

## **1. EXCELLENCE** (4 pages max)

### **1.1. Pre-proposal's context, positioning and objective(s)**

Forensic anthropology, a discipline at the intersection of the biological sciences and the judicial system, is facing a systemic methodological crisis that we refer to as the '**Paradox of Reference**'. The fundamental mission of identifying deceased individuals, which involves establishing the biological profile (sex, age, stature and ancestry) of unknown skeletal remains, relies on comparative standards derived from reference populations. However, the vast majority of the standards currently taught and used in court are based on historical osteological collections (e.g. the Hamann-Todd and Terry collections), which comprise individuals born in the 19th century.

These historical populations are biologically 'biased' compared to contemporary humans. Human morphology evolves rapidly over generations in response to environmental, nutritional and sanitary changes, and this trend has accelerated over the last few centuries. Consequently, applying 19<sup>th</sup> century metrics to 21<sup>st</sup> century forensic cases (e.g. modern crime victims or migrants in the Mediterranean) may introduce systematic bias and potentially lead to misidentifications and miscarriages of justice.

While Europe has established modern identified collections of skeletons, such as **CAL Milano** (Italy, n=2127)(Cattaneo et al. 2018), the **21st Century Collection of Coimbra** (Portugal, n=302)(Ferreira et al. 2021), or archaeological collections **UMR 7268 ADES** (France, n>10000), these physical reservoirs face a "**Data Scarcity Wall.**" Ethical, legal (GDPR), and logistical constraints make it extremely difficult to physically collect the "millions" of skeletons required to train robust Deep Learning algorithms.

This project, **SYNOS**, proposes a paradigm shift: resolving data scarcity not by collecting more bones, but by generating **synthetic, biologically valid data** to train the next generation of forensic AI.

### **Project Objectives and Research Hypotheses**

The primary objective of SYNOS is to develop **SCAFFOLD** (*Synthetic Creation and Augmentation Framework For Osteometric Learning Data*), a bio-informed generative AI architecture capable of creating infinite "virtual populations" to democratize Machine Learning (ML) in human identification.

#### **Research Hypotheses:**

1. **H1 (Bio-Fidelity):** Generative Adversarial Networks (GANs) constrained by biological laws of relative bone proportions (allometry) can generate synthetic skeletal data that is statistically indistinguishable from real data.
2. **H2 (Transferability):** Models trained on synthetic data will generalize to real-world forensic cases with equal or superior accuracy compared to models trained on small real datasets.
3. **H3 (Interpretability):** Integrating Explainable AI (XAI) will render "black box" algorithms transparent enough to meet the legal standards for admissibility of evidence (Daubert criteria).

#### **Specific Objectives (SO):**

- **SO1:** Map the allometric laws and covariance structures of the human skeleton across European populations (France, Italy, Portugal).
- **SO2:** Develop the **Progressive SCAFFOLD Engine**, a generative framework evolving from tabular data to 3D volumetric reconstruction.
- **SO3:** Validate the synthetic data with quantitative statistical metrics (Wasserstein distance) and possibly through a "Visual Turing Test" with forensic experts.
- **SO4: (conditional)** Implement an automated extraction pipeline from clinical CT scans to bridge the gap between dry bone osteometry and living populations.

## Position in Relation to the State of the Art

Current state-of-the-art methods in forensic anthropology are transitioning from manual osteometry to computational approaches, yet they remain limited by data availability.

- Recent studies, such as **Knecht et al.** (Knecht et al. 2023, 2025), have demonstrated that Machine Learning algorithms (e.g., LDA, SVM) significantly outperform traditional methods for sex estimation, achieving up to **95.2% accuracy** using long bone measurements. However, these models are often data-hungry and prone to overfitting when trained on small, specific cohorts.
- In medical imaging, Generative Models (GANs) have been used to synthesize realistic bone micro-architectures (Angermann et al. 2024). However, these applications often lack explicit biological constraints, risking the generation of anatomical "hallucinations."
- No current framework combines **bio-informed constraints** (allometry) with **generative deep learning** to create forensic reference standards. **SYNOS fills this gap by formalizing the "biological priors" that prevent the AI from generating biologically impossible skeletons.**

## Methodology

To mitigate the risks associated with high-dimensional data access (GDPR, technical bottlenecks), SYNOS adopts a "**Curriculum Learning**" methodology. The framework is designed as a "**Progressive SCAFFOLD**," increasing in complexity across three levels:

### Level 1: Tabular Synthesis (The Mathematical Skeleton)

- **Method:** We will train **Conditional Tabular GANs (ctdGAN)** on harmonized metric databases (ADES/Milan/Coimbra).
- **Innovation:** Unlike standard oversampling (e.g. SMOTE), ctdGAN captures the complex, non-linear correlations between variables. The loss function will be modified to include an "**Allometric Penalty**," punishing the generator if it produces biologically incoherent ratios (e.g., aberrant femur/tibia proportions).
- **Outcome:** Infinite tables of "virtual humans" (metric profiles) for training robust classifiers (e.g. SVM, Random Forest).

