



UNIVERSIDADE
LUSÓFONA

CENTRO UNIVERSITÁRIO DE LISBOA
FACULDADE DE MEDICINA VETERINÁRIA
MESTRADO INTEGRADO EM MEDICINA VETERINÁRIA

**USE OF INFRARED THERMOGRAPHY AS A DIAGNOSTIC
TECHNIQUE FOR JOINT DISEASE IN ASIAN ELEPHANTS
(*ELEPHAS MAXIMUS*)**

Dissertação apresentada a provas públicas para a obtenção do grau de mestre em Medicina Veterinária, orientada pela Professora Doutora Sónia Campos e Professor Dr. Rui Patício (co-orientador).

Rita Ganiho Simões Ricou Névoa

2025

www.ulusofona.pt



UNIVERSIDADE
LUSÓFONA

CENTRO UNIVERSITÁRIO DE LISBOA
FACULDADE DE MEDICINA VETERINÁRIA

MESTRADO INTEGRADO EM MEDICINA VETERINÁRIA

**USE OF INFRARED THERMOGRAPHY AS A DIAGNOSTIC
TECHNIQUE FOR JOINT DISEASE IN ASIAN ELEPHANTS
(*ELEPHAS MAXIMUS*)**

Rita Ganilho Simões Ricou Névoa

VERSÃO FINAL

Dissertação defendida por Rita Ganilho Simões Ricou Névoa em provas públicas na Universidade Lusófona, Centro Universitário de Lisboa no dia 24/11 de 2025, perante o júri, nomeado pelo Despacho de Nomeação n.º: 585/2025, de 12 de Novembro, com a seguinte composição:

Presidente: Professora Doutora Mariana Batista (Universidade Lusófona - Centro Universitário Lisboa)

Vogal: Professor Doutor João Martins (Universidade Lusófona - Centro Universitário Lisboa) -
arguente

Orientador: Professora Doutora Sónia Campos (Universidade Lusófona - Centro Universitário Lisboa)

Este trabalho também foi orientado pelo Professor Dr. Rui Patrício (co-orientador), e Dr. Nutthapong Arsakit (orientador externo).

Rita Ganilho Simões Ricou Névoa

2025

www.lusofona.pt

Elephants do not break from weakness - they break from being broken.

Science and conservation walk hand in hand; without understanding, we cannot protect.

When we give voice to silent suffering through science, we give wild animals a better chance at freedom.

The application of science to animal welfare is not a luxury - it is a necessity for ethical conservation.

Acknowledgements

First and foremost, I would like to express my deepest gratitude to all the professors and teaching staff who played a role in my academic journey. Your commitment, knowledge, and encouragement shaped my path and made this achievement possible.

To my supervisors, Professor Dr. Sónia Campos and Professor Dr. Rui Patrício, I offer my heartfelt thanks for your patience, commitment, and guidance throughout this project. Your support and encouragement were essential at every step.

I am deeply thankful to the Wildlife Friends Foundation Thailand (WFFT), especially to its veterinary team, for teaching me so much, for their tireless support, and for being incredibly open and collaborative throughout the realization of this study. Your generosity with your time, knowledge, and trust made this research possible.

To all professionals and institutions who contributed directly or indirectly to this work, thank you for your collaboration and valuable contributions.

On a personal note, I would like to thank my family for their unconditional love, patience, and belief in me, even during the most demanding moments. To my friends, thank you for your encouragement, constant support, and for always reminding me to breathe.

Finally, to my partner, whose unwavering belief in me and relentless support kept me going even when the path felt too long and too steep – thank you for always pushing me forward and reminding me of my strength when I doubted myself. This journey was made possible because of you.

I also wish to express my gratitude to all the wild animals who inspire me with their will to live and constantly remind me that it is in conservation that I truly feel at home.

This dissertation is also a quiet tribute to the strength that comes from resilience and the courage to keep pursuing a dream, even when it feels too big.

Resumo

Os elefantes-asiáticos (*Elephas maximus*), atualmente classificados como “Em Perigo” pela IUCN, enfrentam desafios significativos de conservação, tanto em populações selvagens quanto em cativeiro. Entre os principais problemas de saúde em cativeiro destacam-se as patologias músculo-esqueléticas, sobretudo as articulares, que comprometem a locomoção, a qualidade de vida e a longevidade destes animais. O diagnóstico precoce destas doenças é fundamental, mas frequentemente dificultado pela tendência dos elefantes em mascarar sinais clínicos até fases avançadas.

A termografia infravermelha (IRT) apresenta-se como uma técnica não invasiva e livre de radiação, capaz de detetar variações de temperatura superficial associadas a processos inflamatórios e degenerativos. Neste estudo, realizado com 14 fêmeas de elefante-asiático residentes na Wildlife Friends Foundation Thailand, foram avaliados padrões térmicos corporais e articulares, comparando indivíduos com e sem sinais clínicos de claudicação. Verificou-se a presença de padrões térmicos consistentes entre indivíduos, mas também de assimetrias e “hotspots” em articulações específicas, correlacionados com lesões subclínicas ou com patologia articular já manifesta.

Os resultados confirmam a aplicabilidade da IRT como ferramenta complementar de diagnóstico, permitindo identificar alterações precoces mesmo na ausência de sinais clínicos evidentes. As principais vantagens incluem rapidez, ausência de stress ou necessidade de contenção física, e possibilidade de avaliações repetidas, aspetos cruciais no manejo de espécies selvagens. No entanto, fatores ambientais, comportamentais e técnicos podem influenciar a interpretação das imagens, e o reduzido tamanho amostral limita a generalização dos resultados.

Conclui-se que a IRT representa um recurso promissor no acompanhamento clínico de elefantes-asiáticos em cativeiro, com potencial para detetar lesões osteoarticulares e auxiliar o seu tratamento, melhorar o bem-estar, orientar intervenções precoces e contribuir para a conservação *ex situ* da espécie. Recomenda-se que estudos futuros incluam amostras maiores, padronização de valores de referência e integração da termografia com outras técnicas diagnósticas, como radiografia ou ecografia.

Palavras-chave: Elefante-asiático; termografia infravermelha; doenças articulares; bem-estar animal; conservação.

Abstract

Asian elephants (*Elephas maximus*), currently classified as “Endangered” by the IUCN, face significant conservation challenges, both in wild and captive populations. Among the main health problems in captivity are musculoskeletal disorders, particularly joint pathologies, which compromise locomotion, quality of life, and longevity. Early diagnosis of these diseases is essential but often hindered by the tendency of elephants to mask clinical signs until advanced stages.

Infrared thermography (IRT) is a non-invasive and radiation-free technique capable of detecting variations in surface temperature associated with inflammatory and degenerative processes. In this study, conducted with 14 female Asian elephants housed at the Wildlife Friends Foundation Thailand, body and joint thermal patterns were assessed, comparing individuals with and without clinical signs of lameness. Consistent thermal patterns were observed among individuals, as well as asymmetries and “hotspots” in specific joints, correlated with subclinical lesions or clinically evident joint pathology.

The results confirm the applicability of IRT as a complementary diagnostic tool, allowing the identification of early changes even in the absence of obvious clinical signs. Its main advantages include speed, absence of stress or need for physical restraint, and the possibility of repeated assessments—crucial aspects in the management of wild species. However, environmental, behavioural, and technical factors may influence image interpretation, and the small sample size limits the generalisation of the findings.

It is concluded that IRT represents a promising resource for the clinical monitoring of captive Asian elephants, with the potential to detect osteoarticular lesions and support their treatment, improve welfare, guide early interventions, and contribute to the ex situ conservation of the species. Future studies should include larger samples, standardisation of reference values, and integration of thermography with other diagnostic techniques such as radiography or ultrasonography.

Keywords: Asian elephant; infrared thermography; joint disease; welfare; conservation.

List of Abbreviations

CT – Computed Tomography

DL-PaM O – Dorsolateral-palmaromedial oblique

DL-PtM O – Dorsolateral-plantaromedial oblique

DJD – Degenerative joint disease

E1 to E14 – Elephant 1 to Elephant 14

EMA – Effective Mechanical Advantage

IR – Infrared

IRT – Infrared thermography

IUCN – International Union for Conservation of Nature

LM – Lateromedial

LWIR – Long-wave Infrared

MRI – Magnetic Resonance Imaging

MWIR – Mid-wave Infrared

OA – Osteoarthritis

PaL-DM O – Palmarolateral-dorsomedial oblique

PtL-DM O – Plantarolateral-dorsomedial oblique

RA – Rheumatoid Arthritis

WFFT – WildlifeFriends Foundation Thailand

Table of Contents

Clinical Cases from the Internship.....	14
I. Introduction.....	20
1. Infrared Thermography: Principles, Technical Limitations and Applications.....	22
1.1 How Infrared Thermography Works.....	22
1.2 Technical Limitations and Influencing Factors.....	23
1.3 Applications of Infrared Thermography in Veterinary Medicine.....	25
1.4 Correlation Between Thermographic and Radiographic Methods.....	27
2. Asian Elephant: Limb Anatomy, Movement Biomechanics, Common Musculoskeletal Pathologies and Relevant Welfare to Joint Health.....	28
2.1 Limb Anatomy.....	29
2.2 Biomechanics of Locomotion and Weight Distribution.....	31
2.3 Common Musculoskeletal Pathologies in Captive Elephants.....	33
2.4 Welfare Implications of Musculoskeletal Disorders.....	35
3. Application of Infrared Thermography in Asian Elephants.....	36
3.1 Previous Studies Using IRT in Elephants.....	36
3.2 Thermal Patterns Associated with Joint Pathologies.....	38
3.3 Potential and Limitations of IRT in Elephant Health Monitoring.....	40
3.4 Integration of IRT into Wildlife Veterinary Practice and Welfare Management	41
II. Materials and Methods.....	42
III. Results.....	45
1. Common Thermal Patterns Across Individuals.....	45
2. Individual-Specific Thermal Asymmetries in Joints.....	47
3. Individual-Specific Thermal Asymmetries in Limbs.....	50
4. Multiple Projections to Hotspot Recognition.....	52
5. Thermographic Differences Associated With Clinical Lameness.....	54
IV. Discussion.....	56
V. Conclusion.....	61
VI. References.....	62

List of Graphs

Graph 1. Graphical representation of the mammal species the author worked with at the Rescue Center Costa Rica.....	16
Graph 2. Graphical representation of the bird species the author worked with at the Rescue Center Costa Rica.....	17
Graph 3. Graphical representation of the reptile species the author worked with at the Rescue Center Costa Rica.....	17
Graph 4. Graphical representation of the neonate species the author worked with at the Rescue Center Costa Rica.....	17
Graph 5. Graphical representation of the species that the author released back into the wild at the Rescue Center Costa Rica.....	18
Graph 6. Graphical representation of the mammal species the author worked with at WFFT.	19
Graph 7. Graphical representation of the bird species the author worked with at WFFT.....	20
Graph 8. Graphical representation of the reptile species the author worked with at WFFT....	20
Graph 9. Graphical representation of the most common clinical cases that the author saw at WFFT.....	20

List of Tables

Table 1. Summary of individual characteristics of the 14 Asian elephants (<i>Elephas maximus</i>) included in the study. This data is from February 2025.....	42
Table 2. Presence (1) or absence (0) of common thermal patterns (increased temperature in the medial aspect of the limbs, nails/ungual regions, or ventral abdominal region) across the study population, meaning in each elephant (E1/2/3/4/5/6/7/8/9/10/11/12/13/14).....	45
Table 3. Presence (1) or absence (0) of hotspots across different joints in all the studied elephants. The tibiotarsal joint presented the highest number of hotspots among all examined individuals. Elephants 2, 9, and 14 showed hotspots in more than one joint, in contrast to the remaining elephants, which exhibited hotspots in only one joint or none.....	47
Table 4. Contingency Table - Statistical analysis using the χ^2 test and Fisher's exact test. Testing if the IRT camera is capable of detecting hotspots in different joints. No significant differences were found in hotspot detection between the six joints analysed ($\chi^2 = 7.89$, $df = 5$, $p = 0.163$; Fisher's exact test, $p = 0.162$), indicating that the thermographic system was equally effective in detecting hotspots across all joints. The tibiotarsal joint exhibited the highest number of hotspots among all examined elephants, while elephants 2, 9, and 14 showed hotspots in more than one joint, contrary to the remaining elephants that presented hotspots in only one joint or none.....	49
Table 5. Presence (1) or absence (0) of hotspots across different limbs in all the studied elephants. Both hindlimbs presented the highest number of hotspots among all examined individuals. Elephants 9 and 14 showed hotspots in more than one limb, in contrast to the remaining elephants, which exhibited hotspots in only one limb or none.....	51
Table 6. Contingency Table - Statistical analysis using the χ^2 test and Fisher's exact test. Testing if the IRT camera is capable of detecting hotspots in different limbs. No significant differences were observed in hotspot detection between the forelimbs and hindlimbs ($\chi^2 = 0.381$, $df = 3$, $p = 0.944$; Fisher's exact test, $p = 1.000$), suggesting that the thermographic system was equally capable of identifying hotspots across all limbs studied. Although variations in hotspot presence were noted among individuals, the overall detection pattern was consistent between right and left limbs.....	51
Table 7. Presence (1) or absence (0) of hotspots across different projections (LM, DL-PaM O/DL-PtM O, and PaL-DM O/PtL-DM O) in all the studied elephants. The table summarizes the distribution of thermal hotspots detected across the three projection types used for each joint assessment. Although hotspots were occasionally identified in all projections, in most cases	

they were only visible in one or two of them. This indicates that the use of multiple projection angles increases the sensitivity of hotspot detection and reduces the likelihood of false negatives..... 52

Table 8. Contingency Table - Statistical analysis using the χ^2 test and Fisher’s exact test. Testing if the IRT camera is capable of detecting hotspots in different projections. No statistically significant differences were found between the three thermographic projections analysed (LM, DL-PaM O/DL-PtM O, and PaL-DM O/PtL-DM O) ($\chi^2 = 1.286$, $df = 2$, $p = 0.526$; Fisher’s exact test, $p = 0.571$). These results indicate that the infrared thermography camera performed consistently across all projections, with similar efficiency in hotspot detection. However, certain hotspots were only visible in one or two projections, suggesting that the combined use of multiple projection angles increases diagnostic reliability..... 54

List of Figures

Figure 1. Presence of a hotspot in a horse. Increased heat patterns associated with an inflamed tibio-tarsal joint. The hotspot detected by the camera is shown in red, corresponding to an increased limb temperature, which is captured through the camera's infrared light spectrum. (Eddy, A. L., Van Hoogmoed, L. M., & Snyder, J. R., 2001).....	22
Figure 2. Skeleton of an elephant, illustrating the major skeletal structures relevant to musculoskeletal health (Fowler, M. E., & Mikota, S. K., 2006).....	30
Figure 3. 3D model of the left forelimb skeleton in an Asian elephant; (A): dorsal view; (B): palmar view. Antebrachium - 1: radius, 2: ulna, 3: carpi radiale, 4: carpi intermedium, 5: carpi accessorium (only visible in palmar view), 6: carpi ulnare, 7: carpale I, 8: carpale II, 9: carpale III, 10: carpale IV, 11: metacarpale III, 12: ossa sesamoidea proximales (only visible in palmar view), 13: phalanx proximalis III, 14: phalanx media III, and 15: phalanx distalis III (Petneházy, Ö., Rück, S., Sós, E., & Reinitz, L. Z., 2023).....	30
Figure 4. Contrast-filled CT images. The red arrows show the a. mediana. (A): horizontal plane; (B): sagittal plane (Petneházy, Ö., Rück, S., Sós, E., & Reinitz, L. Z., 2023).....	31
Figure 5. 3D reconstruction of the forefoot vessels on the left limb. Latero-palmar view. 1: a. mediana, 2: a. metacarpea, 3: newly found vessel, 4: branch towards the first digital and prepollex, 5: palmar branch, 6: dorsal branch, 7: arcus palmaris profundus, 8: terminal sections of the dorsal and palmar branches headed towards each other in the digital cushion, and Ca: carpi accessorium (Petneházy, Ö., Rück, S., Sós, E., & Reinitz, L. Z., 2023).....	31
Figure 6. Thermal imaging with distinct patterns activated by arterial blood flow of the body surface of two African elephants observed indoors. (A) and (B) represent the thermal windows on the left side of the elephant. (C) and (D) the thermal windows on the right side of the elephant (Weissenböck, N. M., Weiss, C. M., Schwammer, H. M., & Kratochvil, H., 2010).....	38
Figure 7. Asian elephant with moderate lameness after a fight. Thermography revealed a hotspot above the right carpal joint (Hilsberg-Merz, S., 2008).....	40
Figure 8. Bamboo stick used as a standardized measuring tool during image acquisition. The stick was pre-marked at 2 meters and placed between the thermal camera and the elephant's limb to ensure consistent and safe imaging distance (image of the author).....	43
Figure 9. Increased temperature in the medial aspect of the right forelimb, in Elephant 8 (photo took by the author, with IRT).....	46

