In forensic analysis, assessing the prominence of the brow ridge can aid in determining the sex of skeletal remains, particularly in cases where other features may be less distinct.
- **Occipital Protuberance**: The external occipital protuberance, located at the back of the skull, is often more pronounced in males than females. This bony projection serves as an attachment site for neck muscles and is typically larger and more robust in male skulls (Büntgen *et al.*, 2019) [6]. AI algorithms can be trained to measure this feature accurately, further aiding in sex estimation.
- **Frontal Bone Shape**: The frontal bone, which forms the forehead region, tends to be smoother and more rounded in females, whereas males often display a more sloped and pronounced frontal bone (Kumar *et al.*, 2021) [30]. AI can analyze these morphological variations to contribute to gender identification in forensic investigations.
- **Zygomatic Arch**: The zygomatic arch, or cheekbone, is generally more prominent and robust in males than in females. This sexual dimorphism can be quantitatively assessed using AI techniques, improving the precision of gender estimation based on cranial features (Howells, 1973; Walker, 2008) [22, 53].

### 2.4 Automated Feature Extraction
Automated feature extraction is a transformative application of artificial intelligence (AI) that leverages image recognition and machine learning techniques to analyze skeletal remains effectively. By utilizing advanced algorithms, AI systems can automatically extract relevant features from various imaging modalities, such as 3D scans and X-rays of bones. This capability enhances the efficiency and accuracy of forensic investigations, allowing for rapid gender and age estimation, among other analyses.

- **3D Scans:** Three-dimensional imaging technologies, such as computed tomography (CT) and magnetic resonance imaging (MRI), provide detailed views of bone morphology. AI systems can process these 3D scans to identify and quantify skeletal features that are crucial for gender and age estimation. For example, AI algorithms can analyze the shape and size of the pelvic inlet and sacrum, which are critical indicators of sex. Studies have shown that AI can achieve high accuracy rates in gender classification by utilizing 3D data (Bourgeois *et al.,* 2021; Kousoulis *et al.,* 2022) [5, 28]. This not only streamlines the process but also reduces the subjective bias inherent in traditional methods.

- **X-rays of Bones:** X-ray imaging remains a widely used technique in forensic anthropology and veterinary forensics. AI-powered image recognition systems can analyze X-ray images to extract pertinent features such as the degree of bone fusion, presence of fractures, and overall bone density. For example, machine learning algorithms can be trained to recognize patterns associated with age estimation through the assessment of dental wear and the fusion of epiphyseal plates (Tehrani *et al.*, 2019) [51]. Additionally, AI can assist in detecting subtle features that may be overlooked by the human eye, improving the accuracy of forensic analyses (Higgins *et al.*, 2020) [21].
- **Deep Learning Techniques:** Deep learning, a subset of machine learning, has shown great promise in automated feature extraction from imaging data. Convolutional neural networks (CNNs) are particularly effective in processing complex image data, allowing AI systems to learn hierarchical features directly from the input images (Liu *et al*., 2021) [35]. These networks can be trained on large datasets of skeletal images to enhance their ability to differentiate between male and female skulls, as well as to identify age-related changes in bone structure.
- **Integration with Forensic Databases:** AI systems can be integrated with forensic databases, allowing for cross-referencing and validation of extracted features against established norms. This integration facilitates more accurate identifications and improves the reliability of forensic conclusions (Becker *et al*., 2020) [2].

### 2.5 Fracture Detection
Fracture detection is a critical application of artificial intelligence (AI) in veterinary and medical fields. AI algorithms, particularly those using computer vision techniques, are increasingly being employed to analyze images of bones and accurately identify fractures. This application is especially valuable in veterinary forensic cases and emergency settings, where rapid and accurate diagnosis is essential.