### Level 2: Geometric Synthesis (Landmarks & Contours)

- **Method:** We will employ **Graph Neural Networks (GNN)** to predict 3D landmark configurations from the metric profiles generated in Level 1.
- **Innovation:** Bones will be modeled as graphs where nodes represent anatomical landmarks. This allows for the analysis of *shape* without the heavy computational cost and privacy concerns of full CT scans. This approach bypasses the "GDPR bottleneck" of medical imaging while providing morphometric fidelity.

### Level 3: Volumetric Synthesis (The "Digital Twin") - (conditional)

- **Method:** Utilizing **3D-StyleGAN** architectures (adapted from Angermann et al. 2024), we will generate full volumetric data (pseudo-CT scans) conditioned on the biological profiles from Levels 1 and 2.
- **Innovation:** Implementation of **GAN Inversion** to project real forensic cases into the latent space, allowing for "counterfactual" analysis (e.g., "*What would a femur corresponding to this tibia would look like?*").

## Validation Strategy:

- **Quantitative:** Comparison of distribution manifolds (Real vs. Synthetic) using Maximum Mean Discrepancy (MMD) and Fréchet Inception Distance (FID).
- **Forensic Validation:** Training sex estimation models on synthetic data and testing them on real, independent forensic cases (CAL Milano test set for instance) to verify predictive accuracy.

### Originality and Innovative Aspects

- **Hybrid "Bio-Informed" AI:** SYNOS rejects the "black box" approach. By embedding allometric laws into the neural network's loss function, we ensure that the AI "incorporates biological considerations" rather than "just mimicking" pixel patterns.
- **Privacy-Preserving Forensic Science:** The **SYNOS-Multi-Level** database will be fully synthetic. It generates data *derived* from real populations but containing no personally identifiable information. This resolves the ethical dilemma of data sharing in forensic science, enabling Open Science without compromising privacy.
- **Explainability (XAI):** The project integrates **SHAP (SHapley Additive exPlanations)** values into its predictive models. This ensures that every identification decision (e.g., "Male, 98% probability") is accompanied by a feature-importance breakdown (e.g., "...driven by femoral head diameter"), satisfying the transparency requirements of the **Daubert criteria** (Christensen et Crowder 2009) for admissibility in court.

### Added Value in Terms of Scientific Contribution

- **Knowledge Production:** The project will produce the first **universal synthetic reference database** for forensic anthropology, correcting the historical biases of "classical" collections (Terry, Hamann-Todd).
- **Methodological Contribution:** The "Progressive SCAFFOLD" framework integrates the concept of **risk-managed AI research**, by decoupling scientific progress from data access limitations through iterative complexity.
- **Societal Impact:** By providing robust, unbiased tools for identification, SYNOS directly contributes to solving humanitarian crises (migrant identification) and improving the efficiency of the justice system.

### Gender Dimension in Research Content

The gender dimension is intrinsic to the scientific content of SYNOS, as **biological sex estimation** is the primary variable of the biological profile. The project addresses this dimension at two different levels:

1. **Balanced Data Training:** Historical collections often suffer from sex imbalance (e.g., more males in forensic constituted collections). SYNOS uses ctdGAN to **synthetically rebalance** the training datasets, ensuring that the resulting AI models perform with equal accuracy for male and female remains. This directly mitigates algorithmic bias against women in forensic identification.
2. **Sex-Disaggregated Analysis:** All validation steps (accuracy, sensitivity, specificity) will be reported separately for males and females to ensure no disparity in identification reliability exists, aligning with the highest standards of scientific quality.

### 1.2. Interdisciplinary and intersectoral dimension of the project

The SYNOS project addresses a complex challenge, the "Paradox of Reference" in forensic anthropology, that no single discipline or laboratory could solve in isolation. The consortium brings together a unique ecosystem of experts whose specific competencies are mandatory for the successful development of the **SCAFFOLD** framework.