Figure 10. Increased temperature at the right hindlimb nail/ungual regions, in Elephant 10 (photo took by the author, with IRT).....	46
Figure 11. Warm distribution at the ventral abdominal region, in Elephant 7 (photo took by the author, with IRT).....	46
Figure 12. Elephant 4 - hotspot at the left tibio-tarsal joint, seen in a DL-PaM O projection (photo took by the author, with IRT).....	48
Figure 13. Elephant 5 – hotspot at the right elbow, seen in a LM projection (photo took by the author, with IRT).....	48
Figure 14. Elephant 7 – hotspot at the left knee, seen in a LM projection (photo took by the author, with IRT).....	48
Figure 15. Elephant 8 – hotspot at the right radio-carpal joint, seen in a LM projection (photo took by the author, with IRT).....	49
Figure 16. Elephant 10 – hotspot at the left shoulder, seen in a LM projection (photo took by the author, with IRT).....	49
Figure 17. Thermal asymmetries in Elephant 13. (A) Increased temperature is visible in the tibio-tarsal joint of the right hindlimb, (B) compared to the contralateral side; both seen in a DL-PaM O projection (photo took by the author, with IRT).....	50
Figure 18. Elephant 4 – Hotspot at the left tibio-tarsal hotspot not visible in all three projections. (A) PtL-DM O projection without visible hotspot; (B) LM projection with visible hotspot; (C) DL-PtM O projection without visible hotspot (photos took by the author, with IRT).....	53
Figure 19. Elephant 9 – Hotspot at right radiocarpal not visible in all three projections. (A) DL-PaM O projection with visible hotspot; (B) LM projection without visible hotspot; (C) PaL-DM O projection without visible hotspot (photo took by the author, with IRT).....	53
Figure 20. Elephant 9 – Hotspot at right knee visible in all three projections. (A) DL-PaM O projection with visible hotspot; (B) LM projection with visible hotspot; (C) PaL-DM O projection with visible hotspot (photo took by the author, with IRT).....	53
Figure 21. Elephant 2 – hotspot at the all extent of the right hindlimb, seen in a LM projection (photo took by the author, with IRT).....	54
Figure 22. Elephant 14 – hotspot at the tibia region of the right hindlimb, seen in a DL-PtM O projection (photo took by the author, with IRT).....	55

Clinical Cases from the Internship

The author divided the five-month curricular internship between two distinct institutions, both of which were outside of Portugal. Both internships were conducted in the field of wildlife medicine, with some additional experience working with domestic animals in Thailand. The institutions in question are wildlife rescue and rehabilitation centers, each with sanctuaries dedicated to housing individuals unfit for release into the wild, offering a diverse and practical approach to conservation medicine.

Under the direction of Dr. Raquel Meneses, the first component of the internship was conducted in Costa Rica at the Rescue Center Costa Rica from November 3rd 2024, to January 31st 2025. The second part of the internship was completed at the Wildlife Friends Foundation Thailand (WFFT) in Thailand from February 9th to March 31st 2025, under the supervision of Dr. Nutthapong Arsakit.

The activities carried out in each location will be presented individually in the following sections, organized by animal group and nature of the clinical cases.

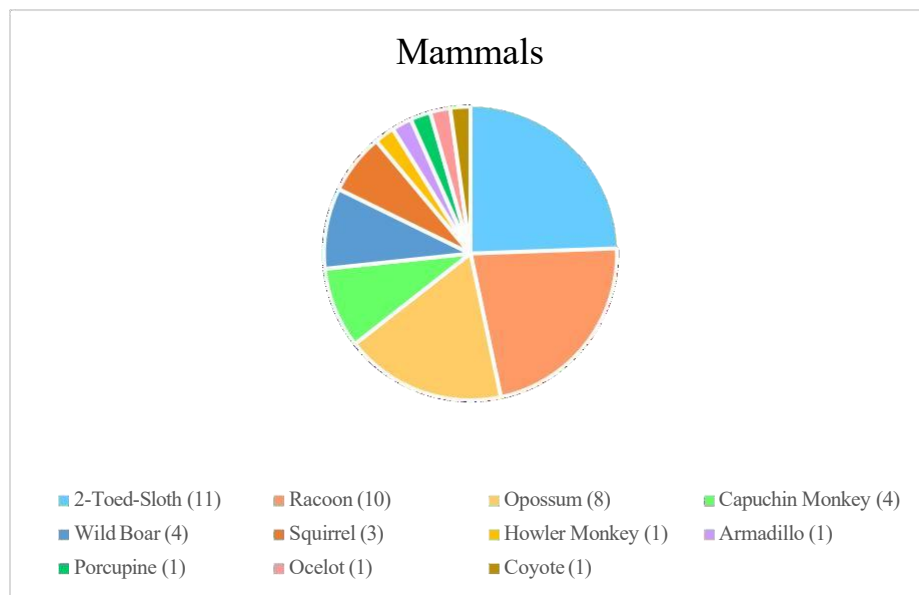
Rescue Center Costa Rica

The "Rescue Center Costa Rica" is a non-governmental organization based in Costa Rica that specializes in the rescue, rehabilitation, and release of wild animals, many of which have been the victims of human-wildlife conflict, vehicle collisions, illegal trading, or electrocution. Additionally, the center offers permanent sanctuary to animals whose physical or behavioural conditions prevent them from being returned to their natural habitat. Facilities include two separate hospitals - one designated exclusively for neonates and the other for adult animals undergoing recovery - and a sanctuary area where non-releasable individuals are housed.

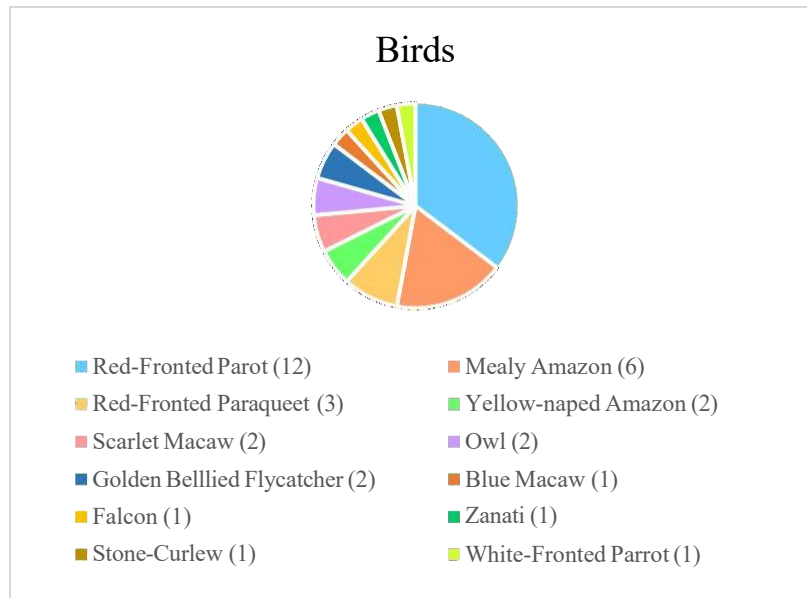
During the internship, clinical monitoring, neonatal care, medical treatments, and necropsies were performed on a variety of wildlife species, including Central American native mammals, birds, and reptiles, as well as non-native species imported through illegal trafficking. During this time, neonatal medicine emerged as a particularly important component, emphasizing the close observation and vital care of neonates of various species. Another crucial area of attention was the behavioural rehabilitation of wild animals, which aims to reduce human interaction and encourage natural behaviours in order to reintroduce them into the wild.

The author observed a total of 84 animals during this period: 45 mammals (Graph 1), 34 birds (Graph 2), and 5 reptiles (Graph 3). A total of 9 necropsies were performed (within four raccoons; two 2-toed sloths, one armadillo, one toucan and one green iguana), and 22 neonates (Graph 4) were cared for. Furthermore, 35 animals were successfully released back into the wild (Graph 5).

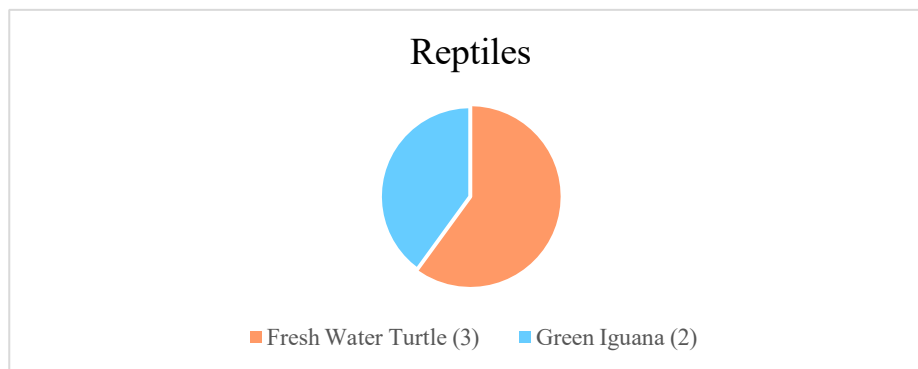
The procedures carried out included sample collection (blood, feces, and bronchoalveolar content), coprological exams, ultrasound, radiography, medication administration, nebulization, assisted feeding of mammal and bird neonates, maintenance and dressing change of an external fixator placed on a wing, physiotherapy on birds and mammals, acupuncture, laser therapy, intensive burn treatment, dietary reformulation, percentile monitoring in malnourished birds, beak and nail trimming of a bird, proper handling and restraint of various species, and wound cleaning. The author also participated in several theoretical and practical sessions on wildlife medicine and conservation.



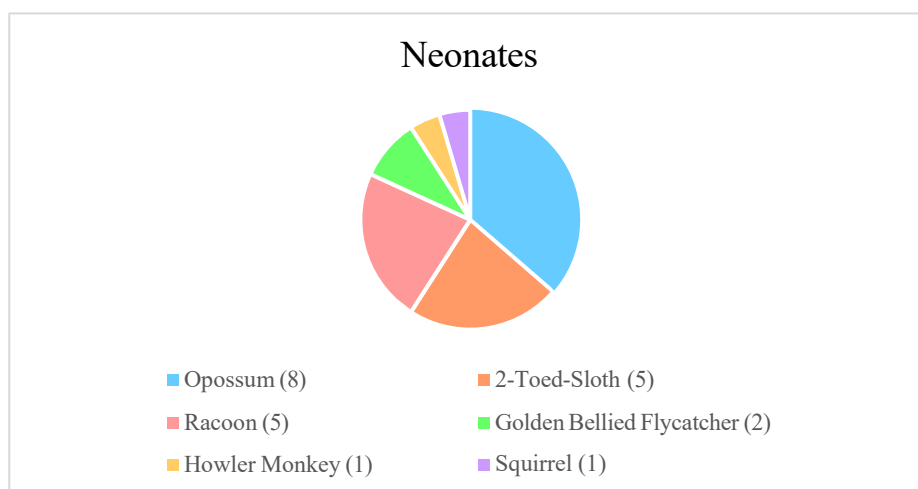
Graph 1. Graphical representation of the mammal species the author worked with at the Rescue Center Costa Rica.



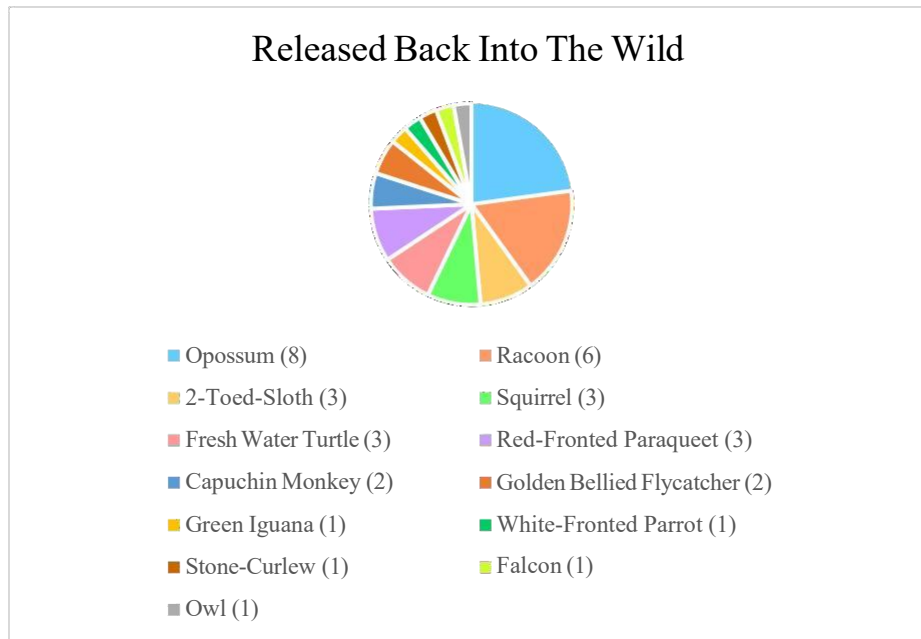
Graph 2. Graphical representation of the bird species the author worked with at the Rescue Center Costa Rica.



Graph 3. Graphical representation of the reptile species the author worked with at the Rescue Center Costa Rica.



Graph 4. Graphical representation of the neonate species the author worked with at the Rescue Center Costa Rica.



Graph 5. Graphical representation of the species that the author released back into the wild at the Rescue Center Costa Rica.

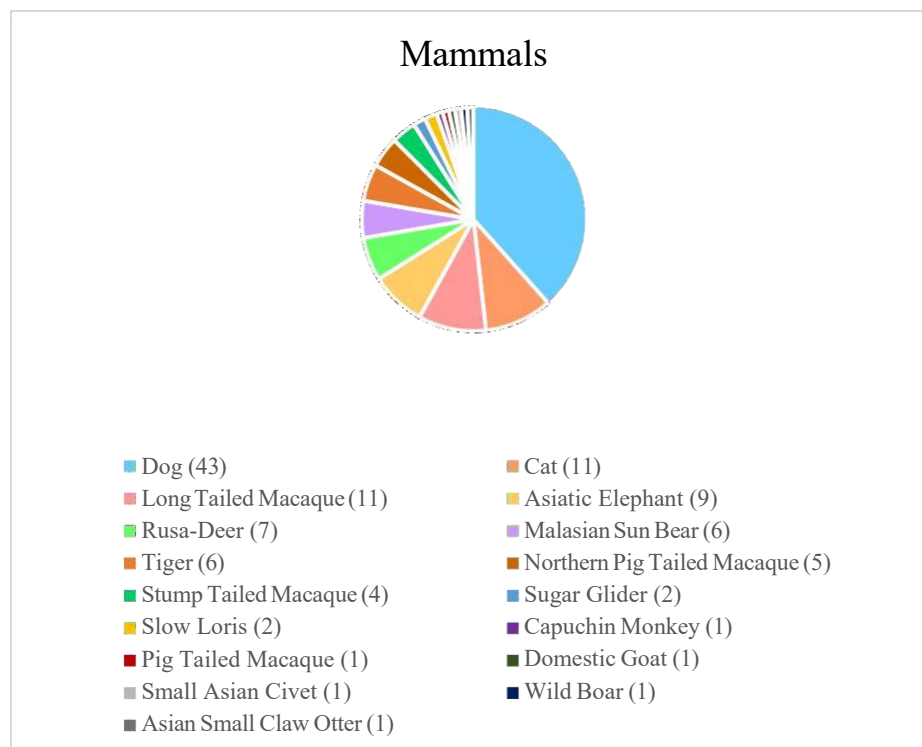
Wildlife Friends Foundation Thailand

WFFT is a major non-governmental organization focused on the rescue, care, and long-term welfare of wild animals affected by illegal trade, tourism exploitation and habitat loss. Located in central Thailand, the facility hosts over 900 animals and includes a large sanctuary area, a fully equipped hospital with an operating theatre, laboratory, diagnostic imaging room, ultrasonography, and endoscopy equipment.

