

**PROGRAMME INSTITUTS ET
INITIATIVES**

Appel à projet – campagne 2021

Proposition de projet de recherche doctoral (PRD)

IBEES - Initiative Biodiversite Evol Ecolo Société

Intitulé du projet de recherche doctoral (PRD): Modeling of the elephants' trunk: From evolution to soft robotics

Directrice ou directeur de thèse porteuse ou porteur du projet (titulaire d'une HDR) :

NOM : Pouydebat Prénom : Emmanuelle
Titre : Directeur de Recherche ou
e-mail : epouydebat@mnhn.fr
Adresse professionnelle : UMR 7179 MECADEV, 55 rue Buffon, CP55, 75005 PARIS
(site, adresse, bât., bureau)

Unité de Recherche :

Intitulé : MECADEV
Code (ex. UMR xxxx) : UMR 7179

École Doctorale de rattachement de l'équipe (future école doctorale de la doctorante ou du doctorant) : ED227-Sciences vie homme : évolution écologie

Doctorantes et doctorants actuellement encadrés par la directrice ou le directeur de thèse (préciser le nombre de doctorantes ou doctorants, leur année de 1^e inscription et la quotité d'encadrement) : Deux étudiantes en 2^eme année (Directrice, avec co-direction), une étudiante en 1^{ère} année (Co-direction, CIFRE). Quotité 1.5 en octobre 2021

Co-encadrante ou co-encadrant :

NOM : Cornette Prénom : Raphaël
Titre : Choisissez un élément : ou Docteur HDR
e-mail : cornette@mnhn.fr

Unité de Recherche :

Intitulé : ISYEB
Code (ex. UMR xxxx) : 7205

École Doctorale de rattachement : ED227-Sciences vie homme : évolution écologie
Ou si ED non Alliance SU :



**SORBONNE
UNIVERSITÉ**

Doctorantes et doctorants actuellement encadrés par la directrice ou le directeur de thèse (préciser le nombre de doctorantes ou doctorants, leur année de 1^e inscription et la quotité d'encadrement) : 1 étudiant en 1^{ère} année (Directeur), 1 en 3^{ème} année (Directeur), 2 en 2^{ème} année (Co-directeur). Quotité 1.5 en octobre 2021

Co-encadrante ou co-encadrant :

NOM : Chablat Prénom : Damien
Titre : Directeur de Recherche ou HDR
e-mail :

Unité de Recherche :

Intitulé : Laboratoire des sciences du numérique de Nantes
Code (ex. UMR xxxx) : 6004

Choisissez un élément :

École Doctorale de rattachement : Ou si ED non Alliance SU : 602

Doctorantes et doctorants actuellement encadrés par la directrice ou le directeur de thèse (préciser le nombre de doctorantes ou doctorants, leur année de 1^e inscription et la quotité d'encadrement) : Trois étudiants en 3^{ème} année (deux Directeur et un co-directeur), un étudiant en 2^{ème} année (Directeur), deux étudiants en 1^{er} année (Un Directeur et un co-directeur). Quotité 2 en octobre 2021.

Cotutelle internationale : Non Oui, précisez Pays et Université :

Selon vous, ce projet est-il susceptible d'intéresser une autre Initiative ou un autre Institut ?

Non Oui, précisez SCAI - Sorbonne Center of Artificial Intelligence

Description du projet de recherche doctoral (en français ou en anglais) :

Ce texte sera diffusé en ligne : il ne doit pas excéder 3 pages et est écrit en interligne simple.

Détailler le contexte, l'objectif scientifique, la justification de l'approche scientifique ainsi que l'adéquation à l'initiative/l'Institut.

Le cas échéant, préciser le rôle de chaque encadrant ainsi que les compétences scientifiques apportées. Indiquer les publications/productions des encadrants en lien avec le projet.

Préciser le profil d'étudiant(e) recherché.

MODELING OF THE ELEPHANTS' TRUNK: FROM EVOLUTION TO SOFT ROBOTICS**1) State of the art**

The manipulation of objects and food is a complex function that has played a major role in the adaptive strategies of the Tetrapods and their survival. Amphibians, marsupials, rodents, carnivores and primates use their more or less developed hand capabilities in relation to their anatomical characteristics and performance. Some species developed very high manipulative capacities without the benefit of fingers! This is the case for many bird species and elephants that use their trunks, or proboscis, in various contexts such as communication, use and manufacture of tools, manipulation of food, etc. Equipped with about 150,000 muscle bundles, precise and powerful at the same time, they are able to handle a peanut and uproot a tree! The trunk performs fundamental functions in the survival of elephants and its diversified evolution remains obscure. How and why did this trunk develop in different ways depending on the species and the population? What is the variability of uses of the trunk according to the environment? How do elephants optimize their movements according to the properties of the grasped or manipulated object?