- **UMR 7268 ADES (Main Supervisor):** As the only laboratory in France hosting a dedicated osteological research collection (Ostéothèque), ADES provides the "**Physical Pillar**" of the project. Our expertise in biological anthropology, osteometry, and forensic taphonomy is essential for defining the biological "ground truth" and validating the synthetic skeletons.
- **LIS UMR 7020 (Co-Supervisor):** Representing the "**Digital Pillar**," the Laboratoire d'Informatique et Systèmes (LIS), supported by the **Institut Laënnec** (Digital Science & AI for Health), will be mobilized via its development cell to help structure the data and will grant access to the LIS calculation servers. The LIS brings the necessary high-level expertise in Generative AI, Deep Learning, and Computer Vision. Their role is to translate biological constraints into mathematical loss functions for the GANs, a task requiring advanced algorithmic skills unavailable in standard anthropology departments.

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These two main partners will have the opportunity to rely on two international partners providing the "**Diversity and Validation Pillar.**" **LABANOF (Milan, Italy)** hosts a collection of 2127 modern skeletons, some of which are associated with full medical histories. The **21st Century Collection of the University of Coimbra (Portugal)** is a collection of 302 modern individuals which is unique for its documentation of modern surgical implants and experimental burning. These specificities are required to validate the model's robustness in "hard-to-identify" forensic scenarios and to test the model's ability to handle pathological variations.

### Interdisciplinary Methodological Approach

The project employs a radical Interdisciplinarity, fusing Biological Anthropology and Data Science not just at the application level, but at the conceptual level.

- Unlike standard "black box" approaches where an AI blindly learns from raw data or images, our methodology directly embeds anthropological knowledge (allometric scaling laws, sexual dimorphism ratios). The "Progressive SCAFFOLD" methodology requires the doctoral fellow to constantly translate **osteological rules** (e.g., the correlation between femur length and humeral head diameter) into **algorithmic constraints** (e.g., specific penalty terms in the GAN's loss function).
- The methodology mirrors the learning process of an anthropology student: starting with simple metrics (Tabular Data), moving to shapes (Landmarks/GNNs), and finally mastering complex forms (Volumetric/3D-StyleGAN). This requires continuous feedback loops where the "biological validity" of the AI's output is assessed not just by mathematical metrics but by a "Visual Turing Test" performed by forensic anthropologists which could evaluate the "plausibility" of the existence of the evaluated bone image.

### Hosting Arrangements

The doctoral fellow will be based at the Medical Campus of La Timone (Marseille). He or she will have a workspace at UMR ADES, to access the osteological collections and immerse themselves in the forensic context. There will be frequent exchanges with the LIS/Institut Laënnec facilities to work on code development and benefit from the computational resources. We will clearly rely on the Regional Datacenter and the Regional Mesocenter for data storage and HPC calculation.

A weekly "Synergy Meeting" will bring together the main supervisor (Pr. Adalian) and the co-supervisor (Dr. Roman) to ensure the convergence of biological and computational objectives. Finally, concerning mobility, the fellow will organize their time to include two significant secondments: a 3-month stay at LABANOF (Milan, Italy) and a 3-month stay at Coimbra (Portugal) to validate allometric rules and models performance.

### Intersectoral Dimension

The intersectoral dimension is anchored by a strategic partnership with a key non-academic actor in the health sector: the **Assistance Publique - Hôpitaux de Marseille (AP-HM)**. The AP-HM is a clinical institution, distinct from the academic research labs. It will provide access to the **Health Data Warehouse (EDS)**, a massive repository of clinical CT scans from living patients. This partnership is essential for **Objective 4 (OS4)**, allowing the project to bridge the gap between "dry bone" forensic anthropology and "living" radiology. It enables the validation of synthetic models against contemporary, living population data, ensuring the tools are applicable in real-time forensic scenarios (e.g., identification of recent disaster victims).

Working with the AP-HM will train the fellow in the handling of sensitive clinical data, strict GDPR compliance, and hospital information systems (PACS/DICOM standards). This experience opens career paths beyond academia, specifically in the booming **MedTech, Forensic Tech** industries, and **Clinical Data Science**.

