NAME AND CONTACT DETAILS

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CAREER PROFILE (Education and Employment)

Education:

2012-2015: PhD in Solid Mechanics, Institut Jean le Rond D'Alembert, UPMC-Paris 6, France.
2010-2012: MSc in Mathematical modelling for Engineering, Politecnico di Torino, Italy.
2006-2010: BSc in Engineering Mathematics, Politecnico di Torino, Italy.

Employment:

Jan2021-present: **Lecturer (above bar)**, School of Maths, University of Galway, Ireland.
Jun2019-Dec2020: **Lecturer (above bar)**, Dep. of Maths, University of Limerick, Ireland.
Mar2017-Feb2019: **Marie Curie Research Fellow**, School of Maths, University of Galway,Ireland.
Feb2016-Feb2017: **Post Doctoral Researcher**, School of Maths, University of Manchester, UK.
Nov2015-Jan2016: **Research Assistant**, School of Maths, University of Galway, Ireland.

KEY ACHIEVEMENTS IN RESEARCH EXCELLENCE & IMPACT

A. Key Achievements in the Generation of Knowledge

1) Constitutive modelling of soft tissues

Research excellence: At the end of my PhD, I successfully applied for different funding schemes to conduct my research on soft tissues mechanics. **My project was funded by two prestigious agencies**, the Irish Research Council (€95k) and the European Commission (€175k). I declined the former grant and accepted the latter which started in March 2017. These were outstanding results considering my **early-career stage** and my age: I was 27 and the average age of Marie Curie fellows is 35. As part of my Marie Curie project, I studied experimentally and theoretically the mechanics of the brain in large torsional deformations in view of estimating brain injuries associated to rotational head impacts. As a result of this work, we proposed a new testing protocol for soft tissues and gels in large torsion. Moreover, in collaboration with Prof. Parnell at the University of Manchester, I **developed a new viscoelastic constitutive framework** for soft materials with fibres.

Impact: The modelling approaches developed in my research on constitutive models for soft tissues are now in use across mechanical and biomedical engineers. In particular, my research on brain mechanics led to the first measurement and quantification of the Poynting effect in brain tissues. This is a nonlinear effect whereby a cylindrical sample undergoing twisting tends to elongate vertically. This study opened a new way to understand brain injuries associated to car and sports accidents involving rotational acceleration. My results have been featured in the main national and local newspapers (Irish Independent, Irish Examiner and Galway Daily). Furthermore, my collaboration with Prof. Parnell led to the development of a novel viscoelastic model which has few key parameters, captures the full 3-dimensional material response and it is easy to implement in fitting of experimental data.

2) Morphogenetic theories

Research excellence: During my doctoral studies I used the **theory of nonlinear elasticity** combined with the **theory of volumetric growth** and **advanced perturbation techniques** to model pattern formation in tubular organs, in particular the gastro-intestinal system and the blood vessels (e.g. arteries ad veins). I developed both analytical and numerical models to predict the formation and evolution of geometrical patterns in soft tissues, respectively. My results have been published in scientific journals and books ranging from applied maths to biomechanics. Furthermore, during my PhD I have developed 2 international collaborations with Stanford University and Polytechnic University of Milan, which are still active now .

Impact: My works "*Pattern Selection in growing tubular organs"* and "*Morphoelastic control of intestinal organogenesis: theoretical prediction and numerical insights"* are two of the first in the literature where **analytical and numerical techniques have been integrated** to model such a complex developmental process and were recognised in the scientific community as pioneering works, particularly for the numerical aspects. Indeed, my results have attracted the **attention of the international press**, as exemplified by the selection of *Pattern Selection in growing tubular organs* for a synopsis in *Physics*, a journal of the American Physical Society which spotlights exceptional research.

3) Optimisation of acoustic metamaterials (SoundBounce)

Research Excellence: As lecturer in the University of Limerick I received funding (118k) to take part in a collaborative Industry project (funded by the European Commission) with Lios (former Restored Hearing), a Dulin-based company that designs and manufactures new acoustic metamaterials. My role was to supervise a postdoctoral researcher to characterise and model the mechanical and acoustic behaviour of SoundBounce, an innovative new noise-cancelling metamaterial designed by the company. Together with my postdoc we conducted mechanical tests to measure the viscoelastic behaviour of the material. We modelled the mechanical response of the material theoretically (with linear viscoelasticity). Furthermore, with the Finite Element software Comsol we built an acoustic model of the product. The FE model allowed us to identify the key geometrical and mechanical parameters in order to optimise the sound absorption properties of the material. This project involved a multi-disciplinary team of mathematicians, chemists, physicians and mechanical engineers.

Impact: The mathematical models that we developed throughout the project contributed to design an **optimised version of SoundBounce**. As result, the product is now able to operate at a broader range of frequencies, is lighter and smaller, making it useful in sound absorption applications ranging from aerospace, construction and home appliances. Thanks to our models the company has reduced the number of experimental trails and has now moved to the commercialisation phase of the product. The company has developed a new website for the product with the results of our research (https://www.sound-bounce.com).