At the same time, the industry needs new technological solutions to improve the movement of heavy loads in congested environments. To do so, there is a need for new robotic arms that are flexible and robust, capable of lifting heavy loads and moving them with precision to ensure the safety of places and people. The solutions found by elephants to survive the various constraints of their changing environments over the course of evolution are all potential bio-inspired solutions. Understanding the links between tasks (pushing, squeezing, pulling, unscrewing, small or large objects, etc.), contexts (with obstacles, without obstacles, open or congested environment, etc.) and biological solutions (anatomy, functional morphology, kinematics, etc.), will help us to develop robots reproducing the movement of the trunk but also the functioning, when existing robotic trunks only reproduce the movement.



The objective of the project is to quantify the morpho-functional and biomechanical repertoire of trunk uses of the current elephant species in order to understand 1) the morpho-functional and biomechanical 3D parameters of trunk grip according to the objects properties and the tasks, 2) how the musculoskeletal system of the trunk can produce such precision, strength, elasticity and shock absorption, 3) to design a mechanism capable of reproducing the movement but also the functioning of the trunk to obtain. This PhD project will conduct to better understand elephant evolution and make the prototype operational for moving heavy loads in the presence of obstacles by doing experimentations on the universal effector and manipulator prototype.

3) Methodologies to reach the scientific objectives

To reach evolutionary and robotics objectives, we need to develop several challenging methodologies. The funding CNRS – PRIME 80 (ELEPHANTMAN project) allowed us to acquire a unique expertise on African elephants in captivity as in the wild (Lefeuvre et al. 2020, in prep.; Soppelsa et al., in prep.) and to propose this new innovative idea. We will exploit our interdisciplinary innovative procedure (AI, markerless 3D kinematics & functional morphology, grasping force quantification) and new experimental designs in zoological parks (i.e. Beauval & La Palmyre). It will allow us to quantify these interdisciplinary parameters during several tasks such as: flexing, pulling, contracting, twisting, and screwing/unscrewing, with vertical obstacles to be moved (to see how the elephant can change direction), manipulation with the tip of the trunk in hyper-extension etc. Finally, we need to explore the detailed anatomy of the trunk by a dissection, muscle properties analyses, and an MRI. This step will help us to build a unique musculo-hydrostatic-skeletal model (based on e.g. Hill-type and/or continuum mechanics modelling approaches) that will be used to identify the existing physiological solutions as a model to develop novel soft robotics applications.

4) Innovative, ambitiousness and originality nature of the project

It is the first time that a project explores the behaviour, form and function of the elephants' trunks with an interdisciplinary approach. The objectives are new and highly challenging: evolution of one of the most amazing animals, and bio-inspiration toward soft robotics. The scientific challenge to inspire such new robotic prototype is huge and resides both in understanding and modelling the trunk' complex muscular architecture and its control, as well as in the ability to transfer such biomechanical knowledge into efficient industrial solutions. Several technological bottlenecks will be rise through innovative and complementary methods: 3D geometric morphometrics, markerless 3D motion analyses, trunk dissection, active 3D finite element modelling of the musculo-hydrostatic-skeletal system, trunk-robot including movement and functioning...

From a general point of view, the evolution of elephants remains a mystery (first elephants had no trunk...) and this novel approach will shed new light on this enigma while meeting a major methodological and bio-inspired challenge. Most of the existing flexible arms, supposedly inspired by the trunk, are polyarticulated structures driven by actuated joints or by cables. The only similarity to the elephant trunk is the external morphology, but not well quantified, and not the functioning. Everything remains to be discovered. The measured kinematic and anatomical data can be used to create a musculo-hydrostatic-skeletal model to which the robotic approach will aim to get closer. Thus, by exploring manipulation



capabilities in an interdisciplinary manner using multifactorial data analysis methods (multivariate analysis such as PCA, MCA...), we not only propose a unique approach to understanding the adaptive mechanisms associated with this organ and its uses but we also address another challenge: bio-inspiration and novel solution for industrial robotics.