## 2. IMPACT (2 pages max)

### 2.1. Expected impact of the project on the candidate's career

The current job market in both academia and the "Forensic Tech" industry is characterized by a skills gap: biological anthropologists rarely possess advanced coding skills, while data scientists often lack the anatomical knowledge required to interpret biological data correctly. The SYNOS project is designed to bridge this gap. By the end of the fellowship, the candidate will have transitioned from a mono-disciplinary researcher to a **dual-expert profile** mastering:

- **Advanced Data Science:** Training in Generative Adversarial Networks (GANs), Graph Neural Networks (GNN), and Python-based frameworks (PyTorch/TensorFlow) under the supervision of LIS/Institut Laënnec.
- **Forensic Anthropology:** Advanced osteometry and taphonomy in a medico-legal context under the supervision of ADES and the internships in LABANOF (Milan, Italy) and Coimbra (Portugal).

Beyond technical expertise, the fellow will acquire new competences and critical transferable skills ensuring long-term employability:

- **Data Governance and Ethics:** Through the management of sensitive data (human remains, CT scans from AP-HM), the fellow will become an expert in GDPR compliance, bioethics, and the ethical auditing of AI algorithms (bias mitigation), skills highly valued by European institutions.
- **Agile Project Management:** Implementing the "Progressive SCAFFOLD" framework will train the fellow in iterative risk management and agile research methodologies.
- **International Leadership:** The mobility scheme (Milan, Coimbra) will integrate the fellow into the premier European forensic network (Forensic Anthropology Society of Europe - FASE), fostering the capability to integrate international consortia.

This unique skill set will open diverse career paths:

- **Academia:** Fostering the "Digital Turn" in anthropology departments or medical schools.
- **Industry:** Positions in the booming **Forensic Tech** sector (e.g., companies developing virtual autopsy software) or **MedTech** (medical imaging analysis), where the ability to interpret 3D biological data is crucial.
- **International Organizations:** Expert roles in organizations handling mass fatality incidents (e.g., ICRC, ICMP) that are increasingly digitizing their identification workflows.

### 2.2. Expected impact for the thematic axis

**Addressing SCHADOC's "Artificial Intelligence and its Applications" Axis:** The project directly addresses the core challenge of this axis: the application of AI to complex, real-world biological problems. SYNOS moves beyond standard "Black Box" AI by implementing **Explainable AI (XAI)** and **Biology-Informed Neural Networks** (embedding allometry into GANs). It demonstrates how AI can be trustworthy and transparent in high-stakes decision-making environments.

**Scientific Contribution: Solving the "Data Scarcity" Crisis:** The primary scientific impact of SYNOS is overcoming the "Data Scarcity Wall." By validating the use of synthetic data for training forensic algorithms, the project offers a scalable solution to the lack of diverse, documented skeletal collections.

- **Knowledge Production:** The project will produce **laws of generative osteometry**, defining how biological variability can be mathematically modeled and synthesized without losing anatomical fidelity.
- **Standardization:** The **SCAFFOLD framework** will provide the community with a standardized protocol for generating reference populations, harmonizing forensic practices across Europe.

#### Societal Impact:

- **Justice and Legal Admissibility:** By integrating SHAP (SHapley Additive exPlanations) values, SYNOS ensures that AI-driven identifications are transparent. This aligns forensic evidence with the **Daubert criteria**, strengthening the reliability of criminal justice systems and reducing the risk of wrongful convictions based on "opaque" science.
- **Human Rights and Migration:** Current forensic methods are often biased towards historical European populations. By generating synthetic data that covers a wider range of human variability, SYNOS enables the creation of **universal identification models**. This is crucial for the dignified identification of migrants and victims of mass disasters who do not fit traditional demographic profiles.

### 2.3. Dissemination, exploitation and communication activities planned

#### Dissemination to Peers (Scientific Community):

- **Open Science:** The project will adhere to FAIR principles. The core deliverable, the "**SYNOS Model**" (pre-trained generative models and anonymized synthetic datasets), will be hosted on public repositories (e.g., Hugging Face, Zenodo) under an MIT license, allowing global researchers to generate their own reference populations.
- **Publications:** Results will be published in high-impact interdisciplinary journals (e.g., *Nature Machine Intelligence*) and specialized forensic journals (*Forensic Science International*, *International Journal of Legal Medicine*).
- **Conferences:** Presentation of results at key annual meetings: AAFS (American Academy of Forensic Sciences) and FASE (Forensic Anthropology Society of Europe).

#### Exploitation (Industry & Stakeholders):

- **Non-Academic Partnership:** The algorithms developed for automatic measurement extraction from CT scans (OS4) will be tested within the **AP-HM Health Data Warehouse**. This serves as a proof-of-concept for clinical deployment, potentially leading to software patents for virtual autopsy or orthopedic planning.