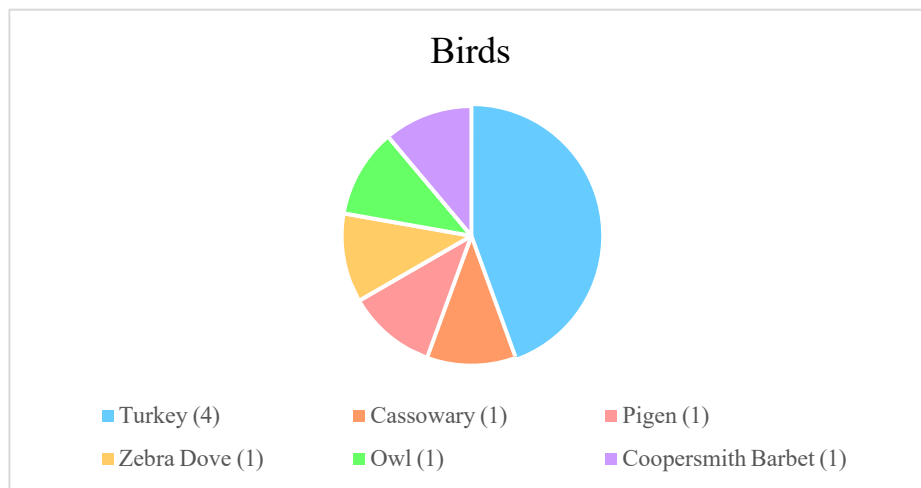
Throughout the internship, the author was involved in the care of 123 animals: 111 mammals (Graph 6), 9 birds (Graph 7), and 3 reptiles (Graph 8). Four necropsies were performed (including a Malaysian sun bear, an otter, a turkey and a wild boar). The clinical activities included radiography, ultrasonography, sample collection (blood, feces, and skin scrapings), anaesthetic monitoring, surgical assistance as circulating nurse, medication preparation and administration, wound cleaning, and the development and provision of enrichment for hospitalized animals. Additionally, physiotherapy and flight training were carried out with one bird, and both physiotherapy and hydrotherapy were applied to a primate. Other procedures included laser therapy, intensive colic management in Asian elephants, and palliative care in elderly primates. Surgical experience also involved the participation in the sterilization and castration of domestic dogs and cats.

Although a smaller number of domestic animals, like dogs and cats, were also treated, the majority of the clinical work in this setting focused on wild animals. From routine treatments to complicated medical cases, the caseload was wide and varied. The most frequently encountered conditions included dominance-related injuries in primates, acute abdominal syndrome and tail sores in Asian elephants, and nutritional or dental issues in tigers – such as appetite loss, food allergies, and oral pathologies (Graphic 9). Additionally, the hospital regularly conducted castration and sterilization campaigns for stray dogs and cats in surrounding areas.

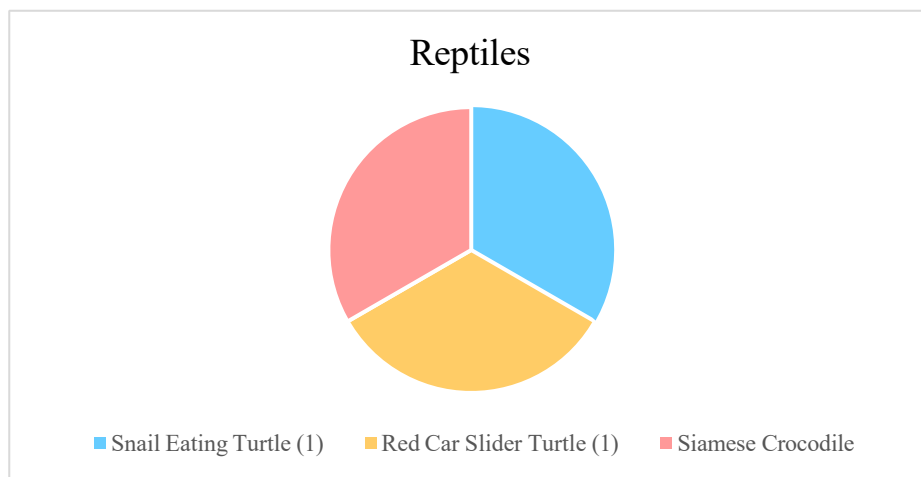
Daily case discussions were held among the veterinary team to encourage questioning, learning, and collaborative problem-solving, contributing significantly to the author’s clinical reasoning and practical skills development.



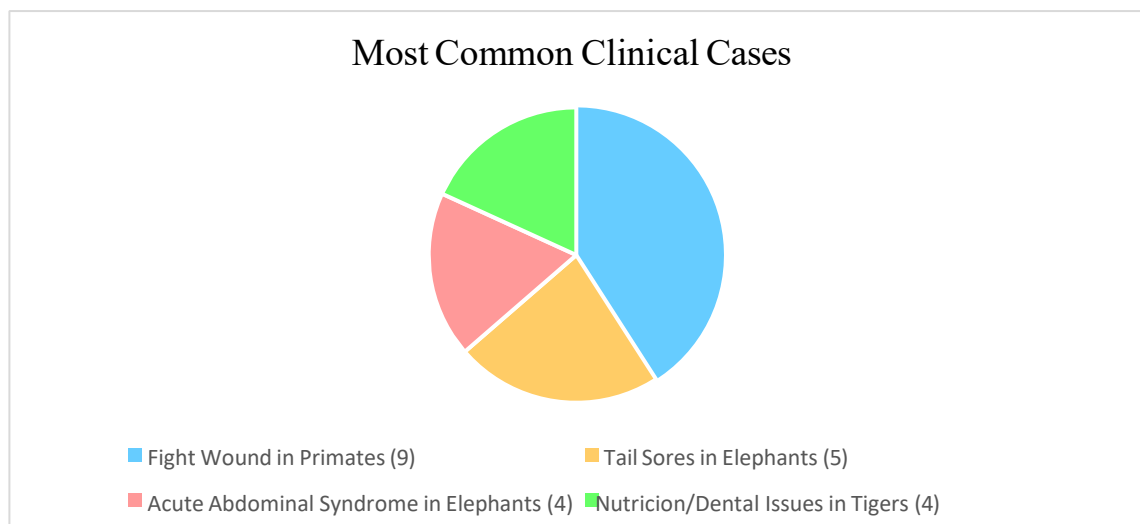
Graph 6. Graphical representation of the mammal species the author worked with at WFFT.



Graph 7. Graphical representation of the bird species the author worked with at WFFT.



Graph 8. Graphical representation of the reptile species the author worked with at WFFT.



Graph 9. Graphical representation of the most common clinical cases that the author saw at WFFT.

I. Introduction

The Asian elephant (*Elephas maximus*), the largest terrestrial mammal in Asia, is currently classified as “Endangered” by the International Union for Conservation of Nature (IUCN) due to multiple threats including habitat loss, fragmentation, human–elephant conflict, poaching, and illegal trade (Lefebvre, Gray, Prosser & Chabot, 2023). These threats not only contribute to the decline of wild populations but also disrupt social structures and reduce disease resilience. Climate change projections suggest that approximately 42% of the species' current habitat may be lost by the end of this century due to a combination of anthropogenic pressures and environmental changes (Lefebvre *et al.*, 2023). Understanding the factors that influence the abundance and distribution of Asian elephants is therefore essential for developing effective conservation strategies, both *in situ* and *ex situ* (Calabrese *et al.*, 2027).

Captive populations play an increasingly important role in conservation programs. However, Asian elephants in captivity often face significant health challenges, particularly musculoskeletal disorders. Joint health is a crucial factor for the welfare of these animals, with a high prevalence of joint diseases such as osteoarthritis and other inflammatory conditions that severely compromise mobility, physical condition, and quality of life (Schiavon *et al.*, 2021). These chronic issues are further exacerbated by inadequate environmental conditions, restricted movement, and the biomechanical stress associated with captivity.

Accurate and early diagnosis of joint diseases is essential to improve both clinical outcomes and welfare. Body temperature has been a vital parameter in medicine since ancient times. While early methods were rudimentary, accurate temperature measurement became possible only after the invention of the thermometer in the 16th century, followed by the development of clinical thermometry and temperature charting in the 19th century. In recent decades, thermal imaging has significantly advanced the understanding of surface temperature in both health and disease. Modern infrared thermography (IRT) is now a fast, cost-effective, and reliable tool supported by standardized protocols (Ring, 2006).

IRT is a non-invasive, non-contact diagnostic method that detects infrared radiation emitted from the body surface, converting it into thermal images that reflect temperature distribution (Davies, 2025). This technique is completely safe, with no radiation emission, and has been successfully applied in human medicine (Ahn *et al.*, 2022) and veterinary medicine, particularly in equines, for the assessment of joint inflammation and musculoskeletal disorders (Purohit & McCoy, 1980; Hilsberg-Merz, 2008). Given that pathological joints often exhibit

thermal variations due to inflammatory or degenerative processes, IRT emerges as a promising tool for detecting joint diseases in Asian elephants (Schiavon *et al.*, 2021).

Additionally, foot pressure distribution during locomotion is closely linked to the anatomical structure of foot tissues and joint biomechanics. The tibio-tarsal and radio-carpal joints are of particular interest as they bear substantial weight and are subject to high biomechanical stress, making them prime candidates for thermographic assessment to detect early thermal anomalies that may indicate joint pathology.

This study aims to evaluate the feasibility of infrared thermography as a diagnostic tool for joint diseases in Asian elephants. Specifically, it seeks to identify characteristic thermal patterns associated with pathological joint conditions. Furthermore, the study addresses the hypothesis that some elephants may present joint diseases without exhibiting overt clinical signs. By enabling earlier detection through IRT, this research aims to contribute to the improvement of health monitoring, management practices, and overall welfare of captive Asian elephants, ultimately supporting their conservation and well-being.

1. Infrared Thermography: Principles, Technical Limitations and Applications

The first use of thermography in medicine dates back to Hippocrates, who applied mud to detect heat variations. The discovery of infrared radiation by Herschel in 1800 and the development of infrared detectors in the 19th century paved the way for its medical applications. Since the 1960s, infrared thermography has been increasingly used in human and veterinary medicine, evolving from a research tool to a reliable diagnostic method. (Hilsberg-Merz, 2008).

Temperature is a key factor in animal physiology, as metabolic heat production is energetically costly. IRT provides a non-contact, non-invasive method to measure surface temperatures, though it only reflects events at the skin and insulating layers (Tattersall, 2016). In endotherms, body heat balance depends on metabolic production and peripheral blood flow, described by the core-shell model: the core remains stable, while the shell varies with blood flow, raising or lowering skin temperature to regulate heat exchange (Tattersall, 2016).

1.1 How Infrared Thermography Works

IRT is a non-invasive imaging technique that measures thermal radiation emitted by the body to create a surface temperature map without physical contact (Calin, Mologhianu, Savastru, Calin, & Brailescu, 2015). In biological tissues, infrared radiation is captured by sensors and converted into digital thermal images, often displayed using false-colour scales, such as the rainbow scale (Ring & Ammer, 2012; Hilsberg-Merz, 2008).

IRT is safe, free from ionizing radiation, and allows early detection of physiological alterations such as inflammation, circulatory dysfunction, and degenerative changes (Davies, 2025; Bhowmik, Shawli Bardhan, Bhattacharjee & Nath, 2016). Its diagnostic value has grown with technological improvements in accuracy and resolution (Davies, 2025; Calin *et al.*, 2015). Temperature variations reflect changes in peripheral blood flow, with vasodilation increasing heat dissipation and vasoconstriction reducing it (Tattersall, 2016). Thus, localized hyperthermia is a key sign of inflammation (Bhowmik *et al.*, 2016).

Certain anatomical regions act as “thermal windows” due to dense arterio-venous anastomoses that regulate heat exchange, typically in less insulated, hairless areas such as eyes, ears, nasal planum, oral region, limbs, shoulders, and inguinal region (Tattersall, 2016; Tilley *et al.*, 2024). These can be obligatory, like the periorbital or urogenital regions, or facultative, varying with environmental and species-specific factors (Hilsberg-Merz, 2008). Other anatomical regions act like “hotspots”, defined as localized areas of increased infrared emission that may indicate underlying inflammation or abnormal metabolic activity within the joint or adjacent soft tissues (Figure 1).

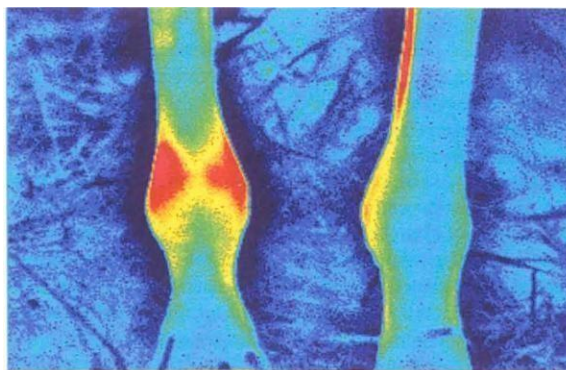


Figure 1. Presence of a hotspot in a horse. Increased heat patterns associated with an inflamed tibio-tarsal joint. The hotspot detected by the camera is shown in red, corresponding to an increased limb temperature, which is captured through the camera’s infrared light spectrum. (Eddy, A. L., Van Hoogmoed, L. M., & Snyder, J. R., 2001).

1.2. Technical Limitations and Influencing Factors

Despite its numerous advantages, IRT presents several technical limitations and is highly susceptible to both intrinsic and extrinsic influencing factors that can affect the accuracy and reliability of measurements.

Recent research has emphasized that the credibility of thermal imaging in medicine fundamentally relies on the correct use of technology combined with a robust understanding of thermal physiology (Ring & Ammer, 2012). Thermography functions by quantifying and evaluating surface temperatures in the outermost millimetres of the skin (Meola & Carlomagno, 2004; Huggins & Rakobowchuk, 2018), which are closely associated with blood circulation (Ringer *et al.*, 2005; Redaelli *et al.*, 2014; Luzi *et al.*, 2013). However, this surface temperature is subject to physiological variations influenced by factors such as circadian rhythms, physical activity, environmental conditions, climate, stress, and pathological processes like inflammation (Casas-Alvarado *et al.*, 2020; Vianna & Carrive, 2005).

A fundamental technical consideration is emissivity, which refers to the ability of an object to emit infrared radiation. While a perfect black body emits 100% of incident radiation, biological tissues act as grey bodies, emitting most radiation while reflecting other portion (Kastberger & Stachl, 2003). This assumption is integrated into infrared cameras, but variations in emissivity between different body surfaces, species, and materials can lead to measurement errors if not properly calibrated.

Additionally, atmospheric conditions – such as air humidity, wind, ambient temperature, water vapor, and suspended particles (dust, rain, snow) – can absorb, scatter, or distort infrared radiation, resulting in inaccurate readings (Kastberger & Stachl, 2003; Cilulko *et al.*, 2012). Solar radiation directly heats the skin surface and the surrounding environment, masking physiological thermal patterns. For this reason, field measurements should be performed under overcast skies, before sunrise, after sunset, or preferably in shaded environments to minimize solar artifacts (Hilsberg-Merz, 2008; Cilulko *et al.*, 2012). Despite the influencing factors described above, modern cameras already incorporate atmospheric correction filters and ambient compensation features to mitigate the impact of environmental variables on measurement accuracy (Kastberger & Stachl, 2003).

Artifacts can also arise from physical contaminants on the animal's body, such as mud, dirt, or water. These substances initially reflect lower temperatures but will eventually equilibrate with the animal's surface temperature based on their own thermal properties, leading to misleading results (Hilsberg-Merz, 2008). Contact with cold surfaces (floors, walls) can also cause local cooling, distorting the thermal profile (Bhowmik *et al.*, 2016).

Environmental factors are compounded by biological variables, such as coat characteristics – including hair density, thickness, colour, and moisture – which have a significant insulating effect (McCafferty, 2007; Casas-Alvarado *et al.*, 2020). Thick fur can mask vascular heat patterns, reducing the sensitivity of thermography to detect superficial circulatory changes (Autio *et al.*, 2007).

Species-specific anatomical and physiological traits further influence thermographic interpretations. Thermoregulatory adaptations – such as skin colour, ear size, gland distribution, and dermal thickness – affect heat dissipation patterns (Hilsberg-Merz, 2008). In hairless species like elephants and rhinoceroses, surface temperatures tend to be relatively uniform, except for areas like the ears, tusks or horns, which typically emit less heat due to lower vascularization. Elephants, for example, display a typical pattern where ears are cooler than the body, while the inner sides of the legs are warmer due to the proximity of superficial blood vessels (Hilsberg-Merz, 2008).

