Fecha de presentación del Informe: Día 7 Mes 03 Año 2019

1. Datos generales del Proyecto

Código del proyecto: CI 2864			
Título del proyecto: BIOMODE: Biomechanical Modeling of Deglutition			
Facultad o Instituto Académico: Facultad de Ingeniería Universidad del Valle – GIPSA-LAB Universidad de Grenoble (FRA)			
Departamento o Escuela: Escuela de Ingeniería Mecánica (Univalle)			
Grupo (s) de investigación: Grupo de Investigación en Fatiga y Superficies GIFS (Univalle) – Grupo de Investigación en Mejoramiento Industrial GIMI			
Entidades: Universidad del Valle – GIPSA-LAB Universidad de Grenoble (FRA)			
Palabras claves: Swallowing, Deglutition, Computational Fluid Dynamics, Oral propulsión, food bolus, Dysphagia			
Investigadores [1]	Nombre	Tiempo asignado	Tiempo dedicado
Investigador Principal	Argemiro Collazos Pino (Univalle)	4 hr/s	4 hr/s
Coinvestigadores	Alexander Ladino (Univalle)	4 hr/s	4 hr/s
	Gonzalo Fernando Casanova (Univalle)	6hr/s	6hr/s
	Nicolas Pierre Hermant (GIPSA-LAB Univalle)	6 hr/s	6 hr/s

[1] Todas las personas relacionadas en el informe y que participen en el proyecto deben haber suscito el acta de propiedad intelectual de acuerdo con los formatos establecidos.

Otros participantes	Nicolás Ramírez Parra (Asistente de investigación Maestría) Mauricio García Posada (Pasante Investigación Pregrado) Juan Camilo Blandón (Pasante Investigación Pregrado) Leonel Albeiro Terán (Apoyo Estudiante Doctorado)		

2. Executive summary:

Abstract

Deglutition or swallowing is the process in which, coordinate motion of several muscles transport the food bolus, from the oral cavity to the low esophageal sphincter. This process is composed by several stages such as food bolus preparation, propulsion, pharyngeal and esophageal stages. In general, any physiological or pathological affection to this coordinated process is known as dysphagia, and it is associated with stroke survivors, Parkinson, multiple sclerosis, and in general aged related diseases. Dysphagia severely affects the life quality of the patient and can cause death, mainly to the effects of food bolus aspiration (aspiration pneumonia).

This research was done in collaboration with GIPSA-LAB, who work under the macro project “eSwallHoome”, funded by the French Agence Nationale de la Recherche (FANR) The research has as the main objective to study and explain the mechanisms of breathing and swallowing via in vivo, *in vitro and in simulacra* approaches. The project Biomechanical modeling of deglutition (Biomode) is focused on modeling the behavior of food bolus during the swallowing process.

This project aimed to contribute to the understanding of the physical phenomena

underlying swallowing. Particularly, this project developed tongue's elastic models and simplified models related with the interaction of a liquid, Newtonian food bolus and the oral cavity during the oral propulsion stage. The approach of the study was both experimental and computational. The highlights of the project included: 1. Mechanical models of tongue's motion and deformation based on hyperelastic muscle's properties. 2. Numerical tools for the simulation of large displacement models coupled with nonlinear elastic materials that would potentially describe the fluid structure interaction during oral propulsion stage and also compare the results with experimental data taken from a simplified bench and 3. Generation of simplified dimensionless models of oral propulsion stage based on the interaction between a Newtonian fluid food bolus and the physiological accurate tongue's dynamics, responsible for oral propulsion.

During the project, GIPSA-Lab/TIMC-IMAG laboratories from Grenoble and Nicolas Hermant from Universidad del Valle, developed a full 3D nonlinear elastic model using finite element method and high displacement models of human tongue biomechanics. Also, a basic fluid structure interaction with Newtonian fluid and a nonlinear latex membrane with high displacement model was implemented in ANSYS® Workbench. Finally, two novel simplified dimensionless models for estimation of fluid/tongue interaction load as function of flow regime and fluid food bolus properties were proposed.

The corresponding products that resulted from this project were: A book chapter corresponding to tongue's 3D FEA model, developed by the Grenoble counterpart and Nicolas Hermant from UNIVALLE; an undergraduate thesis from two students, one master thesis, one international congress, one national congress, a submitted paper A2 (Q2).

3. Project Synthesis:

The project explored and proposed several models related to the deglutition process, from a mechanical and fluid dynamics point of view. The first approach was developed by the The GIPSA-Lab/TIMC-IMAG laboratories from Grenoble and Nicolas Hermant from Universidad del Valle, which developed a full 3D mechanical model of the tongue's motion based in hyperplastic material properties and showed in the book chapter named "Human tongue biomechanical modeling"[2].