#### Communication and Public Engagement (Outreach):

- **"AI for Forensics" Summer School:** Organized in Marseille at the end of the project (M36), this event will train PhD students from the CIVIS alliance, ensuring the legacy of the SYNOS methodology.

### **3. IMPLEMENTATION (2 pages max)**

#### **3.1. Work plan**

##### **Overall Strategy: The "Progressive SCAFFOLD" Approach**

The work plan is designed around a "**Curriculum Learning**" strategy, which ensures the project's feasibility within the 36-month timeframe. Rather than attempting immediate, high-risk 3D volumetric generation, the project progresses through three levels of increasing complexity: (1) **Tabular** (metric profiles), (2) **Geometric** (landmarks/shapes), and (3) **Volumetric** (CT scans). This staged approach decouples the PhD's success from potential data access bottlenecks (e.g., GDPR delays for hospital images), as Levels 1 and 2 rely on osteological data already secured by the partners. May it stop at level 2, the research would already be absolutely innovative, and for the *conditional* level 3, a "Plan B" in case of difficulties to access AP-HM CT-Scans is already prepared: the use of the "The New Mexico Decedent Image Database" (<https://nmdid.unm.edu/>)

##### **Work Packages (WP) and Task Interactions**

The project is structured into four interconnected Work Packages. Interaction between WPs is ensured by the **dual-hosting arrangement** at the La Timone Medical Campus (Marseille), where the fellow will alternate between the biological lab (ADES) and the data science lab (LIS/Institut Laënnec).

- **WP1: Foundations & Biological Priors (M1–M9)**
  - *Objective:* Establish the "Ground Truth" and mathematical constraints.
  - *Tasks:* T1.1 Data Harmonization: Merging metric databases from ADES, Milan, and Coimbra. T1.2 Imputation to handle missing values. T1.3 Allometric Modeling: Computing covariance matrices to define the "Biological Priors" (loss functions) for the AI.
  - *Resources:* Access to ADES Osteotheque; High-Performance Computing (HPC) Mesocentre for statistical modeling.
- **WP2: The SCAFFOLD Generative Engine (M10–M24)**
  - *Objective:* Develop the core AI architecture.
  - *Tasks:* T2.1 **Level 1 (Tabular):** Training Conditional Tabular GANs (ctdGAN) to generate valid metric profiles. T2.2 **Level 2 (Geometric):** Implementing Graph Neural Networks (GNN) to predict 3D landmark configurations from the metric profiles. T2.3 **Level 3 (volumetric):** Developing a 3D-StyleGAN to generate pseudo-CTs, conditioned on the previous levels.
  - *Interaction:* The output of Level 1 serves as the conditional input for Level 2, ensuring biological consistency across scales. Level 3 is conditional, depending on the advances of level 1 and 2 and CT-Scans access.
- **WP3: Validation & Intersectoral Transfer (M19–M30)**
  - *Objective:* Validate models in real-world forensic and clinical scenarios.
  - *Tasks:* T3.1 **Clinical Pipeline:** Deploying automated measurement extraction algorithms on the AP-HM Health Data Warehouse (intersectoral partner) to validate models on living populations / or use the NMDID CT-Scans. T3.2 **XAI Audit:** Using SHAP values to verify the "legal explainability" of the AI's decisions.
- **WP4: Dissemination & Thesis (M31–M36)**
  - *Objective:* Knowledge transfer and graduation.
  - *Tasks:* Thesis writing, organizing the "AI for Forensics" Summer School, and publishing the "SYNOS Model" (Open Science).

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**Feasibility of Secondments and Training**

The 36-month schedule integrates mandatory secondments during the Validation Phase (WP3), ensuring the fellow applies developed tools to diverse datasets:

- **Secondment 1 (M18–M20) at LABANOF (Milan, Italy):** The fellow will test the SCAFFOLD models against the CAL Milano collection’s data, specifically to validate the AI’s performance on pathological bone profiles (which are rare in standard training sets).
- **Secondment 2 (M28–M30) at University of Coimbra (Portugal):** Focus on validating the models on "hard-to-identify" cases.

**Management Structure and Procedures**

- **Supervision:** A weekly meeting will be held (either in-person or through videoconference), bringing together the main supervisor (Anthropology), the co-supervisor (Data Science), and the fellow to resolve interdisciplinary friction points (e.g., translating anatomical concepts into code).
- **Monitoring:** A **Thesis Steering Committee (TSC)** including representatives from Milan and Coimbra will meet every 6 months to validate milestones.
- **Data Management:** A Data Management Plan (DMP) will be established at M1 and updated every 6 months to ensure GDPR compliance.