Technical setup plays a crucial role in ensuring accurate data acquisition. The thermal camera should ideally be positioned at a perpendicular angle (90°) to the target surface, approximately 2 meters away, though this distance may vary depending on the anatomical region being assessed (Bhowmik *et al.*, 2016). Some studies suggest a distance of 1 meter provides sufficient resolution for general assessments (Von Schweinitz, 1999; Eddy *et al.*, 2001; McCafferty, 2007), while certain smaller regions may require closer distances of around 0.5 meters (Casas-Alvarado *et al.*, 2020). Increasing the distance beyond this may reduce image resolution and temperature accuracy due to pixel dispersion and atmospheric distortion (Westermann *et al.*, 2013).

Patient preparation is equally critical. The animal should be clean, dry, and free from any external contaminants (Hilsberg-Merz, 2008). Moreover, the animal must be acclimatized to the ambient conditions for a minimum of 15 minutes – though 2 hours is considered optimal for certain species – to allow skin temperature and peripheral blood circulation to stabilize (Hilsberg-Merz, 2008; Bhowmik *et al.*, 2016). Contact between body parts or with external

surfaces must be avoided, as these points can create artificially cooler regions due to conductive heat loss (Bhowmik *et al.*, 2016).

Behavioural factors also influence thermal readings. Physical activity prior to image capture raises surface temperature due to muscular heat generation, while stress induces autonomic responses that affect peripheral blood flow (Casas-Alvarado *et al.*, 2020; McCafferty, 2007). For instance, Nakayama *et al.* (2005) demonstrated that Rhesus monkeys exhibited significant facial temperature changes when stressed by the threat of capture, illustrating the sensitivity of IRT to both physiological and emotional states.

High ambient temperatures can further compromise data quality by reducing the gradient between core and surface temperatures, making pathological patterns harder to detect (Hilsberg-Merz, 2008). This challenge is particularly significant in field conditions compared to controlled settings like zoological facilities. When interpreting thermograms, one key diagnostic criterion is thermal symmetry - healthy individuals exhibit symmetrical heat patterns between contralateral body regions. Asymmetry is a strong indicator of pathological processes such as inflammation. For example, infrared imaging has been shown to detect arthritis-related inflammation: osteoarthritis (OA) typically presents with unilateral increased temperature, while rheumatoid arthritis (RA) manifests with symmetrical bilateral heat increases (Bhowmik *et al.*, 2016).

Despite ongoing advancements, the high cost of high-resolution thermal cameras and the need for specialized training remain limiting factors for widespread adoption, particularly in wildlife research and veterinary clinical practice (Cilulko *et al.*, 2012). While infrared thermography offers significant advantages as a non-invasive diagnostic tool, its effectiveness depends on meticulous attention to environmental, biological, behavioural, and technical factors. Careful control and standardization of these variables are essential to ensure reliable and reproducible results.

1.3. Applications of Infrared Thermography in Veterinary Medicine

IRT is increasingly applied in both medical and veterinary contexts for a variety of purposes. In human medicine, it includes organ diagnostics, monitoring of sports injuries, disease progression, and evaluating conditions such as arthritis, respiratory diseases, and even breast cancer. In veterinary medicine specifically, it is widely used to detect injuries and inflammation in horses, livestock, and zoo animals.

Over the past 50 years, thermal imaging has served primarily as a research tool to study diseases in which skin temperature changes reflect inflammation or abnormal blood flow. It can function both as a diagnostic method and as an outcome measure in clinical trials. Traditionally, inflammation was evaluated through signs such as pain, swelling, and heat – perceived by touch during acute joint inflammation. However, subtle changes in temperature, indicative of evolving inflammation, are not always perceptible to the human hand and are effectively detected via thermography (Ring & Ammer, 2012).

IRT has shown great promise in the evaluation of musculoskeletal and neurovascular disorders. When muscle tissue is strained or torn, it releases chemicals that increase heat in the affected area. These changes manifest as patterns of hyperthermia, such as those seen in fibromyalgia or in cases of altered gait due to back or foot conditions. Although not a primary diagnostic tool, IRT has been used in legal settings as documentary evidence of injury and impairment (Davies, 2025).

Among the most explored applications is its use in rheumatic and degenerative joint diseases, such as RA and OA. These are common progressive disorders associated with pain and loss of function. In RA, immune-mediated synovial inflammation leads to joint swelling, whereas in OA, cartilage degeneration and secondary inflammation cause pain and structural damage. Contrary to the older belief that OA is solely degenerative, current research shows that inflammation is a central element in its pathophysiology. IRT can detect temperature increases resulting from increased blood flow and metabolism in inflamed tissues, offering insight into disease presence, stage, and treatment response (Schiavon *et al.*, 2021). The ability to analyse thermal symmetry between affected and unaffected joints supports diagnostic accuracy and disease monitoring. IRT's non-invasive, radiation-free nature, enhanced by improvements in camera resolution and clinical protocols, makes it a feasible and reliable technique for tracking inflammatory activity (Schiavon *et al.*, 2021).

In pain assessment, especially in animals, IRT offers an objective, physiological approach. Traditional pain evaluation relies heavily on behavioural scales and physiological markers, which can be subjective or require invasive procedures. IRT measures temperature variations caused by vasomotor responses such as vasodilation or vasoconstriction, which occur through autonomic nervous system activation during pain perception. These responses result from inflammatory mediators like prostaglandins, cytokines, and histamines, which increase vascular permeability, leading to localized heat – detectable via thermography (Whittaker *et al.*,

2023). This objective method is especially useful in veterinary contexts where behavioural observation is difficult or unreliable, such as in large or wild animals. However, debates remain over the direct relationship between detected thermal changes and pain intensity, and whether IRT can reliably guide analgesia protocols. Choosing the appropriate anatomical "thermal window" is critical for obtaining accurate readings (Whittaker *et al.*, 2023).

IRT has also proven valuable in wildlife thermophysiology and reproductive monitoring. In elephants, for instance, thermoregulation is facilitated through ear flapping, which can dissipate up to 100% of resting metabolic heat. IRT allows non-invasive quantification of such adaptations (Tattersall, 2016). The ability to acquire thousands of temperature points within milliseconds enables dynamic assessment of moving animals, eliminating the need for sedation or physical restraint – making it ideal for use in zoological and conservation settings (Ring & Ammer, 2012; Hilsberg-Merz, 2008; Cilulko *et al.*, 2012).

In zoology, ecology, and wildlife medicine, IRT is used to monitor injuries, infections, and reproductive parameters such as estrus, pregnancy, and fertility. It also plays a role in detecting lameness through dynamic thermal analysis during movement (Cilulko *et al.*, 2012; Hilsberg-Merz, 2008).

1.4. Correlation Between Thermographic and Radiographic Methods

Radiography remains the gold standard for anatomical assessment of bone and joint structures; however, thermography has emerged as a valuable complementary method, offering physiological insights into inflammatory processes. Unlike radiographs, which provide structural imaging, IRT detects temperature variations on the skin surface – subtle changes that can reflect underlying metabolic and vascular alterations associated with disease.

Thermography offers a functional perspective, capturing physiological processes rather than solely anatomical structure. This makes IRT especially useful in early diagnosis, monitoring treatment response, and tracking disease progression, where radiography may lag in detecting subtle but clinically relevant changes (Varju, 2004).

In the context of hand OA, several studies have examined the correlation between thermographic and radiographic findings. One such comparison found that slight degenerative changes observed in radiographs were linked to higher surface temperatures, indicative of active inflammation, while more severe radiographic damage corresponded to lower temperatures, likely due to a reduction in metabolic activity and inflammation at advanced

stages of the disease (Ring & Ammer, 2012; Varju, 2004). These findings support the hypothesis that OA progresses in distinct phases, beginning with active inflammation and progressing toward more degenerative stages characterized by decreased vascular activity and thermal emission.

Since IRT introduction for civilian use in 1958, infrared thermal imaging has seen significant technological advancements, becoming more affordable, portable, and reliable, thanks to improvements in industrial development and computerization. Modern applications now benefit from standardized protocols for image acquisition, region-of-interest selection, and data processing – enhancing reproducibility and clinical utility (Ring & Ammer, 2012).

2. Asian Elephant: Limb Anatomy, Movement Biomechanics, Common Musculoskeletal Pathologies and Relevant Welfare to Joint Health

The Asian elephant (*Elephas maximus*) has disappeared from about 95% of its historical range. As one of the few remaining megaherbivores, calves are born measuring around 90 cm in height and weighing 100 kg. Males grow faster from the age of two, reaching 240–300 cm and 3500–6000 kg as adults, while females reach 195–240 cm and 2000–3500 kg. Females become sexually mature at 10–14 years, with reproductive cycles every 14–16 weeks and a gestation period of 20–21 months, typically giving birth every 4–5 years. Males mature at a similar age and leave their natal herds to avoid inbreeding (Sukumar, 2006).

A study made in 2019 revealed that Asian elephants are distributed across 13 countries in South and Southeast Asia, occupying approximately 486,800 km². The wild population is estimated between 48,323 and 51,680 individuals, with around 15,000 elephants in captivity (Menon & Tiwari, 2019).

The main threat to the species is habitat loss and fragmentation, driven by human population growth, competition for space and resources, and rapid economic development, leading to significant forest loss and declining wild populations (Sukumar, 2006). This species faces other threats, as poaching and the increasing illegal trade of body parts, particularly skin, which affects both males and females. Although the overall population has remained relatively stable over the last two decades, significant declines have been reported in certain regions (Menon & Tiwari, 2019).

Nearly one-third of Asian elephants live in captivity, where management is often challenging due to varied practices and limited veterinary care. Many are kept isolated, which

is unsuitable for such highly social animals, and breeding rates in captivity are very low. Poor conditions, lack of exercise, and inadequate welfare contribute to higher mortality and health problems among captive elephants (Sukumar, 2006). Elephants are kept in captivity for different purposes, including logging, tourism, transportation, and participation in cultural or religious events (Fowler, Miller, Lamberski, & Calle, 2019). The methods used to train and manage elephants in these contexts are often controversial. In several regions, there is still a widespread belief that controlling an elephant requires firmness, intimidation, or even harsh treatment. This approach is deeply rooted in tradition, as mahouts (elephant handlers) typically rely on techniques passed down through generations (Fowler, Miller, Lamberski & Calle, 2019). These traditional methods often involve the use of fear and aggression to tame both wild-caught and captive-born elephants. Despite the growing awareness of animal welfare and the known risks – such as serious injuries and deaths affecting mahouts, bystanders, and elephants – these outdated practices remain common and are slow to change (Fowler, Miller, Lamberski & Calle, 2019).

2.1. Limb Anatomy

Elephants' skeleton (Figure 2) is highly specialized to support their massive weight, with over 200 bones and limb structures adapted for load-bearing (Fowler & Mikota, 2006). In the forelimbs, the semi-digitigrade, rounded forefoot supports ~60% of body weight, with robust bones lacking medullary cavities; the ulna is larger than the radius, highlighting its role in weight-bearing (Petneházy, Rück, Sós & Reinitz, 2023; Fowler & Mikota, 2006).

The carpus and tarsus each have eight bones in two rows, articulating with the metacarpals/metatarsals (Figure 3) (Petneházy *et al.*, 2023). Digits I–V are present, though only the toenails are externally visible; digits II–IV usually have three phalanges, while I and V have two, adapted for load distribution (Petneházy *et al.*, 2023). The number of toenails correlates with digit structure (Figure 3) (Miller *et al.*, 2007; Fowler & Mikota, 2006). A unique feature is the prepollex (forelimb) and prehallux (hindlimb), functioning as “sixth digits” to stabilize and redistribute weight (Petneházy *et al.*, 2023; Miller *et al.*, 2007).

Although the bone arrangement resembles digitigrade animals, thick foot pads make elephants functionally plantigrade. Forelimb bones form vertical columns, while hindlimbs are angled, with digits II–IV forming a stabilizing tripod (Miller *et al.*, 2007). Variations such as absent or malformed phalanges and sesamoids are often seen in radiographic and CT imaging (Petneházy *et al.*, 2023).

Limb vascularization is equally specialized. Distal to the elbow, the median artery supplies the limb, forming the deep palmar arch and giving rise to digital arteries (Figure 4) (Petneházy *et al.*, 2023). Although the vascularization of the digital cushion is not fully documented, analogous structures in other species have dedicated branches. Petneházy *et al.* (2023) identified a new arterial branch from the metacarpal artery, likely contributing to prepollex supply (Figure 5).

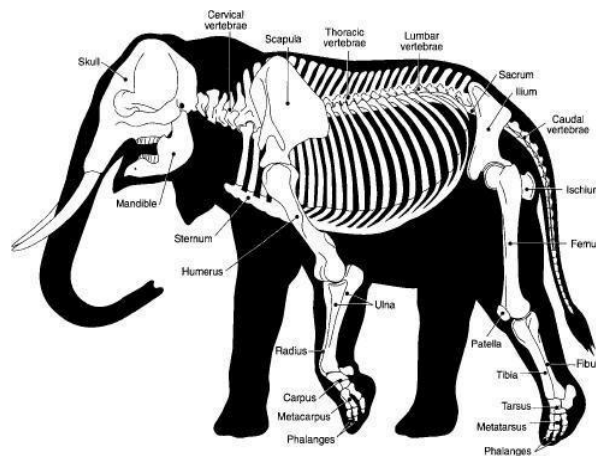


Figure 2. Skeleton of an elephant, illustrating the major skeletal structures relevant to musculoskeletal health (Fowler, M. E., & Mikota, S. K., 2006).

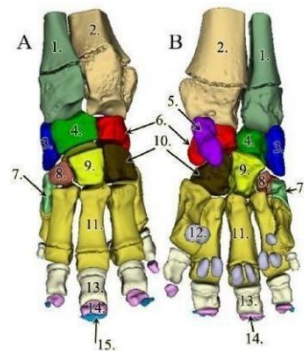


Figure 3. 3D model of the left forelimb skeleton in an Asian elephant; (A): dorsal view; (B): palmar view. Antebrachium - 1: radius, 2: ulna, 3: carpi radiale, 4: carpi intermedium, 5: carpi accessorium (only visible in palmar view), 6: carpi ulnare, 7: carpale I, 8: carpale II, 9: carpale III, 10: carpale IV, 11: metacarpale III, 12: ossa sesamoidea proximales (only visible in palmar view), 13: phalanx proximalis III, 14: phalanx media III, and 15: phalanx distalis III (Petneházy, Ö., Rück, S., Sós, E., & Reinitz, L. Z., 2023).

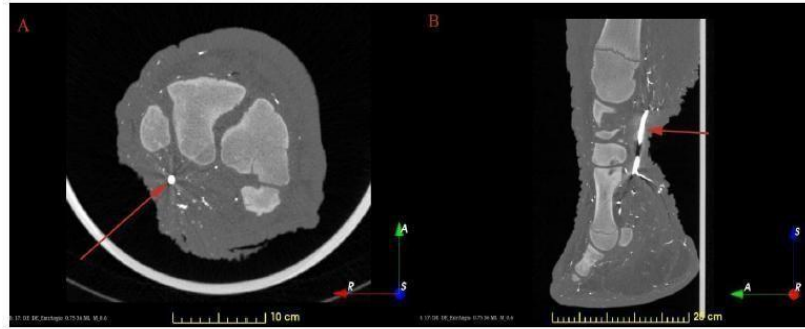


Figure 4. Contrast-filled CT images. The red arrows show the a. mediana. (A): horizontal plane; (B): sagittal plane (Petneházy, Ö., Rück, S., Sós, E., & Reinitz, L. Z., 2023).

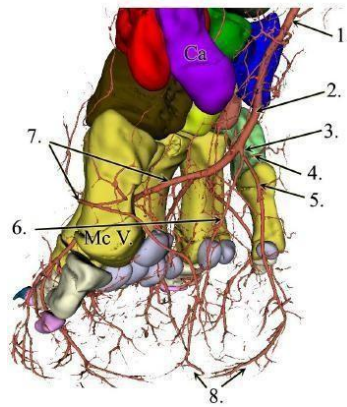


Figure 5. 3D reconstruction of the forefoot vessels on the left limb. Latero-palmar view. 1: a. mediana, 2: a. metacarpea, 3: newly found vessel, 4: branch towards the first digital and prepollex, 5: palmar branch, 6: dorsal branch, 7: arcus palmaris profundus, 8: terminal sections of the dorsal and palmar branches headed towards each other in the digital cushion, and Ca: carpi accessorium (Petneházy, Ö., Rück, S., Sós, E., & Reinitz, L. Z., 2023).