5) Position of the project in regard to the iSiM objectives

Our project is federative and transversal and proposes an interdisciplinary research, bringing together several disciplines in order to give the researchers involved (with different skills) the opportunity to compare their knowledge and experiences. This project also proposes societal issues and involves various keywords and themes from several Sorbonne University institutes:

- Initiatives Biodiversity, Evolution, Ecology, Society (IBEES): this project will allow a better understanding of the adaptation capacities of an emblematic species whose survival is largely threatened today. Our interdisciplinary approach will involve the processing and modeling of our data and will offer a privileged field in the bio-inspiration domain.
- Institut Sciences du Calcul et des Données (ISCD) & Sorbonne Central for Artificial Intelligence (SCAI): this project involves complex data analysis, the use of Artificial Intelligence, algorithmic analyses involved in the robotic bio-inspired part of the project.
- Initiative "Mastering Safe and Sustainable Technological Systems": the ultimate applied goal of this project is to design a flexible robotic arm that ensures the safety of people when moving heavy loads, despite the presence of obstacles. Finally, the scientific community gathered around this project is a definite factor of success.

6) Partners complementarity

Emmanuelle Pouydebat (DR, UMR 7179 CNRS-MNHN) will supervise this PhD project. She has supervised more than 18 interdisciplinary projects, and has obtained more than 1.000.000 euros in total. More than 65 international publications and 60 talks have valorised her work. She is one of the world's leading specialists in the field of animal grasping and handling (ethology, biomechanics) and has been awarded several prizes (i.e. 2019: CNRS Silver Medal and Chevalière de la légion d'honneur). Our project, extremely innovative, is structured around main collaborations essential to its originality, involving people recognized in their respective fields: functional morphology (AI-HDR Raphaël Cornette, Co-supervisor, ISYEB-UMR 7205 CNRS-MNHN), robots-manipulators & bio-inspired robotics (DR Damien Chablat, Co-supervisor, LS2N-UMR6004, Ecole Centrale de Nantes), Musculoskeletal modeling & 3D movement analysis (PR. Laurence Chèze, collaborator, LBMC-UMR T9406, Univ. Lyon 1 & Gustave Eiffel).

Bibliography

- Fasquelle, B., Furet, M., Khanna, P., Chablat, D., Chevallereau, C., & Wenger, P. (2020). A bio-inspired 3-DOF light-weight manipulator with tensegrity X-joints. In IEEE ICRA'2020.
- Hanot, P., Herrel, A., Guintard, C., & Cornette, R. (2017). Morphological integration in the appendicular skeleton of two domestic taxa: the horse and donkey. *Proceedings of the Royal Society B: Biological Sciences*, 284(1864), 20171241.
- Lefeuvre M., Cornette R., Gouat P., Mulot B., Pouydebat E. (2020). Behavioural variability among captive African elephants in the use of the trunk while feeding. *Peer J*. 8: e9678.
- Moissenet F, Chèze L, Dumas R. (2017). Individual muscle contributions to ground reaction and to joint contact, ligament and bone forces during normal gait. *Multibody System Dynamics* 40(2):193–211.



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Reghem E., Chèze L., Coppens Y., Pouydebat E., (2013). Grasping's kinematic in five primates: Lemur catta, Sapajus xanthosternos, Gorilla gorilla, Pan troglodytes, Homo sapiens. Journal of Human Evolution 65: 303-312.

Sustaita, D, Pouydebat E., Abdala, V., Manzano, A., Herrel A., (2013). Getting a grip on tetrapod grasping: Form, function and evolution. Biological reviews 88(2): 380-405.

Venkateswaran, S., Chablat, D., & Boyer, F. (2019). Numerical and experimental validation of the prototype of a bio-inspired piping inspection robot. Robotics, 8(2), 32.

Profile of the desired candidate

The candidate should have a strong motivation for interdisciplinarity and ideally have experience with morphological and biomechanical analyses. A good theoretical knowledge in evolutionary biology and the field of bio-inspiration related to robotics will be an advantage. Finally, of course, a knowledge of elephants, their evolution and their behaviors is the basis of this project.

**Merci d'enregistrer votre fichier au format PDF et de le nommer :
«ACRONYME de l'initiative/institut – AAP 2021 – NOM Porteur.euse Projet »**

***Fichier envoyer simultanément par e-mail à l'ED de rattachement et au programme :
cd_instituts_et_initiatives@listes.upmc.fr avant le 20 février.***

Modeling of the elephants' trunk: From evolution to soft robotics

TRUNKMOD

PI 1. Emmanuelle Pouydebat

PI 2. Raphaël Cornette

Curriculum Vitae of the PI - Emmanuelle Pouydebat

47 years old, 1 child (6 years old) - Research Director – CNRS/MNHN

Education

- 2004 – PhD : Museum National d’Histoire Naturelle/CNRS/Collège de France
- 2012 – Habilitation to Drive Researches: University Paris-Sud 11, Orsay.