B. Key Achievements in the Development of Individuals

So far I have supervised 10 Undergraduate and 7 Postgraduate students. Among the Postgraduate students, I mentored **3 Masters students**, now employed in different biomedical companies abroad; **1 post Master trainee**, now enrolled in a PhD programme; and 3 PhD students as part of their initial training for the SFI Centre for Research Training in Foundations of Data Science in UL. During my Marie Curie Fellowship, I have been involved in the supervision of 3 PhD students: I have supervised the experimental, the modelling and the numerical aspects of a PhD student in Physics (NUI Galway), a visiting PhD student in Mechanical Engineering (from Zhejiang University) and a visiting PhD student in Biomedical Engineering (from UCD), respectively. As a member of the Mathematics Consortium for Science and Industry (MACSI) at UL, I have supervised a **postdoctoral researcher based in *Lios*** (former Restored Hearing) on the modelling of a new acoustic meta-material (SoundBounce). *Lios* is a Dublin-based company that produces innovative solutions for acoustic noise reduction. I **recruited a PhD student** who will be starting in October 2021. Since 2012 I have been building an active and solid network of international collaborators that has always led to successful results and publications. In UL I was the **Erasmus coordinator** for the Maths Department and while in this role, I established new Erasmus destinations for maths students in Europe, assisted the students in planning their academic year abroad, helped them selecting the host institution and guided them in the choice of modules. In February 2019, I have been invited to deliver a series of lectures on the mechanics of soft tissues at an **international doctoral school** on "Modelling biomaterials" (Kacov, Czech Republic). So far, I have organised several minisymposia in international conferences and taught undergraduate large modules and advanced postgraduate modules in Applied Mathematics.

C. <u>Key Achievements Supporting Broader Society & the Economy</u>

Since the beginning of my career, I have always been very active in **reaching out to the general public with my research**, especially in being a role model to young students and pupils. During my Marie Curie Fellowship, I participated in many local outreach activities: I was a contestant for FameLab Galway with a talk on black holes; I delivered a series of lectures to primary and secondary school pupils on different research topics (brain mechanics, maths & geometry of pattern formation, bicycle mechanics, visualisation of acoustic waves). In UL I took part in the **Young Modellers project**, where I supervised a group of TY students on developing a modelling strategy to major societal challenges (ice cap melting, design of a eco-friendly city).

Furthermore, I have established a rich and active **international network of collaborators in academia and industry**. Particularly, the company Lios has implemented my research to enhance their in-house acoustic meta-material SoundBounce, which is used to reduce sound noise in aircrafts, construction sites and home insulation systems.

D. <u>Key Achievements Supporting the Research Community</u>

I am an active **reviewer for several journals** in fields ranging from Applied Mathematics to Physics, Soft Matter and Biomechanics (such as Proceedings of the Royal Society A, Physical Review Letters, Soft Matter, Journal of the Mechanics and Physics of Solids, Biomechanics and Modeling in Mechanobiology). I edited a Special Issue on "Constitutive modelling of soft tissues" for the International Journal of Nonlinear Mechanics. I am an **international reviewer** for Cineca, the Italian consortium that assigns and manages funding provided by the Ministry of Education, University and Research. I am taking part in the **Women in STEM campaign** (https://stories.nuigalway.ie/women-in-stem/) at NUI Galway to promote the role of women in Engineering and Mathematics. I have recently joined the ISIMM, the International Society for the Interaction of Mechanics and Mathematics.

SECTION 2 – Publication Details

A. SELECTED SENIOR-AUTHOR PUBLICATIONS

1. **Poynting effect of brain matter in torsion.** Published in *Soft Matter*. In this study, I performed mechanical tests on porcine brain samples to characterise the behaviour of brain matter in large torsion. I used a rotational rheometer to measure the torque and the normal force required to twist cylindrical brain samples. Together with Prof. Ní Annaidh's group in University College Dublin, I developed a novel testing protocol to determine the elastic behaviour of the brain in torsion. Our modelling approach provides a sound and robust method to measure both torsional and vertical forces experienced by the tissue under large twisting. I designed and conducted the mechanical tests, developed the modelling approach and performed the statistical analysis of the data. Moreover, I supervised a PhD student on the development of the numerical simulations of rotational head impacts and led and coordinated the preparation of the scientific article related to this study. Our numerical simulations were able to show that the vertical forces developed during rotational head impacts can lead to levels of strain in the brain compatible with permanent brain injuries. Moreover, for the first time we were able to measure the vertical forces experienced by brain tissues during twisting. This study opened a new way to understand brain injuries associated to car and sports accidents.