2.2. Biomechanics of Locomotion and Weight Distribution

Elephants are the largest extant terrestrial mammals. Although such a large body size confers certain energetic advantages, including a lower energy cost per unit of body mass during locomotion, it also presents significant biomechanical challenges. Specifically, while body

forces increase proportionally with volume, the strength of biological tissues scales only with cross-sectional area, resulting in increased structural vulnerability compared to smaller animals (Genin, Willems, Cavagna, Lair & Heglund, 2010).

Historically, elephant limbs have been characterised as rigid, vertical columns adapted for static weight-bearing. However, this view has been increasingly challenged by recent kinematic analyses. Although their limbs appear relatively straight during the stance phase, particularly at slow speeds, substantial flexion occurs during the swing phase. The ankle joint, previously considered functionally rigid, demonstrates spring-like behaviour, whereas the more flexible wrist remains relatively stable during ground contact. With increasing speed, elephants utilise between 31% and 77% of their joints' total range of motion, with distal joints contributing most significantly to this movement. These patterns are consistent with findings in horses and humans and suggest that elastic energy storage may occur during locomotion. Notably, joint angular velocity rather than range of motion appears to be the principal mechanism by which elephants increase locomotor speed. Additionally, no substantial differences in limb kinematics have been identified between African (*Loxodonta Africana*) and Asian elephants (*Elephas maximus*), and locomotor patterns remain relatively consistent across age groups (Ren, 2008).

Further studies have demonstrated that elephants possess a lower effective mechanical advantage (EMA) than predicted for their size, lower even than that of smaller cursorial mammals such as horses. As EMA decreases with speed, elephants must generate proportionally greater muscular force to maintain locomotion, thereby increasing their energetic cost. In contrast to many quadrupeds that functionally divide braking and propulsive roles between fore and hindlimbs, elephants employ a more symmetrical limb strategy. Both limb pairs contribute similarly to vertical ground reaction forces, resembling the coordinated propulsion of a four-wheel-drive vehicle. While this strategy reduces peak loading, it may introduce additional mechanical cost due to occasional horizontal opposition between limbs (Ren, Miller, Lair & Hutchinson, 2010).

Despite these mechanical challenges, elephants are capable of surprisingly efficient and stable locomotion. They maintain a lateral sequence footfall pattern across all speeds and do not exhibit a full-body aerial phase typical of running gaits in other mammals. Instead, they transition to a bouncing gait at higher speeds, marked by increased limb compliance and

occasional brief aerial phases of the hindlimbs. Their maximum recorded speed is approximately 6.8 m/s (Hutchinson, 2006).

A crucial anatomical adaptation that supports elephant locomotion is the unique structure of their feet. Each foot comprises five digits embedded within a thick, fibrous-fatty digital cushion that acts as a shock absorber and pressure redistributor. This combination of stiff and compliant tissues facilitates the distribution of high loads over a broad contact area during locomotion. As elephants grow, pressure distribution patterns evolve, with peak pressures increasing in parallel with body mass and being predominantly localised on the lateral digits (digits III–V). Importantly, these digits correspond to the anatomical regions most frequently affected by musculoskeletal pathologies, particularly in captive individuals (Panagiotopoulou, Pataky, Hill & Hutchinson, 2012).

Panagiotopoulou, Pataky, Hill & Hutchinson (2012) confirmed that pressure distribution correlates with both anatomical scaling and behavioural preferences, reinforcing the importance of these biomechanical insights for the optimisation of foot health management, enclosure design, and clinical interventions in elephants.

Together, these findings highlight the complex interplay between anatomical structure, locomotor dynamics, and weight distribution in elephants. Their biomechanical strategy reflects a series of specialised adaptations that enable them to manage the physical demands imposed by their exceptional body mass, while maintaining both safety and energetic efficiency during locomotion.

2.3. Common Musculoskeletal Pathologies in Captive Elephants

Foot and joint disorders are among the most prevalent and serious health concerns affecting captive elephants. Studies consistently report that up to 50% of individuals suffer from foot pathologies, highlighting the need for improved monitoring and prevention strategies (Avni-Magen *et al.*, 2017; Saddiq, 2020; Regnault *et al.*, 2017).

Commonly reported conditions include pododermatitis, cracked toenails, abscesses, sole ulcers, bone infections such as osteomyelitis, and joint inflammation or arthritis (Avni-Magen *et al.*, 2017; Luikart & Stover, 2005). Chronic foot injuries often lead to long-term pain and impaired mobility, and despite intensive veterinary intervention, many lesions progress and become difficult to manage successfully. These conditions are one of the leading causes of euthanasia in captive elephants (Regnault *et al.*, 2017).

The etiology of foot disorders is multifactorial. Poor hygiene, inappropriate flooring, reduced activity levels, obesity, poor limb conformation, and trauma are all recognized risk factors (Luikart & Stover, 2005; Saddiq, 2020; Fowler & Mikota, 2006). Additionally, foot pathology may result from internal structural changes, such as bone remodelling due to uneven weight distribution, rather than external causes alone. These changes weaken the digital cushion and nails, increasing susceptibility to infection and further deformity, thereby initiating a cycle of deterioration (Luikart & Stover, 2005).

The unique structure of the elephant's foot contributes to the complexity of these conditions. Elephants possess a large, cushioned heel and ground-contacting nails that help distribute pressure, especially through the middle and lateral digits. However, these digits bear the most load during locomotion, making them more prone to disease (Regnault *et al.*, 2017). Interestingly, despite bearing more than 60% of the body weight, the forelimbs are not disproportionately affected, suggesting that anatomical or functional differences may play a protective role.

Degenerative joint disease (DJD) is a major musculoskeletal pathology in elephants and frequently coexists with chronic foot problems. It has a multifactorial origin involving mechanical overload, biological processes and management-related stressors, such as prolonged chaining or hard surfaces (Fowler & Mikota, 2006). Repetitive stress, limited exercise, and obesity contribute to progressive cartilage degradation, joint inflammation, and subchondral bone changes. These degenerative processes lead to reduced joint mobility, fibrosis, and chronic pain (Fowler & Mikota, 2006; Sirikaew, 2029). OA is the most common form of DJD and has been documented in both African and Asian elephants. In captivity, excess weight and restricted physical activity disturb cartilage homeostasis and upregulate catabolic enzymes, resulting in joint inflammation and swelling. Affected elephants may avoid lying down due to pain, further complicating their condition (Sirikaew, 2029). Although therapeutic options are limited, swimming and anti-inflammatory medications are often employed to reduce discomfort and joint stress (Sirikaew, 2029).

Diagnosing foot and joint pathologies remains challenging, as elephants, like many wild animals, tend to mask clinical signs until disease is advanced. This evolutionary adaptation complicates early detection in captive settings (Fowler & Mikota, 2006). Clinical signs such as lameness may not appear until irreversible structural changes have occurred. Therefore, routine

and thorough physical examinations are essential, with special attention to the feet and forelimbs for asymmetry, swelling, or heat (Fowler & Mikota, 2006).

Imaging plays a critical role in diagnosis. While radiography is the primary diagnostic tool for detecting musculoskeletal disorders, more advanced modalities like CT and Magnetic Resonance Imaging (MRI) are rarely used due to size constraints (Regnault *et al.*, 2017). IRT, however, has shown promise in identifying inflammation in the early stages, even before visual signs are evident (Avni-Magen *et al.*, 2017).

Preventive measures are essential to reduce the incidence and severity of musculoskeletal disorders. These include regular exercise, appropriate flooring, weight management, clean environments, and routine radiographic screening. Given elephants' large size, unique biomechanics, and longevity, they are particularly vulnerable to chronic load-related foot and joint conditions. A better understanding of their musculoskeletal anatomy and biomechanics is vital to improving health outcomes and longevity in captive populations (Regnault *et al.*, 2017; Luikart & Stover, 2005).

2.4. Welfare Implications of Musculoskeletal Disorders

Musculoskeletal disorders, particularly foot and joint pathologies, are among the leading welfare concerns in captive elephants. These conditions not only compromise physical health but also significantly affect mobility, behaviour, and psychological well-being, underscoring the close link between veterinary health and animal welfare.

In captivity, foot problems are the most commonly reported health issue in elephants, often resulting from inadequate husbandry practices (Mumby, 2013). Factors such as hard, wet, or unsanitary flooring, restricted movement, and prolonged standing on concrete or cold surfaces contribute directly to the development of conditions like pododermatitis and DJD (Hittmair & Vielgrader, 2000). Additionally, poor feeding practices, lack of bedding, and chronic exposure to urine or moisture are recognized risk factors for musculoskeletal deterioration (Saddiq *et al.*, 2020).

Lameness is one of the most visible clinical consequences of these disorders and serves as a key welfare indicator. It can severely limit the elephant's ability to move, rest comfortably, or engage in natural behaviours, leading to chronic pain and reduced quality of life. However, despite the evident impact of such conditions, there remains a lack of comprehensive scientific research into the exact mechanisms by which husbandry-related factors contribute to

musculoskeletal disease progression (Saddiq *et al.*, 2020). Improving the understanding of elephant foot anatomy and biomechanics could lead to more effective preventive and diagnostic approaches.

The welfare of captive elephants is also influenced by broader management contexts. In countries like Thailand, elephants are extensively used in tourism for riding, bathing, feeding, and entertainment. Elephants used in tourism, often suffer from foot problems due to walking long hours on hard surfaces, wounds from improper handling, gastrointestinal issues from contaminated food and obesity related to lack of exercise and poor nutrition (Bansiddhi, Brown & Thitaram, 2020).

Even with improvements in veterinary care and husbandry standards, several systemic challenges persist in maintaining optimal welfare for captive elephants (Regnault *et al.*, 2017). Issues such as outdated training methods, limited regulatory oversight, and inconsistent management continue to jeopardize animal welfare in many facilities. Preventive health strategies, including regular foot care, provision of appropriate substrates, space for movement, and weight control, are essential to mitigate the onset of painful musculoskeletal conditions and to improve overall quality of life.

3. Application of Infrared Thermography in Asian Elephants

3.1. Previous Studies Using IRT in Elephants

IRT has been increasingly applied in elephant research to explore patterns of thermoregulation, physiological stress responses, and, more recently, potential indicators of locomotor and joint health.

A study by Tilley *et al.* (2024) used IRT to monitor thermal variations in ten female Asian elephants (*Elephas maximus*) in Nepal, during two types of physical activity. Although no statistically significant differences were found between polo-playing and non-polo-playing individuals, both groups showed notable post-activity increases in skin temperature across multiple body regions. The most pronounced changes were recorded in the ear pinnae, reinforcing their primary role as thermoregulatory surfaces. In a complementary study, Tilley *et al.* (2024) assessed joint loading and thermal variation in the forelimbs of Asian elephants, chosen due to their predominant role in weight-bearing and their kinematic similarity to horses. No significant differences were observed between forelimb and core body temperatures,

suggesting the presence of compensatory biomechanical or thermoregulatory mechanisms that may dampen localised stress responses.

In a cold-climate ex situ study, Lefebvre, Gray, Prosser & Chabot (2023) analysed thermoregulation in Asian elephants housed in Canada. Over two months, 374 thermal images were collected from 10 elephants (aged 1 to 56 years), using 15-minute intervals during observation sessions. This study focused on ear surface temperature as a proxy for thermoregulatory adjustments in low ambient temperatures. Results confirmed that vascular activity in the ears plays a central role in conserving or dissipating heat, depending on environmental conditions. The research also indicated that age, sex, body weight, and behavioural activity all influence surface temperature. Thermal windows were identified in both younger and older individuals, revealing a shared adaptive strategy for coping with cold, with implications for captive care and species conservation under changing climates.

Hilsberg-Merz (2008) provided comparative thermographic data from both African (*Loxodonta africana*) and Asian (*Elephas maximus*) elephants, observing heat emission patterns in feeding animals. Elevated temperatures were commonly recorded at the mouth, trunk tip, and forefoot tips, with thermal signatures corresponding to major blood vessels. The eyes, mouth, and anus consistently functioned as thermal windows, while the ears exhibited relatively lower surface temperatures. The study also noted that sunlight exposure significantly affected thermographic readings and that ear temperature increases could be linked to psychological stress in some individuals.

In a foundational investigation, Weissenböck, Weiss, Schwammer & Kratochvil (2010) used IRT to evaluate surface temperature variation in African elephants under different ambient conditions. The study highlighted the functional role of the pinnae as thermal windows, where thermoregulation is controlled by vasodilation and vasoconstriction within a dense subcutaneous vascular network. Thermal imaging revealed distinct patterns activated by arterial blood flow to specific ear regions (Figure 6). Additionally, statistical analyses indicated that ambient temperature, age, and body weight significantly influenced thermal window expression, supporting the use of IRT in assessing physiological responses to environmental stressors.

Together, these studies demonstrate the growing utility of IRT in understanding elephant physiology and behaviour, particularly in relation to thermoregulation and environmental adaptation. Although primarily used for monitoring surface temperature, these findings have

laid the groundwork for exploring its application in early disease detection and welfare assessment in both captive and wild elephant populations.

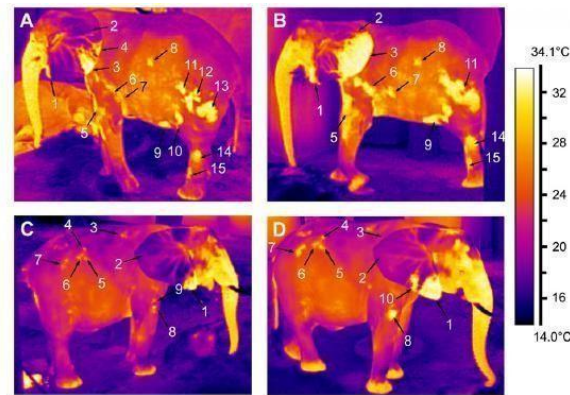


Figure 6. Thermal imaging with distinct patterns activated by arterial blood flow of the body surface of two African elephants observed indoors. (A) and (B) represent the thermal windows on the left side of the elephant. (C) and (D) the thermal windows on the right side of the elephant (Weissenböck, N. M., Weiss, C. M., Schwammer, H. M., & Kratochvil, H., 2010).

3.2. Thermal Patterns Associated with Joint Pathologies

IRT has proven to be a valuable diagnostic and monitoring tool in detecting joint and inflammatory conditions in large mammals, particularly elephants. The technique operates by capturing surface temperature variations that may indicate underlying vascular, inflammatory, or neurological processes. Due to their sparse body hair and large body surface area, elephants are especially well-suited for thermographic imaging (Kastberger & Stachl, 2003; Mota-Rojas *et al.*, 2022).

Inflammation leads to increased local heat production, a hallmark feature that is effectively captured by IRT, especially when the affected area is near the surface of the skin. In elephants, limbs and feet are often used as accessible regions for early thermographic assessment. The podal or phalangeal thermal window is particularly useful for this purpose, being richly vascularized and thus responsive to changes in local blood flow. Inflammation, frequently triggered by bacterial infection or mechanical stress, prompts the release of immune

mediators that cause vasodilation and hyperaemia – manifesting as areas of increased infrared radiation (Mota-Rojas *et al.*, 2022).

In a study conducted on Asian elephants (*Elephas maximus*), thermography detected pre-inflammatory areas exhibiting surface temperatures up to 2°C higher than surrounding healthy tissue. The diagnostic sensitivity and specificity for foot inflammation were reported as 89.2% and 83.4%, respectively. These findings highlight IRT's ability to detect early inflammatory changes even before the onset of visible clinical signs. However, systemic inflammatory responses may lead to more diffuse thermal patterns, which can challenge precise lesion localization (Mota-Rojas *et al.*, 2022).

Another study by Avni-Magen, Zaken, Kaufman & Kelmer (2017) further supported the diagnostic potential of IRT in elephants. In this investigation, thermal anomalies were classified as negative, positive, or pre-inflammatory. Interestingly, the so-called pre-inflammatory regions – those with no overt clinical symptoms – showed the greatest temperature increases. Areas with visible signs of inflammation exhibited significantly elevated temperatures when compared to adjacent unaffected tissue. These results reinforce IRT's utility as an early detection tool and its capacity to monitor disease progression over time in both skin and foot pathologies.

Thermographic imaging has also proven effective in clinical settings where physical examination yields inconclusive results. For instance, Hilsberg-Merz (2008) documented a case in which an Asian elephant with abnormal gait displayed no visible injuries, yet IRT identified localized inflammation in the right elbow joint (Figure 7). The same study highlighted thermographic signatures of pododermatitis: mild cases revealed increased heat in isolated nails, while severe forms presented diffuse thermal elevation across the entire foot. IRT not only facilitated diagnosis but also allowed veterinarians to monitor treatment efficacy throughout the healing process – a critical advantage given the chronic and prolonged nature of foot pathologies in elephants. Furthermore, Kastberger & Stachl (2003) emphasized that dead phalanges could be indirectly identified via thermography through surrounding hyperthermic zones caused by inflammation and hypothermic zones on necrotic tissue.