Positions

- 2007 – 2012, Assistant Professor, Toulon University-HandiBio, France.
- 2012 – 2016, Delegation CNRS and Chargé de Recherche (CR1) CNRS (UMR 7179)
- 2017 - Present, Research Director (DR2) at the French CNRS, MNHN (UMR 7179) – Sections 52 & 31

Appointments

- 2009 – 2011, Elected member of the UFR Council of Toulon Univ. / Member of the Scientific Council of HandiBio, Toulon / Group leader of the “Primate Biomechanics” team, HandiBio lab., Toulon
- 2012 – 2020, Elected member of the Administrative Council of SFDP then scientific committee SFDP-EFP
- 2014 – 2016, Elected member of the Council of the UMR 7179
- 2021 - ... Responsible for animal welfare FUNEVOL

Awards

- 2001 – 2020, Médaille d’argent du CNRS, Chevalière de la Légion d’Honneur, Prix de l’Académie des Sciences, Belles-lettres et arts de Bordeaux, Aires Culturelles Program, Fondation Marcel Bleustein Blanchet pour la vocation, Fondation Singer Polignac, Société des Amis du MNHN, Best Poster Prize (SB 2009), Award for scientific excellence of the CNRS (2009-2013 & 2014-2018).

Research grants as a Coordinator: more than 16 (~1000000 Euros total)

- 2018 – 2020 : ELEPHANTMAN - Interdisciplinary modelling of the trunk - CNRS-PRIME 80 : (52k€, 1PhD)
- 2012 – 2020: Manipulation in tetrapods: from crayfish to hominids - CIFRE convention, Emergence SU, ATM MNHN, Defi Auton CNRS, Doctoral Funding ENS, Doctoral and Post-doctoral funding Labex BCDiv, doctoral funding FDV, Research grant of the BQR Toulon, Doctoral funding ED Toulon-Marseille...

Peer-reviewed publications: > 65 total (1 < IF < 9), 1st or last author > 80%

- Main journals: *Biological Journal of The Linnean Society*, *Journal of Human Evolution*, *American Journal of Physical anthropology*, *Journal of Experimental Biology*, *International Journal of Primatology*, *Scientific reports*, *J R Soc Interface*, *Behavioural Processes*, *Animal Behaviour*, *Journal of Evolutionary Biology*, *Biological reviews*, *Behavioural Brain Research*, *Journal of biomechanics*, *American journal of primatology*...

Published abstracts: > 60 total Congresses & seminars: > 72 total

Organization of congress and symposia: 9 International invited presentation: 8

Books & Chapters : 13

- L’intelligence animale – 2017 (Odile Jacob) ● Quand les animaux et les végétaux nous inspirent - 2019 (Odile Jacob) ● Atlas de Zoologie poétique (Arthaud) ● 2018 & *Sexus animalus* – 2020 (Arthaud) ● All of them translated in several languages.

Editor & Associated editor for 4 international journals

Reviewer for ≈ 15 journals and several grants (ANR, Research Council KU Leuven...)

PhD and HDR juries ≈ 15

Teaching for various Masters

Student supervised: 7 post-doc, 8 PhD, 21 M2

Scientific diffusion: *General public conferences* (40), *Magazine articles* (49), *Television* (22), *Radio* (>45), *Cinema Doc* (1), *General public scientific events* (5)

Curriculum Vitae of the Co-PI - Raphael Cornette
Research Director – CNRS/MNHN

Dr Raphaël Cornette, HDR

53 years old, Paris, France

Institut de Systématique Evolution Biodiversité (ISYEB) - UMR7205 Equipe Evolution et Développement des Variations Phénotypiques, Muséum national d'Histoire naturelle, CNRS, SU, EPHE, UA, 57 rue Cuvier CP50, 75005 Paris, France E-mail: raphael.cornette@mnhn.fr
https://www.researchgate.net/profile/Raphael_Cornette2

Education:

- 2018 - HDR: University Paris-Sud, Orsay, France. *Origins and modalities of morpho-functional patterns: a history between form and function.*
- 2012 - Phd: Museum National d'Histoire Naturelle, Paris, France. *Form and Function: modularity, disparity and performance of the manducateur apparatus of Crocidura russula, (Soricomorpha, Soricidae).*

Research:

My general research framework concerns phenotypic variation. More precisely, I study relationships between form and function, this association being the principal target of natural selection. I work using morphometrics (traditional, geometric, in 2D and 3D). Vertebrates present very various morpho-functional patterns that occupy the main part of my work. These approaches are also applied on archaeological and palaeontological specimens providing a better understanding of phenotypic evolution. During my research, I carried out 30 field missions (Africa, Asia, European islands) and obtained 15 fundings for around 40 000 euros.