**Risk Management**

The project's feasibility is secured by a robust risk mitigation strategy:

Risk	Impact	Likelihood	Mitigation Strategy (Contingency)
<b>R1: Delayed access to Hospital CT Data (AP-HM)</b>	High	Medium	<p><b>"Progressive SCAFFOLD" Strategy:</b> The thesis is designed to be viable even without immediate CT access. WP2 Levels 1 &amp; 2 (Tabular/Geometric) rely on <i>dry bone</i> data already in possession of the partners. Level 3 (CT) is an "added value" layer, not a blockage point.</p> <p>Moreover, the use of the “The New Mexico Decedent Image Database” could serve as a plan B. this open access repository provides researchers with access to whole human body computed tomography (CT) scans and a rich body of associated metadata. <a href="https://nmdid.unm.edu/">https://nmdid.unm.edu/</a></p>
<b>R2: "Mode Collapse" (AI generates repetitive samples)</b>	Medium	Medium	Use of stabilized architectures ( <b>WGAN-GP, ADA</b> ) and supervision by LIS / Laënnec experts. The biological "priors" (WP1) act as constraints to force diversity.

#### 4. REFERENCES

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#### ETHICS SELF-ASSESSMENT

**"Does the research project involve the development, deployment and/or use of Artificial Intelligence-based systems?":**

**Yes.** The SYNOS project fundamentally relies on the development, deployment, and use of advanced Artificial Intelligence systems to address the issue of data scarcity in forensic anthropology.

To ensure ethical compliance and trustworthiness, the project implements specific procedures addressing transparency, robustness, bias mitigation, and human oversight, as detailed below:

##### 1. Transparency and Information (Explainability)

- **Rejection of the "Black Box" Approach:** The project explicitly rejects opaque AI models. Instead, it adopts a **"bio-informed" methodology** where anthropological knowledge (allometric scaling laws, sexual dimorphism ratios) is directly translated into algorithmic constraints.
- **Logic of Decision Making:** To satisfy the requirements of transparency and explainability (crucial for legal admissibility under **Daubert criteria**), the AI system integrates **SHAP (SHapley Additive exPlanations)** values. Every identification decision (e.g., "Male, 98% probability") will be accompanied by a detailed analysis of feature importance (e.g., "...driven by femoral head diameter"), accessible to the user via a clear interface.
- **User Information:** A specific notice will be designed to clearly indicate that the device relies on an AI system, explicitly stating the associated margins of error to prevent over-reliance compared to deterministic tools.

## 2. Technical Robustness and Safety

- **Stabilized Architectures:** To prevent technical failures such as "mode collapse" (where the AI generates repetitive or limited variations), the project employs stabilized architectures like **WGAN-GP** (Wasserstein GAN with Gradient Penalty) and **ADA** (Adaptive Discriminator Augmentation).
- **Progressive Framework:** The "**Progressive SCAFFOLD**" strategy mitigates development risks by evolving from simple tabular data to complex 3D volumetry, ensuring the system remains viable even if access to high-dimensional clinical data is delayed.
- **Validation Strategy:** Robustness is tested through a "**Visual Turing Test**" where forensic anthropologists evaluate the biological plausibility of the synthetic outputs, ensuring the AI does not produce anatomical "hallucinations."

## 3. Bias Mitigation and Fairness

- **Correction of Historical Bias:** Standard forensic collections are often biased towards historical European populations. SYNOS aims to produce the first **universal synthetic reference database**, correcting these biases to allow for the dignified identification of under-represented groups (e.g., migrants, victims of mass disasters).
- **Algorithmic De-biasing:** The project utilizes **ctdGAN** (Conditional Tabular GAN) to synthetically rebalance training datasets. This ensures that the resulting models perform with equal accuracy across different groups (e.g., male/female), mitigating algorithmic bias.
- **Sex-Disaggregated Analysis:** All validation steps (accuracy, sensitivity, specificity) will be reported separately for males and females to guarantee no disparity in identification reliability exists.