These findings suggest that abnormal thermal patterns – whether localized hotspots or widespread increases in limb temperature – can serve as early, non-invasive indicators of joint disease and other musculoskeletal disorders in elephants. While further research is needed to refine interpretation protocols and account for variables such as systemic inflammation, current

evidence underscores the utility of IRT in supporting diagnostic, prognostic, and welfare-related assessments in both wild and captive populations.

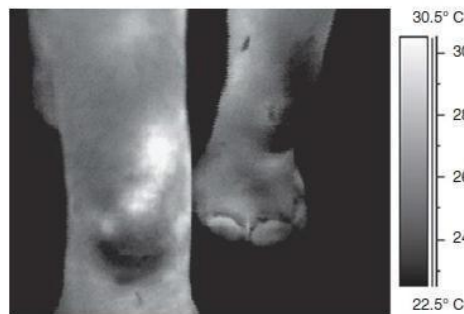


Figure 7. Asian elephant with moderate lameness after a fight. Thermography revealed a hotspot above the right carpal joint (Hilsberg-Merz, S., 2008).

3.3. Potential and Limitations of IRT in Elephant Health Monitoring

IRT poses unique challenges in zoo and wildlife medicine, as it requires species-specific anatomical knowledge and is influenced by uncontrollable factors such as animal movement, sunlight, and surface conditions. Unlike clinical settings, environmental parameters are harder to standardize when working with elephants. However, IRT is most effective in species with little hair, such as elephants, and the operator must have a thorough understanding of the animal's normal skin and anatomy to interpret thermal images accurately (Hilsberg-Merz, 2008). Despite these challenges, IRT remains a valuable tool for monitoring elephant health and welfare in both captivity and the wild. While non-veterinarians can perform assessments, collaboration with a zoo veterinarian is recommended for optimal interpretation and decision-making (Hilsberg-Merz, 2008).

In veterinary medicine, thermography has shown various advantages by aiding in the assessment of injuries, medical conditions, and post-surgical outcomes in animals, making it a useful complementary diagnostic technique for elephants (Casas-Alvarado *et al.*, 2020). Specifically, thermal imaging demonstrates high sensitivity (89.2%) and specificity (83.4%) in detecting pathologies, indicating that IRT is a powerful screening tool for early detection of health issues, but positive findings generally require confirmation through further diagnostic tests (Avni-Magen, Zaken, Kaufman & Kelmer, 2017).

3.4. Integration of IRT into Wildlife Veterinary Practice and Welfare Management

IRT is a valuable non-invasive tool in wildlife veterinary medicine and welfare management, enabling heat dissipation assessment during inflammatory processes and recovery without disturbing the animal (Casas-Alvarado, 2024). Its capacity for remote temperature measurement, at close or long distances (up to 1000 m), eliminates the need for physical contact or multiple sensors, reducing stress and allowing continuous monitoring (McCafferty, 2007; Avni-Magen, Zaken, Kaufman & Kelmer, 2017).

Abnormal temperature distributions detected by IRT can indicate circulatory problems or inflammation, making it a powerful complementary diagnostic technique (McCafferty, 2007). Since the 1960s, IRT applications have expanded to include thermal physiology, disease surveillance, and population monitoring in both wild and captive mammals (McCafferty, 2007).

Studying wild animals is inherently challenging due to behaviours like nocturnality, camouflage, and high alertness, which limit traditional data collection methods. Thermal imaging helps overcome these obstacles by providing unique insights non-invasively, improving wildlife research outcomes. Advances in thermographic technology and related fields suggest that IRT will become an increasingly common and valuable tool in future wildlife studies due to its versatility and ease of use (Cilulko, Janiszewski, Bogdaszewski & Szczypińska, 2012).

In terms of welfare management, IRT supports effective health monitoring by measuring skin radiation from thermal windows. Species differences such as skin thickness, coat colour, and hair length influence IRT readings, underscoring the need for species-specific research to optimize its application (Mota-Rojas, 2022). Understanding thermoregulation and coat characteristics is also critical, as darker coats absorb more heat, and some species have patterns that regulate temperature (Mota-Rojas, 2022).

Veterinarians and animal caretakers benefit from IRT by gaining insights into enclosure conditions that help prevent heat stress and improve preventive health care. Furthermore, thermography enhances scientific knowledge of captive wildlife health, providing data that can inform conservation strategies when applied to wild populations. Overall, IRT contributes significantly to ensuring the physical and emotional well-being of animals in human care (Mota-Rojas, 2022).

II. Materials and Methods

This retrospective study was conducted at the Wildlife Friends Foundation Thailand, a rescue center located in Phetchaburi province, Thailand. Data collection took place between March 17th and March 27th, 2025.

A total of 14 Asian elephants (*Elephas maximus*) were included in the study. All individuals were females, ranging in age from 34 to 70 years, with body condition scores between 3 and 8 in a scale of 1 to 9 (Tang, Y., *et al*, 2024), and estimated body weights from 2489.1 kg to 3146.7 kg (Table 1). All the elephants had large enclosures that allowed them to walk free, bath, eat, interact with each other and play with enrichment made by the mahouts (elephant caretakers) and volunteers. Out of the 22 elephants housed at the center, only those considered safe to approach were selected for the study, based on behavioural history and safety recommendations from the mahouts.

Table 1. Summary of individual characteristics of the 14 Asian elephants (*Elephas maximus*) included in the study. This data is from February 2025.

Name	Sex	Age	Weight (Kilograms)	Body Score
Elephant 1	Female	61	2803.8	7
Elephant 2	Female	70	2489.1	3
Elephant 3	Female	50	2851.7	6
Elephant 4	Female	57	2931.5	7
Elephant 5	Female	62	2866.8	7
Elephant 6	Female	64	2727.5	7
Elephant 7	Female	59	2877.4	7
Elephant 8	Female	67	2679.8	7
Elephant 9	Female	55	2807.9	5
Elephant 10	Female	62	2873.9	6
Elephant 11	Female	41	3045.4	6
Elephant 12	Female	62	2648.3	5
Elephant 13	Female	62	2799.4	7
Elephant 14	Female	34	3146.7	8

All elephants at the facility receive monthly dietary supplementation as part of their preventive healthcare and nutritional management. The supplementation protocol includes iron, omega-3, calcium, vitamin E, vitamin A, zinc, folic acid, and B-complex vitamins. In addition, all elephants are administered a nutraceutical product commercially known as Athril, formulated to relieve joint pain, swelling, and stiffness associated with arthritis.

Infrared thermal imaging was performed using a Kaiweets thermal imager, model KTI-K01, produced and sold by Kaiweets. The camera has an infrared resolution of 256×192 pixels and a thermal sensitivity of ≤ 45 mK, with a temperature detection range from -20°C to $+550^{\circ}\text{C}$. The device operates within a spectral range of 8–14 μm . Emissivity was set to 0.95, and environmental relative humidity was approximately 70%. All images were captured at a fixed distance of 2 meters from the limb, measured using a bamboo stick pre-marked with the corresponding length (Figure 8). The camera features four imaging modes (IR, Visible, Fusion, and Picture-in-Picture) and six colour palettes.



Figure 8. Bamboo stick used as a standardized measuring tool during image acquisition. The stick was pre-marked at 2 meters and placed between the thermal camera and the elephant's limb to ensure consistent and safe imaging distance (image of the author).

Thermal images were collected in the early morning, between 8am and 8:30am, under stable environmental conditions (sunny weather, no precipitation or strong winds, ambient temperature of 28°C , and high humidity despite the dry season). Each elephant was photographed in their natural enclosure, without physical restraint. Positive reinforcement with food was used to keep the elephant stationary in shaded areas. A mahout was always present during the procedure to manage animal behaviour and ensure the safety of the investigator, who maintained a consistent 2-meter distance from the animals. Emergency escape routes were planned and available at all times.

A total of 168 thermal images were captured, with twelve images obtained per elephant – three for each limb. Each limb was imaged using three distinct projections: lateromedial (LM), dorsolateral-palmaromedial oblique (DL-PaM O) or dorsolateral-plantaromedial oblique for hind limbs (DL-PtM O), and palmarolateral-dorsomedial oblique (PaL-DM O) or plantarolateral-dorsomedial oblique for hind limbs (PtL-DM O). These multiple projections were used to ensure that the camera captured the maximum number of thermal hotspots and to help identify potential artifacts, similar to the rationale used in radiographic imaging. The focus (central spot meter) was placed on the radio-carpal joints of the forelimbs and the tibio-tarsal joints of the hind limbs in order to allow consistent and comparable imaging between limbs and individuals. Nevertheless, the images consistently encompassed the three main joints of each limb: shoulder/hip, elbow/knee, and radio-carpal/tibio-tarsal.

The central spot meter was used in each thermal image to measure the surface temperature; however, rather than focusing solely on this central value, the broader thermal pattern of the joint and surrounding limb areas was assessed, providing a more comprehensive evaluation of possible inflammation. In this context, a thermal window refers to a specific anatomical area with consistent vascularization and minimal hair coverage, which allows for reliable heat emission and serves as a standardized region for thermographic evaluation. Additionally, particular attention was given to the presence of hotspots, defined as localized areas of increased infrared emission that may indicate underlying inflammation or abnormal metabolic activity within the joint or adjacent soft tissues.

Image acquisition and analysis were consistently performed by the same person – the author – in order to avoid inter-observer variability.

This was an observational and descriptive study designed to evaluate the applicability of infrared thermography (IRT) as a diagnostic tool for joint disease in Asian elephants. Each elephant served as its own control, with contralateral limbs without suspected lesions providing internal comparison. The presence or absence of hotspots was recorded for each thermal image, and categorical variables were summarised as counts and percentages. To assess whether hotspot detection depended on the limb, projection, or joint evaluated, contingency tables were constructed and analysed using Pearson's chi-square test. Fisher's exact test was applied when expected cell counts were less than five. Statistical significance was set at $p < 0.05$.

III. Results

Among all the elephants examined, only two presented with visible lameness affecting the right hindlimb (Elephant 2 and 14), while the remaining individuals showed no clinical signs of joint pathology.

1. Common Thermal Patterns Across Individuals

Several repeated thermal features were observed across individuals (Table 2). Increased temperature in the medial aspect of the limbs (Figure 9) was present in elephant 2, 4, 5, 6, 7, 8, 9, 11, 12, 13, and 14. Elevated temperature at the nails/ungual regions (Figure 10) was detected in all the elephants, however, the distribution varied, with some individuals showing increased temperature in a single limb, while others presented this finding in multiple or all limbs. A warm distribution at the ventral abdominal region (Figure 11) was observed in elephant 1, 3, 7, 10, 12, and 14.

These results are purely observational and descriptive. No statistical analysis was performed for this section, as the aim was only to report common qualitative thermal patterns observed across individuals rather than to test for associations.

Table 2. Presence (1) or absence (0) of common thermal patterns (increased temperature in the medial aspect of the limbs, nails/ungual regions, or ventral abdominal region) across the study population, meaning in each elephant (E1/2/3/4/5/6/7/8/9/10/11/12/13/14).

	Medial aspect of the limbs	Nails/ungual regions	Ventral abdominal region
E1	0	1	1
E2	1	1	0
E3	0	1	1
E4	1	1	0
E5	1	1	0
E6	1	1	0
E7	1	1	1
E8	1	1	0
E9	1	1	0
E10	0	1	1
E11	1	1	0
E12	1	1	1
E13	1	1	0
E14	1	1	1
TOTALof “YES”	11	14	6



Figure 9. Increased temperature in the medial aspect of the right forelimb, in Elephant 8 (photo took by the author, with IRT).



Figure 10. Increased temperature at the right hindlimb nail/ungual regions, in Elephant 10 (photo took by the author, with IRT).



Figure 11. Warm distribution at the ventral abdominal region, in Elephant 7 (photo took by the author, with IRT).

2. Individual-Specific Thermal Asymmetries in Joints

Localized hotspots not consistently shared across all elephants were recorded. Hotspots were observed across the six joints assessed: tibio-tarsal, knee, hip, radio-carpal, elbow, and shoulder. Elephant-specific hotspots included: Elephant 2 with a hotspot along the right hind limb tibia; Elephant 3 at the left shoulder; Elephant 4 at the left tibio-tarsal joint (Figure 12); Elephant 5 at the right elbow (Figure 13); Elephant 7 at the left knee (Figure 14); Elephant 8 at the right radio-carpal joint (Figure 15); Elephant 9 with a hotspot at both right and left knee and at the right radio-carpal joint; Elephant 10 at the left shoulder (Figure 16); Elephant 11 at the left tibio-tarsal joint; Elephant 13 at the right tibio-tarsal joint; and Elephant 14 at the left radio-carpal joint and right tibio-tarsal joint.

The presence of hotspots across different joints is summarized in Table 3. Statistical analysis using the χ^2 test and Fisher's exact test indicated no significant differences in hotspot detection across the six joints ($\chi^2 = 7.89$, $df = 5$, $p = 0.163$; Fisher's exact test, $p = 0.162$), suggesting that the thermographic system was equally capable of detecting hotspots across the different joints studied (Table 4).

Table 3. Presence (1) or absence (0) of hotspots across different joints in all the studied elephants. The tibiotarsal joint presented the highest number of hotspots among all examined individuals. Elephants 2, 9, and 14 showed hotspots in more than one joint, in contrast to the remaining elephants, which exhibited hotspots in only one joint or none.

	Tibio-tarsal joint	Knee joint	Hip joint	Radio-carpal joint	Elbow joint	Shoulder joint
E1	0	0	0	0	0	0
E2	1	1	0	0	0	0
E3	0	0	0	0	0	1
E4	1	0	0	0	0	0
E5	0	0	0	0	1	0
E6	0	0	0	0	0	0
E7	0	1	0	0	0	0
E8	0	0	0	1	0	0
E9	0	1	0	1	0	0
E10	0	0	0	0	0	1
E11	1	0	0	0	0	0
E12	0	0	0	0	0	0
E13	1	0	0	0	0	0
E14	1	0	0	1	0	0



Figure 12. Elephant 4 - hotspot at the left tibio-tarsal joint, seen in a DL-PaM O projection (photo took by the author, with IRT).



Figure 13. Elephant 5 – hotspot at the right elbow, seen in a LM projection (photo took by the author, with IRT).



Figure 14. Elephant 7 – hotspot at the left knee, seen in a LM projection (photo took by the author, with IRT).



Figure 15. Elephant 8 – hotspot at the right radio-carpal joint, seen in a LM projection (photo took by the author, with IRT).



Figure 16. Elephant 10 – hotspot at the left shoulder, seen in a LM projection (photo took by the author, with IRT)

Table 4. Contingency Table - Statistical analysis using the χ^2 test and Fisher's exact test. Testing if the IRT camera is capable of detecting hotspots in different joints. No significant differences were found in hotspot detection between the six joints analysed ($\chi^2 = 7.89$, $df = 5$, $p = 0.163$; Fisher's exact test, $p = 0.162$), indicating that the thermographic system was equally effective in detecting hotspots across all joints. The tibiotarsal joint exhibited the highest number of hotspots among all examined elephants, while elephants 2, 9, and 14 showed hotspots in more than one joint, contrary to the remaining elephants that presented hotspots in only one joint or none.

	Value	df	p
Fisher's exact test			0.162
N	84		

3. Individual-Specific Thermal Asymmetries in Limbs

Thermographic analyses revealed thermal asymmetries between contralateral limbs in nearly all elephants evaluated. Hotspots were observed across the four limbs assessed: right and left forelimb plus right and left hindlimb (Table 5). Elephant 4 showed asymmetry between both forelimbs, with a hotspot at the left one (Figure 12); Elephant 5 showed asymmetry between both forelimbs, with a hotspot at the right one (Figure 13); Elephant 10 showed asymmetry between both hindlimbs, with a hotspot at the left one (Figure 16); Elephant 13 showed asymmetry between both hindlimbs, with a hotspot at the right one (Figure 17);

Statistical analysis using the χ^2 test and Fisher's exact test indicated no significant differences in hotspot detection across the four limbs ($\chi^2 = 0.381$, $df = 3$, $p = 0.944$; Fisher's exact test, $p = 1.000$), suggesting that the thermographic system was equally capable of detecting hotspots in all limbs studied (Table 6).