Peer-reviewed publications (1<IF<12)

- 113 publications; H-index (Google Scholar): 24; 1708 citations.

Supervision:

- 3 Postdoctoral researchers, 10 Phd students and 39 Master students.

Teaching:

- In charge of "Morphometrics and shape analysis" in the Doctoral School (ED 227) of the MNHN (Paris) and of the "Morphometrics and shape analysis" in the Master SEP of the MNHN (Paris)
- Examiner for the Master SEP of the MNHN (Paris)

Expertise:

- In charge of the transversal axis "Shape analyses and Phenomics" of UMR 7205 – ISYEB
- Expert for the National Research Agency (ANR)
- Participation in 5 ANR and 1 European Research Council (ERC)
- Participation in 8 thesis juries and 11 thesis committees
- Expert in wildlife for scientific purposes
- Reviewer for Evolution, PalEvol, PLOS1, Biological Journal of the Linnean Society, Journal of Zoology, The Anatomical Record, Zootaxa, Ibis, Mammalia...

Administrative responsibilities:

- Elected member of the new « Origines et Evolution » department since 2020
- Elected member of the « Systématique et Evolution » department since its creation
- Elected member of the UMR 7205 – ISYEB since its creation

5 significant publications

Bardo A., M.-H. Moncel, C.J. Dunmore, T.L. Kivell, E. **Pouydebat**, R. **Cornette** (2020) The implications of thumb movements for Neanderthal and modern human manipulation. *Scientific Reports* **10**, 19323. <https://doi.org/10.1038/s41598-020-75694-2>.

Lefeuvre M., **Cornette** R., Gouat P., Mulot B., **Pouydebat** E. (2020). Behavioural variability among captive African elephants in the use of the trunk while feeding. *Peer J.* 8: e9678 doi: 10.7717/peerj.9678.

Reghem E., Chèze L., Coppens Y., **Pouydebat** E., (2013). Grasping's kinematic in five primates: *Lemur catta*, *Sapajus xanthosternos*, *Gorilla gorilla*, *Pan troglodytes*, *Homo sapiens*. *Journal of Human Evolution* 65: 303-312.

Soppelsa J., Lefeuvre M., Mulot B., **Cornette** R., **Pouydebat** E., (In prep). Morpho-functional analyses of the distal part of the African elephant trunk according to the food properties.

Sustaita, D, **Pouydebat** E., Abdala, V., Manzano, A., Herrel A., (2013). Getting a grip on tetrapod grasping: Form, function and evolution. *Biological reviews* 88(2): 380-405.

Summary of the project (5 lines)

Elephant trunks perform a wide variety of vital functions. Its diversified evolution remains obscure, and its adaptation represent unique bio-inspired solutions. This challenging project aims at an interdisciplinary modeling of the trunk (biomechanics, musculo-hydrostatic-skeletal), using innovative methods (markerless 3D kinematics & forces, artificial intelligence) to understand elephant trunk evolution and inspire new flexible robotic arm solutions.

Scientific description (5 pages max.)

Objectives and description of the project (2 pages environ¹)

1) State of the art

The manipulation of objects and food is a complex function that has played a major role in the adaptive strategies of the Tetrapods and their survival. Amphibians, marsupials, rodents, carnivores and primates use their more or less developed hand capabilities in relation to their anatomical characteristics and performance. Some species developed very high manipulative capacities without the benefit of fingers! This is the case for many bird species and elephants that use their trunks, or proboscis, in various contexts such as communication, use and manufacture of tools, manipulation of food, etc. Equipped with about 150,000 muscle bundles, precise and powerful at the same time, they are able to handle a peanut and uproot a tree! The trunk performs fundamental functions in the survival of elephants and its diversified evolution remains obscure. How and why did this trunk develop in different ways depending on the species and the population? What is the variability of uses of the trunk according to the environment? How do elephants optimize their movements according to the properties of the grasped or manipulated object?

At the same time, the industry needs new technological solutions to improve the movement of heavy loads in congested environments. To do so, there is a need for new robotic arms that are flexible and robust, capable of lifting heavy loads and moving them with precision to ensure the safety of places and people. The solutions found by elephants to survive the various constraints of their changing environments over the course of evolution are all potential bio-inspired solutions. Understanding the links between tasks (pushing, squeezing, pulling, unscrewing, small or large objects, etc.), contexts (with obstacles, without obstacles, open or congested environment, etc.) and biological solutions (anatomy, functional morphology, kinematics, etc.), will help us to develop robots reproducing the movement of the trunk but also the functioning, when existing robotic trunks only reproduce the movement.