## 4. Privacy and Data Governance

- **Privacy-Preserving AI:** The core output, the **SYNOS-Multi-Level database**, is fully synthetic. While derived from real population statistics, it contains **no Personally Identifiable Information (PII)**. This resolves the ethical dilemma of data sharing in forensic science.
- **GDPR Compliance:** For the clinical validation phase involving real patient data from the **AP-HM Health Data Warehouse**, strict pseudonymization protocols are applied at the source. No transfer of European databases between sites is required.
- **Data Minimization:** The use of **Graph Neural Networks (GNN)** to model bones as landmarks rather than full volumetric scans minimizes the need for processing heavy, sensitive medical images.

## 5. Human Agency and Oversight

- **Human-in-the-loop:** The AI system is designed to support, not replace, the forensic expert. The final decision remains with the human operator.
- **Expert Supervision:** The creation of the synthetic database is supervised by a dual committee of data scientists (LIS/Laennec) and forensic anthropologists (ADES/LABANOF/Coimbra) to ensure continuous quality control and ethical adherence.

**Could the AI based system/technique potentially stigmatise or discriminate against people (e.g. based on sex, race, ethnic or social origin, age, genetic features, disability, sexual orientation, language, religion or belief, membership to a political group, or membership to a national minority)?**

**YES.** The project explicitly acknowledges the risk that AI systems can perpetuate or amplify existing biases, particularly in forensic anthropology where historical reference collections often suffer from demographic imbalances (e.g., overrepresentation of males or specific ancestries). To prevent stigmatization and discrimination, the SYNOS project has integrated specific mitigation procedures into its design and methodology:

### 1. Correction of Historical and Demographic Biases

- **Universal Reference Database:** The project aims to produce the first "**universal**" **synthetic reference database**, specifically designed to correct the biases inherent in "classical" historical collections (such as the Terry or Hamann-Todd collections).
- **Protection of Vulnerable Groups:** By generating more diverse synthetic data, the project aims to enable the dignified identification of individuals who do not fit traditional demographic profiles, such as **migrants** and victims of mass disasters, thereby directly reducing the risk of exclusion or misidentification for these populations.

### 2. Algorithmic Rebalancing (Fairness by Design)

- **Synthetic Rebalancing:** The project utilizes the **ctdGAN** (Conditional Tabular GAN) architecture to synthetically rebalance training datasets. This technical measure ensures that under-represented classes are augmented, guaranteeing that the resulting AI models perform with equal accuracy for **male and female remains**, as well as across different ancestral groups.
- **Mitigation of Gender Bias:** This approach directly mitigates algorithmic biases that have historically been unfavorable to women in forensic identification methods.

### 3. Rigorous Validation Protocols

- **Sex-Disaggregated Analysis:** To ensure no disparity in identification reliability exists, all validation metrics (accuracy, sensitivity, specificity) will be reported **separately for males and females**. This adheres to the highest standards of scientific quality described in the "**Gendered Innovations**" framework.
- **Detection of Under-representation:** Regular audits of the databases will be conducted to identify under-represented subgroups. The project commits to adopting measures to detect and bridge these gaps throughout the AI lifecycle.

### 4. Contextual Relevance and Diversity

- **European Context:** The datasets used are specifically curated to correspond to the **European context** of use, mapping allometric laws across diverse populations (France, Italy, Portugal).
- **Pathological Diversity:** The inclusion of international partners (LABANOF in Milan and the University of Coimbra) ensures the model is robust against pathological variations and modern medical interventions (e.g., implants), preventing discrimination against individuals with disabilities or specific medical histories.

### 5. Interdisciplinary Oversight

- **Inclusion:** The interdisciplinary and intersectoral dimension of the project is leveraged to design a system usable by different types of end-users with varied capabilities, ensuring that the technology benefits society broadly without enforcing unfair biases.

**Does the AI system/technique interact, replace or influence human decision-making processes (e.g. issues affecting human life, health, well-being or human rights, or economic, social or political decisions)?**

**YES.** The AI systems developed within the SYNOS project (SCAFFOLD framework) are specifically designed to interact with and influence human decision-making processes in the critical context of forensic identification. These decisions have profound implications for human rights, the administration of justice, and the closure sought by families of missing persons.

However, the project is strictly designed to **support** rather than **replace** human expertise. To ensure the system influences decisions positively while preserving human autonomy, the following specific procedural and technical safeguards are implemented:

**1. Preservation of Human Autonomy (Human-in-the-Loop)**

- **Decision Support Tool:** The AI system is conceptualized as an assistive tool for the forensic anthropologist, who remains the final decision-maker. The algorithm provides a probability and a suggested profile, but the expert validates the conclusion based on their professional judgment and context.
- **Visual Turing Test Validation:** The development process incorporates a "Visual Turing Test" where certified forensic anthropologists assess the biological plausibility of the AI-generated skeletons. This ensures that the AI's output is continuously validated by human expertise, creating a feedback loop that keeps the "biological reality" at the center of the process.