2. **A modified formulation of quasi-linear viscoelasticity for transversely isotropic materials under finite deformation**. Published in the *Proceedings of the Royal Society A*. In collaboration with Dr Shearer and Prof. Parnell, **I developed a theory of quasi-linear viscoelasticity (QLV) for transversely isotropic (TI) materials under finite deformation**. The theory captures the stress-relaxation behaviour of soft tissues with one family of fibres, such as muscles, tendons and ligaments. Stress-relaxation is observed when a tissue is deformed and then held in position. In nonlinear viscoelastic materials, the resulting stress curve decays with time, and the shape of the curve is dictated by the amount of deformation imposed and the viscoelastic properties of the material. Our constitutive model accounts for distinct relaxation responses which are incorporated into an integral formulation of nonlinear viscoelasticity, according to the physical mode of deformation. The theory is consistent with linear viscoelasticity in the small strain limit and makes use of relaxation functions that can be determined from small-strain experiments, given the time/deformation separability assumption. After considering the general constitutive form applicable to compressible materials, we specialised the model to incompressible materials. Our model suggests that **the Poynting effect is present in TI, neo-Hookean, QLV materials under simple shear, in contrast to neo-Hookean elastic materials subjected to the same deformation**. Its presence is explained by the anisotropic relaxation response of the medium. As lead author on this paper, I develop and implemented the mathematical model and lead the writing of the paper. Moreover, our model captures the non-linear feature of **strain-dependent relaxation** whereby the relaxation curve depends on how much the material is stretched. QLV models have always been criticised for not capturing this non-linear phenomenon. For the first time, we incorporated this feature in a modified QLV formulation.

3. **Morphoelastic control of gastro-intestinal organogenesis: theoretical predictions and numerical insights.** Published in *Journal of the Mechanics and Physics of Solids*. With nine meters in length, the gastrointestinal tract is not only our longest, but also our structurally most diverse organ. During embryonic development, it evolves as a bi-layered tube with an inner endodermal lining and an outer mesodermal layer. Its inner surface displays a wide variety of morphological patterns, which are closely correlated to digestive function.

In this study, I developed a mathematical model to predict the **formation of a variety of patterns** observed on the surface of the inner layer in different parts of the gastro-intestinal system. I used the theory of nonlinear elasticity, the theory of volumetric growth and the theory of small on large deformations, to model surface morphogenesis as the instability problem of constrained differential growth. Our model showed that geometric and mechanical factors can explain intestinal pattern formation. I further implemented Finite Elements (FE) simulations in Abaqus to **predict pattern evolution** in the post-buckling regime. Our model explains why longitudinal folds emerge in the *esophagus* with a thick and stiff outer layer, whereas circumferential folds emerge in the *jejunum* with a thinner and softer outer layer. In intermediate regions like the *feline esophagus*, longitudinal and circumferential folds emerge simultaneously. Our model could serve as a valuable tool to explain and predict alterations in esophageal morphology as a result of developmental disorders or certain digestive pathologies including food allergies. This was **one of the first studies in the literature to use FE simulations to predict pattern evolution in soft tissues** and the numerical codes are have since been used in the field to predict evolution of folds and wrinkling in soft materials by mathematicians, mechanical and biomedical engineers. As lead author, I developed the theoretical model, implemented the model in Mathematica, performed the numerical simulations in Abaqus, and led and coordinated the writing of the paper.

B. OTHER PUBLICATIONS

1. Andrini A, **Balbi V**, Bevilacqua G, Lucci G, Pozzi G, Riccobelli D (2022). Mathematical modelling of axonal cortex contractility. Brain Multiphysics (3) 100060. Here we study how the axon remodels (contracts in the hoop and axial directions) to maintain a homeostatic state which is optimal for its functionality.
2. **Balbi V** & Righi M. Foundations of viscoelasticity and application to soft tissues mechanics, available on arXiv (https://arxiv.org/abs/2108.08078). Chapter in "Modelling of Biomaterials". Publisher: Birkhauser. Editors: Josef Málek and Endre Suli, 2021.
   Here we review the foundations of the theory of Quasi-Linear Viscoelasticity and show how to apply this theory to model the viscoelastic response of soft tissues in torsion.
3. **Balbi V,** Destrade M & Goriely A (2020). Mechanics of human brain organoids. Physical Review E, 101(2), 022403. I proposed a morphoelastic model to predict lyssencephaly, a brain malformation occurring at the early stages of human brain organoids development.
4. Ciarletta P, **Balbi V**, & Kuhl E (2014). Pattern selection in growing tubular tissues. Physical review letters, 113(24), 248101. In this study, I developed theoretical and numerical simulations for the onset of elastic instabilities during growth of cylindrical tissues.
5. **Balbi V** & Ciarletta P (2016). Mathematical modeling of morphogenesis in living materials. In Mathematical Models and Methods for Living Systems (pp. 211-274). Springer, Cham.
   A chapter where we detailed the theory of volumetric growth and show how to model elastic instabilities associated to constrained growth in different geometric settings.
6. **Balbi V** & Ciarletta P (2013). Morpho-elasticity of intestinal villi. Journal of the Royal Society Interface, 10(82), 20130109. The first publication where we analyse the effect of mechanical anisotropy on the onset of growth related instabilities in soft tissues.
7. **Balbi V** & Ciarletta P (2015). Helical buckling of thick-walled, pre-stressed, cylindrical tubes under a finite torsion. Mathematics and Mechanics of Solids, 20(6), 625-642.
   Here I developed a mathematical model to predict the onset of elastic instabilities associated to torsional deformations in cylindrical tubes.