2) Objectives of the project

The objective of the project is to quantify the morpho-functional and biomechanical repertoire of trunk uses of the current elephant species in order to understand 1) the morpho-functional and biomechanical 3D parameters of trunk grip according to the objects properties and the tasks, 2) how the musculoskeletal system of the trunk can produce such precision, strength, elasticity and shock absorption, 3) to design a mechanism capable of reproducing the movement but also the functioning of the trunk to obtain. This PhD project will conduct to better understand elephant evolution and make the prototype operational for moving heavy loads in the presence of obstacles by doing experimentations on the universal effector and manipulator prototype.

3) Methodologies to reach the scientific objectives

To reach evolutionary and robotics objectives, we need to develop **several challenging methodologies**. The funding CNRS – PRIME 80 (ELEPHANTMAN project) allowed us to acquire a unique expertise on African elephants in captivity as in the wild (Lefevre et al. 2020, in prep.; Soppelsa et al., in prep.) and to propose this **new innovative idea**. We will exploit our **interdisciplinary innovative procedure (AI, markerless 3D kinematics & functional morphology, grasping force quantification)** and new experimental designs in

¹ Police Arial ; Taille de police 11 ; interligne simple, **Taille max. du fichier 5Mo**

zoological parks (i.e. Beauval & La Palmyre). It will allow us to quantify these interdisciplinary parameters during several tasks such as: flexing, pulling, contracting, twisting, and screwing/unscrewing, with vertical obstacles to be moved (to see how the elephant can change direction), manipulation with the tip of the trunk in hyper-extension etc. Finally, we need to explore the detailed anatomy of the trunk by a dissection, muscle properties analyses, and an MRI. This step will help us to build a **unique musculo-hydrostatic-skeletal model** (based on e.g. Hill-type and/or continuum mechanics modelling approaches) that will be used to understand trunk evolution and identify the existing physiological solutions as a model to develop **novel soft robotics** applications.

4) Innovative, ambitiousness and originality nature of the project

It is the first time that a project explores the behaviour, form and function of the elephants' trunks with an interdisciplinary approach. The **objectives are new and highly challenging**: evolution of one of the most amazing animals, and bio-inspiration toward soft robotics. The scientific challenge to inspire such new robotic prototype is huge and resides both in understanding and modelling the trunk' complex muscular architecture and its control, as well as in the ability to transfer such biomechanical knowledge into efficient industrial solutions. Several technological bottlenecks will be rise through **innovative** and complementary **methods**: 3D geometric morphometrics, markerless 3D motion analyses, trunk dissection, active 3D finite element modelling of the musculo-hydrostatic-skeletal system, trunk-robot including movement and functioning...

From a general point of view, the evolution of elephants remains a mystery (first elephants had no trunk...) and this novel approach will shed new light on this enigma while meeting a major methodological and bio-inspired challenge. Most of the existing flexible arms, supposedly inspired by the trunk, are polyarticulated structures driven by actuated joints or by cables. The only similarity to the elephant trunk is the external morphology, but not well quantified, and not the functioning. Everything remains to be discovered. The measured kinematic and anatomical data can be used to create a musculo-hydrostatic-skeletal model to which the robotic approach will aim to get closer. Thus, by exploring manipulation capabilities in an interdisciplinary manner using multifactorial data analysis methods (multivariate analysis, etc.), we not only propose a **unique approach** to understanding the adaptive mechanisms associated with this organ and its uses but we also address another **challenge**: bio-inspiration and novel solution for industrial robotics.

Feasibility. Risk assessment and management (1/2 page environ1)

The feasibility is high and both evaluation and risk management are under control. First, this PhD project will benefit from previous preliminary studies (figure 1) during which we already quantified the behavioural variability of trunk uses and developed the various protocols that will be used during this PhD: experimental procedures to quantify trunk functional morphology and biomechanics data (forces, AI markerless 3D kinematics). The procedures are already available and efficient. Second, the management is available and have already worked altogether with success. Each supervisor and other collaborators involved are specialists in their respective domains and will assure the success of the supervision and the PhD project. Third, the sanitary conditions may delay us as we could be prohibited from manipulating in the zoo. Nevertheless, we are confident that by the time this thesis project begins the situation will have improved. In addition, we benefit from many hours of films of the uses of the trunk of the elephants of Namibia and the project could very well start, in case of still constrained sanitary conditions, by the analysis of these videos.