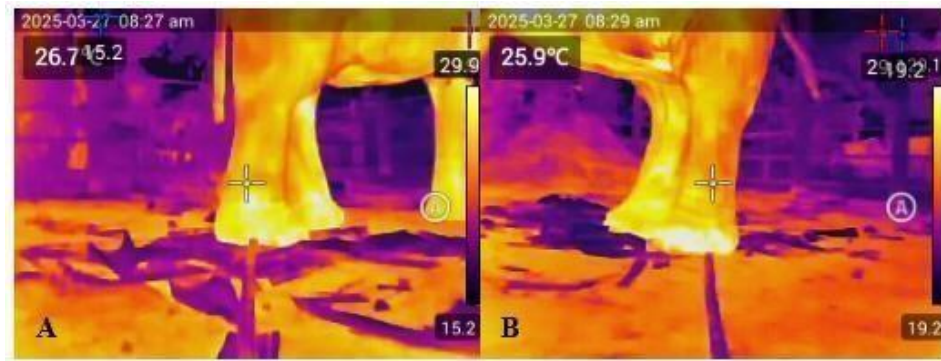


Figure 17. Thermal asymmetries in Elephant 13. (A) Increased temperature is visible in the tibio-tarsal joint of the right hindlimb, (B) compared to the contralateral side; both seen in a DL-PaM O projection (photo took by the author, with IRT).

Table 5. Presence (1) or absence (0) of hotspots across different limbs in all the studied elephants. Both hindlimbs presented the highest number of hotspots among all examined individuals. Elephants 9 and 14 showed hotspots in more than one limb, in contrast to the remaining elephants, which exhibited hotspots in only one limb or none.

	Right Forelimb	Left Forelimb	Right Hindlimb	Left Hindlimb
E1	0	0	0	0
E2	0	0	1	0
E3	0	1	0	0
E4	0	0	0	1
E5	1	0	0	0
E6	0	0	0	0
E7	0	0	0	1
E8	1	0	0	0
E9	1	0	1	1
E10	0	1	0	0
E11	0	0	0	1
E12	0	0	0	0
E13	0	0	1	0
E14	0	1	1	0

Table 6. Contingency Table - Statistical analysis using the χ^2 test and Fisher's exact test. Testing if the IRT camera is capable of detecting hotspots in different limbs. No significant differences were observed in hotspot detection between the forelimbs and hindlimbs ($\chi^2 = 0.381$, $df = 3$, $p = 0.944$; Fisher's exact test, $p = 1.000$), suggesting that the thermographic system was equally capable of identifying hotspots across all limbs studied. Although variations in hotspot presence were noted among individuals, the overall detection pattern was consistent between right and left limbs.

	Value	df	p
Fisher's exact test			1.000
N	56		

4. Multiple Projections to Hotspot Recognition

Variation in hotspot detection was noted depending on the projection used for thermographic assessment. The three projections analysed were: LM, DL-PaM O/ DL-PtM O, and PaL-DM O/PtL-DM O (Table 7).

For example, in Elephant 4, the left tibio-tarsal hotspot was most evident in the LM projection and less visible or absent in the oblique views (Figure 18). In Elephant 9, the right radiocarpal hotspot was only visible in the DL-PaM O projection (Figure 19), while the right knee hotspot was visible in all three projections (Figure 20).

Statistical analysis using the χ^2 test indicated no significant differences in hotspot detection between the projections ($\chi^2 = 3.08$, $df = 2$, $p = 0.215$), suggesting that the thermographic system was equally capable of detecting hotspots regardless of the projection used (Table 8).

Table 7. Presence (1) or absence (0) of hotspots across different projections (LM, DL-PaM O/ DL-PtM O, and PaL-DM O/PtL-DM O) in all the studied elephants. The table summarizes the distribution of thermal hotspots detected across the three projection types used for each joint assessment. Although hotspots were occasionally identified in all projections, in most cases they were only visible in one or two of them. This indicates that the use of multiple projection angles increases the sensitivity of hotspot detection and reduces the likelihood of false negatives.

	LM	DL-PaM O/ DL-PtM O	PaL-DM O/PtL-DM O
E1	0	0	0
E2	1	1	1
E3	1	1	0
E4	1	0	0
E5	1	0	1
E6	0	0	0
E7	1	1	0
E8	1	1	1
E9	0	1	0
E10	1	1	1
E11	1	1	0
E12	0	0	0
E13	0	1	0
E14	1	1	1



Figure 18. Elephant 4 – Hotspot at the left tibio-tarsal hotspot not visible in all three projections. (A) PtL-DM O projection without visible hotspot; (B) LM projection with visible hotspot; (C) DL-PtM O projection without visible hotspot (photos took by the author, with IRT).



Figure 19. Elephant 9 – Hotspot at right radiocarpal not visible in all three projections. (A) DL-PaM O projection with visible hotspot; (B) LM projection without visible hotspot; (C) PaL-DM O projection without visible hotspot (photo took by the author, with IRT).



Figure 20. Elephant 9 – Hotspot at right knee visible in all three projections. (A) DL-PaM O projection with visible hotspot; (B) LM projection with visible hotspot; (C) PaL-DM O projection with visible hotspot (photo took by the author, with IRT).

Table 8. Contingency Table - Statistical analysis using the χ^2 test and Fisher's exact test. Testing if the IRT camera is capable of detecting hotspots in different projections. No statistically significant differences were found between the three thermographic projections analysed (LM, DL-PaM O/DL-PtM O, and PaL-DM O/PtL-DM O) ($\chi^2 = 1.286$, $df = 2$, $p = 0.526$; Fisher's exact test, $p = 0.571$). These results indicate that the infrared thermography camera performed consistently across all projections, with similar efficiency in hotspot detection. However, certain hotspots were only visible in one or two projections, suggesting that the combined use of multiple projection angles increases diagnostic reliability.

	Value	df	p
χ^2	3.08	2	0.215
N	42		

5. Thermographic Differences Associated With Clinical Lameness

Two elephants exhibited clinical lameness. Elephant 2 showed lameness of the right hindlimb and a corresponding thermal hotspot at the all extent of the same limb (Figure 21). Elephant 14 displayed lameness of the right hindlimb and associated hotspots at the right tibio-tarsal joint and tibial region (Figure 22).

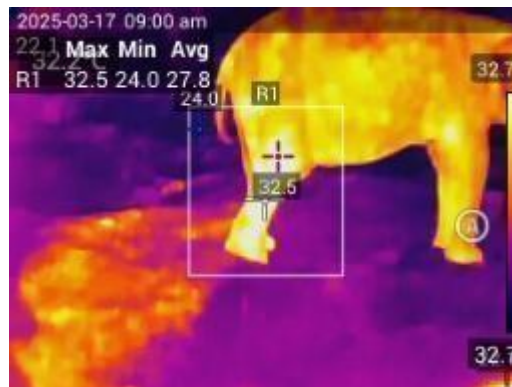


Figure 21. Elephant 2 – hotspot at the all extent of the right hindlimb, seen in a LM projection (photo took by the author, with IRT).



Figure 22. Elephant 14 – hotspot at the tibia region of the right hindlimb, seen in a DL-PtM O projection (photo took by the author, with IRT).

IV. Discussion

The primary objective of this study was to evaluate the feasibility of infrared thermography (IRT) as a diagnostic tool for the early detection of joint disease in Asian elephants (*Elephas maximus*). The working hypothesis proposed that IRT could identify inflammatory changes even in the absence of overt clinical signs. The findings presented in Tables 4, 6 and 8 confirmed this assumption, as hotspots were detected across different limbs, projections, and joints, without significant dependence on any of these variables. This indicates that the camera was capable of consistently identifying focal areas of hyperthermia under different imaging conditions.

Distinct thermal asymmetries were also documented across individuals, with focal hotspots corresponding to clinically affected joints in elephants presenting lameness (Figures 20 and 21), and subclinical hotspots detected in animals without evident gait abnormalities (Figures 11 to 19). In the two elephants exhibiting clinical lameness, thermography revealed localized areas of hyperthermia over the affected joints, consistent with inflammation. In contrast, elephants without overt lameness but presenting focal hotspots (excluding the nail regions) likely represent cases of subclinical inflammation.

These results reinforce the potential of IRT to identify musculoskeletal pathology at earlier stages (Varju, 2004), which is particularly relevant since elephants, as prey species, often mask signs of weakness. Moreover, in clinically lame individuals, hotspots were larger and involved multiple joints of the same limb, suggesting that IRT may also capture more extensive pathological involvement.

Several recurring thermal patterns were observed across the study population (Table 2). Increased temperatures were consistently noted in the ventral abdomen, the medial aspect of the limbs, and the ungual regions, similar to what was seen in a study made by Weissenböck, N., *et al* (2010). These widespread findings likely reflect “thermal windows”, anatomical regions with high vascularization and heat emission, rather than pathological changes (Tilley *et al.*, 2024; Hilsberg-Merz, 2008). By contrast, focal hotspots located asymmetrically in specific joints provided stronger evidence of inflammation. The presence of contralateral asymmetries reinforces the diagnostic potential of IRT, since thermal symmetry is considered a hallmark of healthy individuals and thermal asymmetry is a strong indicator of pathological processes, such as inflammation (Bhowmik *et al.*, 2016).

In this study, all elephants consistently displayed higher temperatures in the podal extremities, supporting the classification of this region as a reliable thermal window due to its rich vascularisation and constant exposure to mechanical load. The elevated and symmetrical heat emission observed in the phalangeal and digital pad areas is therefore interpreted as a physiological feature rather than evidence of pathology. Although podal disorders are highly prevalent in captive elephants and represent a major cause of morbidity (Luikart, K. A., & Stover, S. M., 2005), the present work deliberately excluded this region from the analysis of pathological hotspots. This decision was based on the difficulty of distinguishing, through thermography alone, between physiological heat associated with the thermal window and focal hyperthermia resulting from disease. Complementary diagnostic modalities such as radiography, ultrasonography, or microbiological testing would be required to accurately differentiate these conditions.

The use of multiple projections proved particularly valuable: some hotspots were only visible in specific angles (Figure 17 and 18). This methodological choice was based on the same diagnostic principle applied in radiography, where capturing multiple projections is essential to accurately localize lesions and avoid false negatives resulting from superimposed anatomical structures (Mumby *et al.*, 2013; Hittmair & Vielgrader, 2000). Similarly, applying this multi-angle approach in infrared thermography enhances the detection of subtle temperature variations and improves the precision of hotspot localization across complex joint regions, highlighting the importance of standardising multi-view imaging. These temperature variations may reflect focal involvement of joint subregions or, alternatively, artefacts caused by environmental factors such as dirt, mud, or solar radiation. Longitudinal assessment would be required to fully differentiate these scenarios.

Interestingly, although elephants bear approximately 60% of their body weight on the forelimbs and biomechanics suggest that the radiocarpal joint would be the most mechanically stressed, the tibio-tarsal joint emerged as the most commonly affected site (as shown in Table 3 and 4), in agreement with previous studies (Regnault *et al.*, 2017). This finding emphasises the complex interaction between biomechanics, substrates, and husbandry conditions in shaping the distribution of joint pathology.

In addition to qualitative evaluation, statistical tests were applied to assess whether the presence of hotspots was associated with specific limbs, projections, or joints. Pearson's chi-square test was used as it is appropriate for categorical data and allows testing of independence

between two variables. Fisher's exact test was applied whenever expected cell counts were below five, ensuring robust analysis despite the small sample size. In all cases, p-values exceeded the significance threshold of 0.05, indicating no statistical association between hotspot presence and any of the tested variables.

Given the demonstrated influence of age, sex, body weight, and behavioural activity on surface temperature (Lefebvre, Gray, Prosser & Chabot, 2023; Weissenböck, Weiss, Schwammer & Kratochvil, 2010), the present study prioritised the evaluation of thermal patterns rather than absolute temperature values. This approach minimises the confounding effects of inter-individual variability and enhances the capacity to identify focal hotspots that may indicate inflammation. By focusing on relative asymmetries and distributional changes in thermal emission, rather than precise numerical thresholds, the analysis becomes more robust to intrinsic and extrinsic factors that naturally modulate skin temperature in elephants. Such a strategy facilitates the detection of clinically relevant alterations while avoiding misinterpretation of normal physiological fluctuations. From a clinical perspective, this methodology also increases the practical utility of IRT, allowing veterinarians to employ it as a rapid screening tool without the need for individualised calibration of reference values, thereby streamlining its application in routine health monitoring.

These results suggest that IRT is capable of detecting hotspots independently of the imaging angle, anatomical site, or limb examined, supporting the consistency of the method. The lack of significant associations also reduces the risk of systematic bias linked to positioning or projection, which is critical for field applications in large animals where standardisation is often challenging. However, it should be noted that non-significant results do not necessarily prove equivalence; rather, they indicate that within the current sample size, no detectable dependency was observed. Larger datasets would be required to confirm these findings with higher statistical power.

The results align with previous work demonstrating the utility of IRT in detecting musculoskeletal disorders in elephants. Hilsberg-Merz (2008) described hotspots corresponding to inflamed joints in lame elephants, while Avni-Magen *et al.* (2017) reported high sensitivity in detecting pre-inflammatory lesions of the feet. The present findings reinforce these observations, particularly the potential for IRT to detect pathology in clinically sound individuals.

In other species, such as horses, thermographic asymmetries are widely used as indicators of lameness and joint inflammation (Ring & Ammer, 2012; Schiavon *et al.*, 2021). The parallels observed here suggest that diagnostic principles established in equine medicine can also be applied to elephants. Nonetheless, some discrepancies exist. For example, Tilley *et al.* (2024) found no significant thermographic changes in elephant forelimbs under different workloads, whereas this study identified localized hotspots in non-lame individuals. Such differences may result from methodological variations, environmental influences, or population-specific factors. Beyond elephants and horses, veterinary applications of IRT in bovines and canines have also demonstrated its value in detecting subclinical joint and hoof inflammation, supporting the broader applicability of thermography across taxa.

Stress-induced hyperthermia is a well-documented physiological response in mammals, characterised by a rapid rise in peripheral or core temperature associated with sympathetic activation (Oka, 2018; Stewart *et al.*, 2005). In wildlife, this response can occur even in the absence of physical exertion or pathology, potentially confounding the interpretation of thermographic data. Elephants, in particular, may exhibit stress-related thermal fluctuations due to handling, environmental changes, or the mere presence of observers. For this reason, minimising stress during image acquisition was a fundamental aspect of this study. Animals were not restrained, and only positive reinforcement was used to position them calmly, thereby reducing the likelihood of artefactual hyperthermia. Ensuring low-stress conditions is essential for obtaining reliable thermographic measurements and strengthens the validity of IRT as a diagnostic tool in wildlife species.

This study highlights the main advantages of IRT: it is non-invasive, safe, rapid, and particularly suitable for use in large and potentially dangerous species, when compared with other diagnostic tools. Elephants were imaged unrestrained, using only positive reinforcement, thereby minimising stress and maximising welfare. Importantly, the non-contact nature of IRT allows repeated monitoring without health risks or the need for chemical restraint, which is especially relevant in conservation and sanctuary settings.

Nevertheless, several limitations must be acknowledged. Thermography is sensitive to environmental variables, including ambient temperature, humidity, wind, and solar exposure, and artefacts caused by dirt or water on the skin may affect interpretation. The relatively small sample size limited statistical power, meaning that subtle associations may not have been detected. Variability between individuals, such as differences in skin thickness, pigmentation,

or behaviour during imaging, may also have influenced results. Furthermore, IRT images should not be interpreted in isolation, but in combination with clinical evaluation and complementary diagnostic methods. These constraints justify cautious interpretation of the findings.

The elephants in this study were housed under sanctuary conditions with high welfare standards, including natural substrates, large enclosures, and enrichment measures. Preventive husbandry strategies, such as joint supplementation and sand mounds to facilitate recumbency, were in place. Such interventions are crucial, as they mitigate the onset and progression of musculoskeletal disorders and highlight the importance of management practices in improving joint health.

The ability of IRT to detect both clinical and subclinical pathology supports its use as a screening tool for routine veterinary monitoring of captive elephants. Its non-contact nature reduces the need for sedation or prolonged handling, both of which are high-risk in this species. Early detection of inflammatory processes may enable timely interventions – ranging from husbandry adaptations to therapeutic supplementation – thereby improving longevity and welfare. From a conservation perspective, healthier captive elephants are more likely to contribute to breeding programs and ex situ conservation.