- **Computer Vision Techniques:** AI algorithms leveraging computer vision are capable of detecting fractures by analyzing medical imaging data such as X-rays, CT scans, and MRI images. Convolutional neural networks (CNNs), a type of deep learning model, are commonly used for this purpose due to their ability to identify complex patterns within image data. By training on large datasets of labeled bone images, these models learn to distinguish between normal bone structures and those with fractures (Rajpurkar *et al.*, 2018) [42].
- **High Accuracy in Fracture Detection:** AI-based systems have demonstrated remarkable accuracy in fracture detection, often outperforming human radiologists in identifying subtle fractures. A study by Lindsey *et al.* (2018) [33] found that an AI model achieved a sensitivity of over 95% for detecting wrist fractures in radiographic images, highlighting the potential of AI to assist clinicians in diagnostic decision-making. This capability can significantly reduce diagnostic errors and ensure timely treatment, which is crucial in both human and veterinary medicine.
- **Automated Segmentation and Classification:** In addition to detecting fractures, AI algorithms can perform automated segmentation of the bone region and classify the type of fracture (e.g., complete, incomplete, comminuted). For example, an AI model may identify the exact location of a fracture, measure its length, and determine whether it is displaced or non-displaced (Yang *et al*., 2020) [55]. Such detailed information is invaluable for planning surgical interventions and determining appropriate treatment protocols.
- **AI in Veterinary Forensics:** In veterinary forensics, accurate fracture detection plays a key role in determining the cause of injury, which may be linked to abuse or accidents. AI's ability to process large datasets and extract subtle features makes it particularly useful in these contexts, as it can help differentiate between different types of trauma (Sinha *et al*., 2021) [48]. This can aid in legal investigations involving animal welfare cases, providing objective and reliable evidence.
- **Reduction of Diagnostic Workload:** Incorporating AI into fracture detection workflows also helps reduce the diagnostic workload for veterinarians and radiologists. AI systems can serve as an initial screening tool, flagging images with potential fractures for further review by a specialist. This not only saves time but also ensures that critical cases receive prompt attention (Kim *et al*., 2019) [26].

### 2.6 Trauma Pattern Analysis
Trauma pattern analysis is an essential aspect of forensic investigations, where artificial intelligence (AI) plays a pivotal role in identifying and characterizing different types of trauma on bones. AI algorithms, particularly those employing deep learning, have been trained to detect and differentiate trauma types by analyzing radiographic and CT images. This capability enhances diagnostic accuracy and aids in forensic investigations, including veterolegal cases.

- **Blunt Force Trauma**: Blunt force trauma results in fractures that exhibit distinct characteristics, such as bending or shearing patterns. AI systems can analyze these features, including the shape, direction, and location of fractures, to determine the nature of the force applied, including its magnitude and direction. By training on extensive datasets of blunt trauma cases, AI models have been shown to effectively classify trauma type and suggest potential causes of injury (Beirne *et al.*, 2020) [3]. This is particularly useful for forensic experts in determining whether the trauma resulted from accidental falls or intentional acts of violence.
- **Sharp Force Trauma**: Sharp force trauma results in clean, linear fractures, typically caused by instruments such as knives or other sharp objects. AI systems can distinguish these injuries by analyzing the edges of the bone, which often appear sharp and well-defined. Convolutional neural networks (CNNs) are effective at recognizing these subtle differences in bone images. A study by Hajihosseini *et al.* (2021) [16] demonstrated that AI could accurately classify sharp force trauma with over 90% accuracy, suggesting its utility in differentiating these types of injuries from blunt trauma or other fracture patterns. This capability is crucial for cases involving animal abuse, as it provides evidence for determining the type of weapon used.
- **Gunshot Wounds**: Gunshot wounds leave unique signatures on bones, including entry and exit wounds, radiating fracture lines, and extensive fragmentation. AI-based trauma analysis can detect and characterize these features by analyzing high-resolution images of skeletal

remains. Machine learning algorithms can assess the size, shape, and location of entry and exit wounds to distinguish between different types of firearms and ammunition (Vranic *et al*., 2019) [52]. Furthermore, AI can differentiate between contact, close-range, and distant gunshot wounds based on the morphology of bone damage, providing valuable information for forensic investigations.

- **Multi-Modal Analysis**: AI systems are increasingly capable of integrating data from multiple imaging modalities, such as X-rays, CT scans, and MRI, to provide a comprehensive understanding of the trauma. By combining these different types of data, AI can identify trauma patterns with greater accuracy compared to using a single imaging modality. For instance, combining X-ray images with 3D CT reconstructions can provide a detailed view of fracture characteristics, aiding in the identification of trauma mechanisms and the differentiation of accidental and non-accidental injuries (Schwartz *et al.*, 2022) [47].
- **Trauma Pattern Classification and Prediction**: AI is also capable of predicting the progression of bone healing in response to different types of trauma. By analyzing longitudinal datasets, machine learning models can predict how a fracture is likely to heal based on the initial characteristics of the trauma, the type of intervention, and the overall health of the individual. This helps veterinarians and forensic experts determine the best course of treatment and assess the likelihood of recovery (Kwon *et al.*, 2021) [31].