This work starts with the fundamentals of the tongue's anatomy and performs a review of constitutive models proposed in literature for tongue's tissues. Also, and as the main subject of the chapter, a two-parameter Yeoh strain-energy model was proposed and its FEA implementation was developed to simulate deformations in tongue's tissue in response to muscle activations. The model parameters were estimated from indentation experiments on a fresh cadaver of a 74-year old woman and the simulated tongue was activated by prescribed deformations of activation muscle.

In summary, the results of the numerical model and the experimental parameters can replicate the order of strain and stress found in literature and compared with Magnetic Resonance Imaging (MRI), emphasizing the importance of the choice for a particular constitutive law in order to model the behavior of an organ excited by prescribed muscular forces.

The second approach evaluate the ability of the CAE ANSYS® Workbench platform to simulate fluid structure interactions between hyperelastic materials driven by a Newtonian fluid flow. To develop this objective, a simplified model of the interaction between a Newtonian fluid and a hyperelastic membrane emulating the soft palate region of the oral cavity was developed, both experimentally and computationally.

The experimental and numerical models were based on a simple domain, a 90-degree bend with rectangular cross section roughly emulating the oral cavity and the pharynx as

[2] Nicolas Hermant, Pascal Perrier, Yohan Payan, Chapter 19 - Human Tongue Biomechanical Modeling, Editor(s): Yohan Payan, Jacques Ohayon, Biomechanics of Living Organs, Academic Press, 2017, Pages 395-411, ISBN 9780128040096, https://doi.org/10.1016/B978-0-12-804009-6.00019-5.

a pipe. This configuration evaluated the displacements of a hyperelastic membrane when it is subjected to a pressurized fluid flow. The hyperelastic membrane was located in the 90 corner of the bench as a planar section.

Both, experimental and numerical approaches used a 2^3 factorial design of experiments, where two fluids (water and vegetal oil), two latex thicknesses (Caliber 20 and 16) and horizontal / inclined positions (horizontal and 45 degrees' inclination) were evaluated.

In the case of the experimental bench, fluid flow was developed by displacement pump with variable frequency. Prior to the experiment, repeatability analyses for various latex probes and for ON/OFF pump cycles were made. Pressure drop along the membrane was measured and membrane displacements were determined via imaging processing.

For the numerical model, pressure measurements from the experimental bench were used as boundary conditions for the numerical model. Also, the Neo-Hookean model for nonlinear hyperelastic isotropic materials was selected for the membrane's mechanical behavior with corresponding latex properties. One-way FSI was performed according to numerical design experiments.

As results, for small displacements numerical data were in reasonable agreement with experimental, that is in the cases of water and horizontal/inclined configurations. However, for the oil case, greater deformations were achieved in experimental results in comparison to numerical results. Furthermore, various setups configurations and also with the help of ANSYS support, many convergence and stability issues related with the highly deformed membrane requiring remeshing were found during the process. As conclusion, the ANSYS workbench platform has a limited capability to couple mechanical hyperelastic models with confined fluid flow, inclusive at one way FSI.

The third and final approach dealt with two simplified models of oral propulsion using CFD and developed an additional novel experimental setup for validation.

In the numerical model, real time resonance images from the team in GIPSA-LAB were used to characterize the tongue's dorsum movement. This movement was coupled with ANSYS Fluent through user defined functions and enabled a physiological-accurate movement of the tongue. Dynamic mesh algorithms were also required to account for large deformations in the interior domain due to moving boundary. The model was then, a sagittal physiological accurate two-dimensional representation of the oral stage of swallowing, in which the tongue plays a crucial role.

A full factorial 3^3 design of experiments was implemented to evaluate the influence of swallowing speed and rheology in the loads over the tongue and the fluid flow dynamics of food bolus in general. Additionally, non-dimensional parameters were proposed to evaluate combined effects of the input factors. It was found a clearly defined exponential behavior that predict load conditions over the tongue as a function of rheology and swallowing speed, which can open possibilities of diagnosis and preventive treatments. The latter would require the replication of such a technique in more patients to test repeatability.

Complementary to the physiological accurate model, a second simpler model was also implemented. It had a wedge shape and the food bolus is propelled to the pharynx due to the rigid body motion of the tongue-like boundary. Both models behaved in the same order of magnitudes when comparing integral quantities such as force and shear force over the tongue and presented similar flowrates and velocities at the outlet. Furthermore, such values were consistent with reported values in literature.