**2. Transparency and Explainability (Meeting Legal Standards)**

- **Auditability via XAI:** To prevent "blind trust" in the system, the project integrates **Explainable AI (XAI)** techniques. Specifically, it uses **SHAP (SHapley Additive exPlanations)** values to decompose every prediction (e.g., "Male, 98% probability").
- **Daubert Compliance:** By displaying exactly which features (e.g., femoral head diameter) drove the AI's decision, the system meets the **Daubert criteria** for admissibility in court. This transparency allows the expert to defend the scientific basis of the identification in a legal setting, ensuring the AI's influence is verifiable and contestable.

**3. Bio-Informed Design vs. "Black Box" Risks**

- **Algorithmic Constraints:** Unlike standard "black box" models that learn patterns opaquely, the **Progressive SCAFFOLD** methodology explicitly embeds anthropological knowledge (allometric scaling laws, sexual dimorphism ratios) into the neural networks. This ensures the AI reasons within the bounds of known biological laws, aligning its logic with human expert reasoning.

**4. Prevention of Automation Bias**

- **Clear Communication of Uncertainty:** The system interface will be designed to clearly display **confidence intervals** and margins of error for every estimation, reminding the user that the output is probabilistic, not deterministic.
- **User Training:** Deployment protocols will include mandatory training for forensic practitioners. This training will focus on the system's limitations and the risks of "automation bias" (the tendency to favor machine suggestions over contradictory human evidence), ensuring experts use the tool critically.

## 5. Documentation and Traceability

- **Performance Indicators:** A detailed information notice will accompany the software, specifying the datasets used for training (and their demographic limitations) and the performance metrics (sensitivity/specificity) achieved during validation.
- **Synthetic Data Marking:** All data generated by the system for research or augmentation purposes will be clearly flagged as AI-generated to prevent confusion with real biological records.

**Does the AI system/technique have the potential to lead to negative social (e.g. on democracy, media, labour market, freedoms, educational choices, mass surveillance) and/or environmental impacts either through intended applications or plausible alternative uses**

**Yes.** The AI systems developed in this project operate within the high-stakes domain of forensic human identification, which inherently carries significant social implications regarding justice, fundamental rights, and the treatment of vulnerable populations.

However, the project is explicitly designed to **mitigate existing negative social impacts** found in current forensic practices and to ensure the AI serves as a tool for positive societal transformation. The following arguments detail how these dimensions are addressed:

### 1. Strengthening Democratic Processes and Justice

- **Reliability of Criminal Justice:** The project aims to reduce the risk of wrongful convictions and judicial errors that result from opaque scientific data. By integrating **SHAP (SHapley Additive exPlanations)** values, the SYNOS system guarantees the transparency of AI-based identifications.
- **Alignment with Legal Standards:** This transparency aligns forensic evidence with the **Daubert criteria**, ensuring that AI tools support, rather than undermine, the fairness and accountability of the legal system.

### 2. Addressing Global Challenges and Humanitarian Crises

- **Migrant Identification:** Current forensic methods are often biased towards historical European populations, leading to the potential misidentification or exclusion of individuals from other ancestries. SYNOS contributes directly to resolving **humanitarian crises** by providing robust, impartial tools capable of identifying migrants and victims of mass disasters who do not fit traditional demographic profiles.
- **Dignity and Equality:** By generating synthetic data that covers a wider range of human variability, the project enables the creation of **universal identification models**, ensuring that all individuals, regardless of origin, are treated with equal dignity in death.

### 3. Promoting Open Science and Democratization

- **Fair Access:** To prevent the concentration of advanced forensic capabilities solely in well-funded institutions, the project adheres to **FAIR principles**. The core deliverable, the **"SYNOS Model Zoo"** (pre-trained generative models and anonymized synthetic datasets), will be hosted on public platforms (e.g., Hugging Face, Zenodo) under an **MIT license**. This allows researchers worldwide to generate their own reference populations, democratizing access to high-quality forensic standards.

### 4. Environmental Considerations (Implicit)

- **Data Efficiency:** While not the primary focus, the move towards *synthetic* data generation (via SCAFFOLD) reduces the need for the continuous, resource-intensive physical excavation, transport, and CT-scanning of biological remains, offering a more sustainable model for expanding forensic databases.