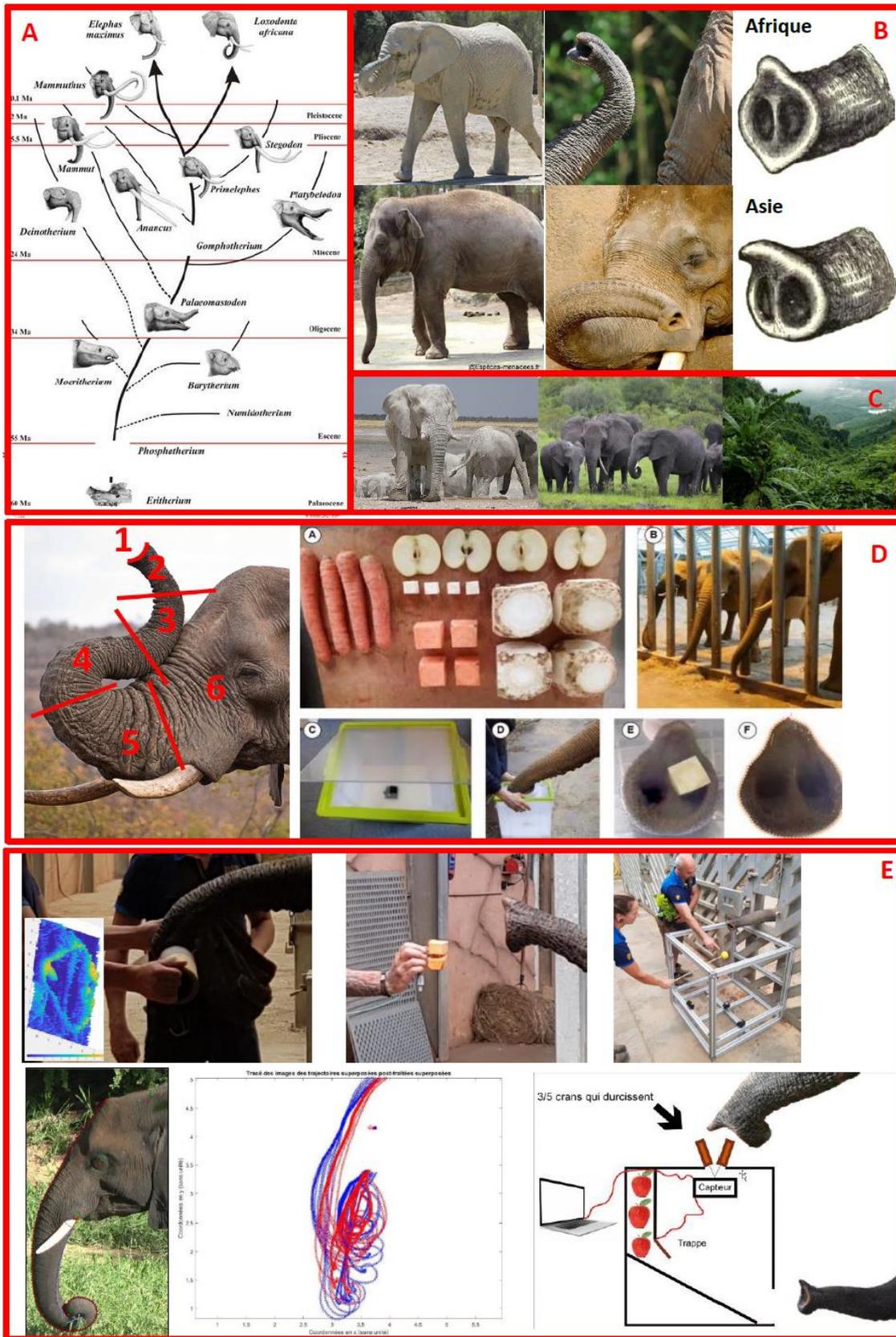


Figure 1. Preliminary approaches tested in ELEPHANTMAN that we will develop and used for TRUNKMOD (Pouydebat-Cornette et al.) – A) Evolution of elephants (various trunks). B-C) Different trunk morphologies and environments according to species and/or population. D) Functional morphology quantification in the wild & from experiments. E) Biomechanical quantification (pressures, forces, kinematics).

Position of the project within national and international context (1/2 page environ1)

Within national and international context, it is the first time that a project explores the behaviour, form and function of the elephants' trunks with an interdisciplinary approach. Most of the existing flexible arms, supposedly inspired by the trunk, are polyarticulated structures driven by actuated joints or by cables. The only similarity to the elephant trunk is the external morphology, but not well quantified, and not the functioning. Everything remains to be discovered to better understand elephants and their evolution but also to suggest innovative solution for soft robotics in France and abroad.