### 2.7 Automated Bone Matching

Automated bone matching is a critical application of artificial intelligence (AI) in forensic anthropology, particularly useful in complex cases involving dismembered remains. AI's capabilities in image analysis, machine learning, and 3D modeling make it a powerful tool for matching bone fragments, reconstructing skeletal structures, and providing evidence for forensic investigations.

- **Image Analysis**: AI algorithms can analyze high-resolution images of bone fragments using advanced computer vision techniques. By identifying unique features such as shape, size, surface texture, and cortical patterns, AI systems can accurately differentiate between bones and categorize them. Convolutional neural networks (CNNs), in particular, have proven highly effective in analyzing bone images and extracting distinguishing features. Studies have shown that AI-based image analysis can significantly reduce the time needed to categorize and match bone fragments, improving the efficiency of forensic investigations (González-Ruiz *et al.*, 2021) [15].
- **Fragment Matching**: AI-driven fragment matching involves training machine learning models on extensive databases of skeletal remains, allowing the AI to learn the characteristics of various bones, such as their morphological features and articulation points. When presented with new fragments, the AI compares them against the database to identify potential matches, even in cases where the fragments are incomplete or damaged. Support vector machines (SVMs) and deep learning models can help classify bone fragments based on their features, improving the accuracy of identification (Smith *et al.*, 2019) [50]. Additionally, AI systems can incorporate probabilistic matching techniques, which provide confidence scores for potential matches, enabling forensic experts to prioritize the most promising candidates.
- **3D Surface Matching**: AI also uses 3D surface matching to compare bone fragments. By capturing 3D scans of bone pieces, AI algorithms can assess their surfaces and geometries to identify the best matches. Forensic anthropologists can use this technology to analyze irregular bone surfaces and determine which pieces fit together, even when dealing with highly fragmented remains. A study by Wang *et al.* (2020) [54] demonstrated that 3D matching algorithms significantly improved the accuracy of fragment alignment, providing precise fits for bone reconstructions.
- **Reconstruction**: Once potential matches are identified, AI can assist in reconstructing the skeletal structure. By analyzing the spatial relationships between matched fragments, AI can determine how the pieces fit together, creating a virtual reconstruction of the skeleton. Techniques such as iterative closest point (ICP) algorithms and AI-based modeling tools can be used to estimate the orientation and placement of each fragment, thereby aiding forensic anthropologists in visualizing the complete skeleton (Chaudhary *et al.*, 2022) [7]. Virtual reconstruction not only helps in determining the identity of the deceased but also in understanding the cause of death, particularly in cases involving trauma or dismemberment.
- **Identification of Anomalies**: AI systems can also be trained to recognize skeletal anomalies, such as pathological changes, congenital defects, or signs of healing fractures. By identifying these anomalies, AI can provide additional clues that may help in the identification of individuals or in understanding the circumstances surrounding their death. This is especially useful in cases where traditional visual inspection methods may fail to detect subtle differences between bone fragments (Fernandes *et al.*, 2021) [11].
- **Case Studies and Applications**: There have been several successful case studies demonstrating the utility of AI in automated bone matching. For example, AI has been used to identify and reconstruct skeletal remains from mass grave sites, where commingled remains made manual identification challenging (Meijer *et al.*, 2023) [37]. By using AI-based matching and reconstruction, forensic teams were able to expedite the identification process, leading to quicker resolution of forensic cases.
- **Challenges and Future Directions**: Despite its potential, AI-based automated bone matching faces challenges, including the need for large, high-quality datasets for training and the variability in bone conditions due to taphonomic processes. Addressing these challenges will require collaboration between forensic scientists, anthropologists, and computer scientists to improve algorithms and ensure that AI systems are robust and reliable. Advances in AI, such as generative adversarial networks (GANs), could also be explored to simulate missing bone fragments and improve the overall accuracy of bone matching and reconstruction.

## 3. Conclusion

In conclusion, the integration of AI-based image analysis significantly enhances skeletal identification in veterolegal cases, improving diagnostic accuracy and efficiency. By automating processes and facilitating the analysis of complex anatomical data, AI empowers veterinary professionals to resolve cases involving skeletal remains more effectively, ultimately advancing both veterinary education and forensic investigations in the field.

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## 5. Conflict of Interest

The authors declare that they have no conflict of interest concerning the publication of this article.

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