Future research should expand sample size, include controlled comparisons across sex and age groups, and evaluate elephants under different management conditions. Integrating IRT with radiography, ultrasonography, or gait analysis would enhance diagnostic accuracy. Longitudinal monitoring is particularly relevant to assess whether subclinical hotspots progress to overt disease, establishing the predictive value of IRT. Advances in imaging resolution and AI-assisted interpretation will likely further increase precision and reduce subjectivity. Moreover, developing standardised reference values for normal joint temperature in elephants could provide a benchmark for early detection and improve comparability between facilities.

This study represents one of the first applications of IRT specifically focused on Asian elephants' joints under sanctuary conditions. Despite limitations, the findings support the feasibility of this technique for early and non-invasive detection of musculoskeletal pathology. The work contributes novel insights into elephant health monitoring, with significant implications for veterinary medicine, welfare, and conservation.

V. Conclusion

This study demonstrated the feasibility of IRT as a non-invasive diagnostic tool for detecting joint disease in Asian elephants (*Elephas maximus*) under sanctuary conditions. The results revealed consistent thermal patterns across individuals, as well as focal asymmetries and hotspots associated with both clinical and subclinical joint pathology. These findings indicate that IRT is capable of identifying inflammatory changes at early stages, even in the absence of overt clinical signs, thus reinforcing its potential value for preventive health monitoring in wildlife.

The application of IRT in this context offers significant advantages. It is safe, rapid, and stress-free, enabling repeated assessments without the need for sedation or physical restraint – factors of particular importance in large and potentially dangerous species. The ability to detect subclinical inflammation has direct welfare implications, as it may facilitate earlier interventions through husbandry modifications, medical treatment or targeted management strategies. From a broader perspective, improved health and longevity of captive elephants also contribute to conservation programs and the sustainability of *ex situ* populations.

Nevertheless, the limitations of IRT must be acknowledged. Image interpretation can be influenced by environmental variables, skin characteristics, and individual behaviour during imaging. Moreover, the relatively small sample size in this study restricts statistical power and generalizability. For these reasons, thermography should not be interpreted in isolation but integrated with clinical evaluation and complementary diagnostic methods.

Future research should prioritize larger and more diverse populations, standardized reference values, and longitudinal monitoring to determine the predictive value of thermographic findings. Combining IRT with modalities such as radiography, ultrasonography, or gait analysis may further enhance diagnostic accuracy.

In conclusion, this work provides novel evidence supporting the integration of IRT into the routine veterinary assessment of Asian elephants. By enabling early and non-invasive detection of musculoskeletal pathology, IRT represents a valuable addition to the toolbox of wildlife veterinarians, with meaningful implications for animal welfare, clinical management, and conservation.

VI. References

- Ahn, Soo Min, et al. “The Value of Thermal Imaging for Knee Arthritis: A Single-Center Observational Study.” *Yonsei Medical Journal*, vol. 63, no. 2, 1 Feb. 2022, pp. 141–147, www.ncbi.nlm.nih.gov/pmc/articles/PMC8819413/, <https://doi.org/10.3349/ymj.2022.63.2.141>.
- Avni-Magen, N., Zaken, S., Kaufman, E., & Kelmer, G. (2017). Use of infrared thermography in early diagnosis of pathologies in Asian elephants (*Elephas maximus*). *Israel Journal of Veterinary Medicine*, 72, 22-27.
- Bansiddhi, P., Brown, J. L., & Thitaram, C. (2020). Welfare Assessment and Activities of Captive Elephants in Thailand. *Animals*, 10(6), 919. <https://doi.org/10.3390/ani10060919>
- Bhowmik, M. K., Shawli Bardhan, Das, K., Bhattacharjee, D., & Nath, S. (2016). Pain related inflammation analysis using infrared images. *Proceedings of SPIE, the International Society for Optical Engineering/Proceedings of SPIE*. <https://doi.org/10.1117/12.2223425>
- Calabrese, A., Calabrese, J. M., Songer, M., Wegmann, M., Hedges, S., Rose, R., & Leimgruber, P. (2017). Conservation status of Asian elephants: the influence of habitat and governance. *Biodiversity and Conservation*, 26(9), 2067–2081. <https://doi.org/10.1007/s10531-017-1345-5>
- Calin, M. A., Mologhianu, G., Savastu, R., Calin, M. R., & Brailescu, C. M. (2015). A review of the effectiveness of thermal infrared imaging in the diagnosis and monitoring of knee diseases. *Infrared Physics & Technology*, 69, 19–25. <https://doi.org/10.1016/j.infrared.2015.01.013>
- Casas-Alvarado, A., Mota-Rojas, D., Hernández-Ávalos, I., Mora-Medina, P., Olmos-Hernández, A., Verduzco-Mendoza, A., Reyes-Sotelo, B., & Martínez-Burnes, J. (2020). Advances in infrared thermography: Surgical aspects, vascular changes, and pain monitoring in veterinary medicine. *Journal of Thermal Biology*, 92, 102664. <https://doi.org/10.1016/j.jtherbio.2020.102664>
- Casas-Alvarado, A., Ogi, A., Villanueva-García, D., Martínez-Burnes, J., Hernández-Avalos, I., Olmos-Hernández, A., Mora-Medina, P., Domínguez-Oliva, A., & Mota-Rojas, D. (2024). Application of Infrared Thermography in the Rehabilitation of

- Patients in Veterinary Medicine. *Animals*, 14(5), 696–696.
<https://doi.org/10.3390/ani14050696>
- Cilulko, J., Janiszewski, P., Bogdaszewski, M., & Szczypińska, E. (2012). Infrared thermal imaging in studies of wild animals. *European Journal of Wildlife Research*, 59(1), 17–23. <https://doi.org/10.1007/s10344-012-0688-1>
 - Davies, Huw. “Medical Thermography.” Ebme.co.uk, 2025, www.ebme.co.uk/articles/clinical-engineering/medical-thermography
 - Eddy, A. L., Van Hoogmoed, L. M., & Snyder, J. R. (2001). The Role of Thermography in the Management of Equine Lameness. *The Veterinary Journal*, 162(3), 172–181. <https://doi.org/10.1053/tvjl.2001.0618>
 - Fowler, M. E., & Mikota, S. K. (2006). *Biology, medicine, and surgery of elephants*. Blackwell Publishing.
 - Fowler, M. E., Miller, R. E., Lamberski, N., & Calle, P. P. (2019). *Fowler’s zoo and wild animal medicine: current therapy*. Volume 9. Elsevier.
 - Genin, J. J., Willems, P. A., Cavagna, G. A., Lair, R., & Heglund, N. C. (2010). Biomechanics of locomotion in Asian elephants. *Journal of Experimental Biology*, 213(5), 694–706. <https://doi.org/10.1242/jeb.035436>
 - Hilsberg-Merz, Sabine. “Infrared Thermography in Zoo and Wild Animals.” *Zoo and Wild Animal Medicine*, 2008, pp. 20–cp1, <https://doi.org/10.1016/b978-141604047-7.50006-3>.
 - Hittmair, K. M., & Vielgrader, H. D. (2000). RADIOGRAPHIC DIAGNOSIS OF LAMENESS IN AFRICAN ELEPHANTS (*LOXODONTA AFRICANA*). *Veterinary Radiology Ultrasound*, 41(6), 511–515. <https://doi.org/10.1111/j.1740-8261.2000.tb01879.x>
 - Hutchinson, J. R. (2006). The locomotor kinematics of Asian and African elephants: changes with speed and size. *Journal of Experimental Biology*, 209(19), 3812–3827. <https://doi.org/10.1242/jeb.02443>
 - Kastberger, G., & Stachl, R. (2003). Infrared imaging technology and biological applications. *Behavior Research Methods, Instruments, & Computers*, 35(3), 429–439. <https://doi.org/10.3758/bf03195520>
 - Lefebvre, J., Gray, C., Prosser, T., & Chabot, A. (2023). Monitoring Thermoregulation Patterns in Asian Elephants (*Elephas maximus*) in Winter Months in Southwestern

- Ontario Using Infrared Thermography. *Journal of Zoological and Botanical Gardens*, 4(2), 312–324. <https://doi.org/10.3390/jzbg4020026>
- Luikart, K. A., & Stover, S. M. (2005). CHRONIC SOLE ULCERATIONS ASSOCIATED WITH DEGENERATIVE BONE DISEASE IN TWO ASIAN ELEPHANTS (*ELEPHAS MAXIMUS*). *Journal of Zoo and Wildlife Medicine*, 36(4), 684–688. <https://doi.org/10.1638/04088.1>
 - McCafferty, D. J. (2007). The value of infrared thermography for research on mammals: previous applications and future directions. *Mammal Review*, 37(3), 207–223. <https://doi.org/10.1111/j.1365-2907.2007.00111.x>
 - Menon, V., & Tiwari, S. KR. (2019). Population status of Asian elephants *Elephas maximus* and key threats. *International Zoo Yearbook*, 53(1), 17–30. <https://doi.org/10.1111/izy.12247>
 - Miller, C. E., Basu, C., Fritsch, G., Hildebrandt, T., & Hutchinson, J. R. (2007). Ontogenetic scaling of foot musculoskeletal anatomy in elephants. *Journal of the Royal Society Interface*, 5(21), 465–475. <https://doi.org/10.1098/rsif.2007.1220>
 - Mota-Rojas, D., Pereira, A. M. F., Martínez-Burnes, J., Domínguez-Oliva, A., Mora-Medina, P., Casas-Alvarado, A., Rios-Sandoval, J., de Mira Geraldo, A., & Wang, D. (2022). Thermal Imaging to Assess the Health Status in Wildlife Animals under Human Care: Limitations and Perspectives. *Animals*, 12(24), 3558. <https://doi.org/10.3390/ani12243558>
 - Mumby, C., Bouts, T., Sambrook, L., Danika, S., Rees, E., Parry, A., Rendle, M., Masters, N., & Weller, R. (2013). Validation of a new radiographic protocol for Asian elephant feet and description of their radiographic anatomy. *Veterinary Record*, 173(13), 318–318. <https://doi.org/10.1136/vr.101696>
 - Panagiotopoulou, Olga, et al. “Statistical Parametric Mapping of the Regional Distribution and Ontogenetic Scaling of Foot Pressures during Walking in Asian Elephants (*Elephas Maximus*).” *Journal of Experimental Biology*, vol. 215, no. 9, 1 May 2012, pp. 1584–1593, jeb.biologists.org/content/215/9/1584.long, <https://doi.org/10.1242/jeb.065862>.
 - Panagiotopoulou, O., Pataky, T. C., Hill, Z., & Hutchinson, J. R. (2012). Statistical parametric mapping of the regional distribution and ontogenetic scaling of foot pressures during walking in Asian elephants (*Elephas maximus*). *Journal of Experimental Biology*, 215(9), 1584–1593. <https://doi.org/10.1242/jeb.065862>

- Petneházy, Ö., Rück, S., Sós, E., & Reinitz, L. Z. (2023). 3D Reconstruction of the Blood Supply in an Elephant's Forefoot Using Fused CT and MRI Sequences. *Animals*, 13(11), 1789. <https://doi.org/10.3390/ani13111789>
- Purohit, Ram C, and Michael D McCoy. "Thermography in the Diagnosis of Inflammatory Processes in the Horse." *American Journal of Veterinary Research*, vol. 41, no. 8, 1 Aug. 1980, pp. 1167–1174, [avmajournals.avma.org/view/journals/ajvr/41/8/ajvr.1980.41.08.1167.xml](https://doi.org/10.2460/ajvr.1980.41.08.1167), <https://doi.org/10.2460/ajvr.1980.41.08.1167>.
- Regnault, S., Dixon, J. J. I., Warren-Smith, C., Hutchinson, J. R., & Weller, R. (2017). Skeletal pathology and variable anatomy in elephant feet assessed using computed tomography. *PeerJ*, 5, e2877. <https://doi.org/10.7717/peerj.2877>
- Ren, L., Butler, M., Miller, C., Paxton, H., Schwerda, D., Fischer, M. S., & Hutchinson, J. R. (2008). The movements of limb segments and joints during locomotion in African and Asian elephants. *Journal of Experimental Biology*, 211(17), 2735–2751. <https://doi.org/10.1242/jeb.018820>
- Ren, L., Miller, C. E., Lair, R., & Hutchinson, J. R. (2010). Integration of biomechanical compliance, leverage, and power in elephant limbs. *Proceedings of the National Academy of Sciences*, 107(15), 7078–7082. <https://doi.org/10.1073/pnas.0911396107>
- Ring, E. F. J. (2006). The historical development of thermometry and thermal imaging in medicine. *Journal of Medical Engineering & Technology*, 30(4), 192–198. <https://doi.org/10.1080/03091900600711332>
- Ring, E. F. J., & Ammer, K. (2012). Infrared thermal imaging in medicine. *Physiological Measurement*, 33(3), R33–R46. <https://doi.org/10.1088/0967-3334/33/3/r33>
- Saddiq, H. M. U., Ali, R. H., Amjad, M. T., Jaleel, S., Ali, S. M., Fatima, N., & Ullah, S. (2020). Post-Mortem Examination of a Female Elephant Suspected of Having Degenerative Joint Disease: A Case Report. *Advances in Animal and Veterinary Sciences*, 8(10). <https://doi.org/10.17582/journal.aavs/2020/8.10.1009.1012>
- Schiavon, G., Capone, G., Frize, M., Zaffagnini, S., Candrian, C., & Filardo, G. (2021). Infrared Thermography for the Evaluation of Inflammatory and Degenerative Joint Diseases: A Systematic Review. *CARTILAGE*, 13(2_suppl), 1790S1801S. <https://doi.org/10.1177/19476035211063862>
- Sirikaew, N., Chomdej, S., Tangyuenyong, S., Tangjitjaroen, W., Somgird, C., Thitaram, C., & Ongchai, S. (2019). Proinflammatory cytokines and lipopolysaccharides up

- regulate MMP-3 and MMP-13 production in Asian elephant (*Elephas maximus*) chondrocytes: attenuation by anti-arthritic agents. *BMC Veterinary Research*, 15(1). <https://doi.org/10.1186/s12917-019-2170-8>
- Sukumar, R. (2006). A brief review of the status, distribution and biology of wild Asian elephants *Elephas maximus*. *International Zoo Yearbook*, 40(1), 1–8. <https://doi.org/10.1111/j.1748-1090.2006.00001.x>
 - Tang, Y., Jia, T., Zhou, F., Wang, L., Chen, Z., & Zhang, L. (2024). Obesity Prevalence and Associated Factors in Captive Asian Elephants (*Elephas maximus*) in China: A Body Condition Assessment Study. *Animals*, 14(24), 3571–3571. <https://doi.org/10.3390/ani14243571>
 - Tattersall, G. J. (2016). Infrared thermography: A non-invasive window into thermal physiology. *Comparative Biochemistry and Physiology. Part A, Molecular & Integrative Physiology*, 202, 78–98. <https://doi.org/10.1016/j.cbpa.2016.02.022>
 - Tilley, H. B., Murphy, D., Kaja Wierucka, Tsz Ching Wong, Annaëlle Surreault-Châble, & Mumby, H. S. (2024). Physical activity and temperature changes of Asian elephants (*Elephas maximus*) participating in eco-tourism activities and elephant polo. *PLoS ONE*, 19(5), e0300373–e0300373. <https://doi.org/10.1371/journal.pone.0300373>
 - Varju, G. (2004). Assessment of hand osteoarthritis: correlation between thermographic and radiographic methods. *Rheumatology*, 43(7), 915–919. <https://doi.org/10.1093/rheumatology/keh204>
 - Weissenböck, N. M., Weiss, C. M., Schwammer, H. M., & Kratochvil, H. (2010). Thermal windows on the body surface of African elephants (*Loxodonta africana*) studied by infrared thermography. *Journal of Thermal Biology*, 35(4), 182–188. <https://doi.org/10.1016/j.jtherbio.2010.03.002>
 - Weissengruber, G. E., Fuss, F. K., Egger, G., Stanek, G., Hittmair, K. M., & Forstenpointner, G. (2006). The elephant knee joint: morphological and biomechanical considerations. *Journal of Anatomy*, 208(1), 59–72. <https://doi.org/10.1111/j.1469-7580.2006.00508.x>
 - Whittaker, A. L., Muns, R., Wang, D., Martínez-Burnes J., Hernández-Ávalos, I., Casas-Alvarado, A., Domínguez-Oliva, A., & Mota-Rojas, D. (2023). Assessment of Pain and Inflammation in Domestic Animals Using Infrared Thermography: A Narrative Review. *Animals*, 13(13), 2065–2065. <https://doi.org/10.3390/ani13132065>