Position of the project in regard to the iSiM objectives (1/2 page environ1)

Our project is federative and transversal and proposes an interdisciplinary research, bringing together several disciplines in order to give the researchers involved (with different skills) the opportunity to compare their knowledge and experiences. This project also proposes societal issues and involves various keywords and themes from several Sorbonne University institutes:

- Initiatives Biodiversity, Evolution, Ecology, Society (IBEES): this project will allow a better understanding of the adaptation capacities of an emblematic species whose survival is largely threatened today. Our interdisciplinary approach will involve the processing and modeling of our data and will offer a privileged field in the bio-inspiration domain.
- Institut Sciences du Calcul et des Données (ISCD) & Sorbonne Central for Artificial Intelligence (SCAI): this project involves complex data analysis, the use of Artificial Intelligence, algorithmic analyses involved in the robotic bio-inspired part of the project.
- Initiative "Mastering Safe and Sustainable Technological Systems": the ultimate applied goal of this project is to design a flexible robotic arm that ensures the safety of people when moving heavy loads, despite the presence of obstacles. Finally, the scientific community gathered around this project is a definite factor of success.

Partners complementarity

Emmanuelle Pouydebat (DR, UMR 7179 CNRS-MNHN) will **supervise this PhD project**. She **has supervised more than 18 interdisciplinary projects**, and has obtained more than 1.000.000 euros in total. **More than 60 international publications and 60 talks** have valorized her work. She is one of the world's leading specialists in the field of animal grasping and handling (ethology, biomechanics) and has been awarded **several prizes** (i.e. 2019: CNRS Silver Medal and Chevalière de la légion d'honneur). **Our collaboration, extremely innovative**, is structured around main collaborations essential to its originality, involving people recognized in their respective fields: functional morphology (Dr-HDR Raphaël Cornette, CO-PI, ISYEB-UMR 7205 CNRS-MNHN), robots-manipulators & bio-inspired robotics (DR Damien Chablat, collaborator, LS2N-UMR6004, Ecole Centrale de Nantes), Musculoskeletal modeling & 3D movement analysis (PR. Laurence Chèze, collaborator, LBMC-UMR T9406, Univ. Lyon 1 & Gustave Eiffel).

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Research program (1 page).

The program will involve several collaborators and Master students. It will be **composed of five complementary approaches** and organized according to the following steps:

First year

1) State of the art on elephant evolution, trunk utilizations, trunk anatomy & morphology and soft robotic arms inspired from elephant trunks.

2) Experimental grasping of foods and objects of different sizes and shapes during several tasks in at least 10 individuals of two species (African and Asian elephants). The methods aim at obtaining 1) precise 3D functional morphological data from the pincer grip (distal part of the trunk), 2) 3D kinematic data and pressure forces with live 3D modelling with a markerless approach (preliminary data already obtained). This part will help us to understand how elephant adapt their functional strategies according to individuals and species. This section also responds to the need for information regarding the expected specificity of functional couplings, which are generally presented as antagonistic and of high amplitude while offering both high stability and precision with a very wide range of force. (Pouydebat & Cornette).

Deliverables: 3D morphological and biomechanical model of the trunk.

3) Publication and conference

Second year

1) Anatomical analyses and two-scale modelling of the trunk's mechanical behaviour. A dissection followed by medical imaging (MRI) of an elephant trunk will be used to quantify the geometry and architecture of the soft tissues. A continuous musculo-hydrostatic-skeletal model based on finite elements and including active muscles will help to understand the role of the fibers' 3D distribution on a subpart of the trunk. This detailed model will be reduced (based on Hill actuators) and considered as a functional unit of the musculoskeletal model of the whole trunk. The behaviour of this global model will be evaluated according to the experimentally collected kinematics – (Pouydebat, Cornette & Chèze).

Deliverables: Continuous model of a subpart of the trunk / Simplified model of the whole trunk.

2) Publication and conference

Third year

1) Innovative bio-inspired architecture and design of a prehensile trunk prototype able to reproduce the movement of the trunk but also its functioning, involving the control of the torsion by inspiration of the musculoskeletal modelling – (Chablat, Pouydebat, Cornette, Chèze)

Deliverables: A prehensile trunk prototype.

2) Publication and conference

This PhD will help to conduce to the conception of an operational prototype for moving heavy loads an operational trunk robot with its control system and trajectory planning software.