Finally, a novel experimental bench that replicates dynamically the oral stage of swallowing was designed and constructed. The experimental bench consisted in an acrylic chamber and a cam follower system to emulate the motion of tongue's dorsum. It successfully drove the fluid in the chamber to the exit, behaving like a positive displacement pump. To evaluate the fluid dynamics inside the chamber, a home-made particle image velocimetry set up was used. The set-up consisted of reflective particles immersed in the fluid, which were illuminated by a green laser sheet. A camera captured the displacement of the particles and image processing algorithms translated this motion to velocity fields. The setup had to be installed in a darkroom, otherwise, ambient light is interpreted as noise and the image processing is less accurate. The physiological-accurate model showed promising results which were comparable to simpler geometries, literature and experimental benches. Such a technique opens the possibility to analyze real time magnetic resonance imaging (RT-MRI) in further detail, to extract behavioral information of swallowing that could affect loads over the tongue and the bolus fluid dynamics.

4. Current and potential impacts:

- Académico (aportes a la docencia, aportes a la formación de recursos humanos):
  - Two undergraduate students of holding BSc. mechanical engineering with basic skills in computational modelling (Computational Fluids Dynamics, and elasticity). II-2017.
  - One Master's graduate student holding MSc. Student with developed skills in computational modelling (Computational Fluid Dynamics), design of experiments, image processing and programming skills. I-2018
- Investigativo (divulgación de resultados):
  - 1 National event: Oral presentation and proceedings in the Congreso Colombiano de Métodos Numéricos XI - CCMN 2017. Rameriez N, Ladino J.A, Casanova F, Hermant N. Simulation of the human swallowing process from the geometry of a healthy adult. *ISBN: 978-958-48-5477-3*
  - 1 International event: Oral presentation and proceedings in the *International Workshop on Biomechanical and Parametric Modeling of Human Anatomy 2016 in University of British Columbia, Vancouver. PMHA2016*. Ramirez N. Ladino J.A, Casanova F,

Hermant N. *“Simplified models of oral swallowing”*

- One book Chapter Published: Hermant, N., Perrier P., Payan Y. *Chapter 19 – Human Tongue Biomechanical Modeling. Biomechanics of Living Organs. Academic Press Series in Biomedical Engineering. Editors Elsevier / Academic Press. 2017. ISBN: 9780128040607*
- One Q2 submitted article: “Physiological accurate numerical simulation of the propulsive phase of deglutition”. Medical & Biological Engineering & Computing Journal *ISSN: 01400118.*

* Future developments:
    - Application of simulation techniques developed in this Project in RT-MRI
    - Development in depth calibration and subsequent application of Particle Image Velocimetry PIV equipment.
    - Development new algorithms for biological tissue mechanics.
    - Application of methodology for load characterization in dysphagia patients.
* Impactos futuros:
    - Development of strategic alliances of professor N. Hermant with University of Grenoble for continuous research in biomechanics (in process).
    - Strategic alliances with modelling software industry. GIPSA-LAB from University of Grenoble and professor Nicolas Hermant from Universidad del Valle with ANSYS Inc (in development). One of the worldwide companies in engineering simulation.

5. Productos:

Tabla No. 1**. Cantidad y tipo de productos pactados en el *Acta de Trabajo y Compromiso* y productos finalmente presentados**

TIPO DE PRODUCTOS	No. de PRODUCTOS PACTADOS	No. de PRODUCTOS PRESENTADOS

TIPO DE PRODUCTOS	No. de PRODUCTOS PACTADOS				No. de PRODUCTOS PRESENTADOS			
Productos de nuevos conocimientos								
Artículo en revista ISI-SCOPUS:	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
	1					1		
Artículo completo publicado en revistas indexadas	**A1**	**A2**	**B**	**C**	**A1**	**A2**	**B**	**C**
	1					1		
Libros de autor que publiquen resultados de investigación								
Capítulos en libros que publican resultados de investigación								
Productos o procesos tecnológicos patentados o registrados								
☐ Prototipos y patentes								
☐ Software								
Productos o procesos tecnológicos usualmente no patentables o protegidos por secreto industrial								
Normas basadas en resultados de investigación								

TIPO DE PRODUCTOS	No. de PRODUCTOS PACTADOS		No. de PRODUCTOS PRESENTADOS	
Formación de recursos humanos	No. de estudiantes vinculados	No. de tesis	No. De estudiantes Vinculados	No. De tesis
Estudiantes de pregrado	2	2	2	1 (Dos estudiantes)
Semillero de Investigación	2	N/A	2	N/A
Estudiantes de maestría	1	1	1	1
Estudiantes de doctorado	1	N/A	1	N/A
Joven investigador				
Productos de divulgación				
Publicaciones en revistas no indexadas				
Ponencias presentadas en eventos (congresos, seminarios, coloquios, foros)	No. de ponencias nacionales	No. de ponencias internacionales	No. de ponencias nacionales	No. de ponencias internacionales
Propuesta de investigación	1	1	1	1

TIPO DE PRODUCTOS	No. de PRODUCTOS PACTADOS	No. de PRODUCTOS PRESENTADOS
Propuestas presentadas en convocatorias externas para búsqueda de financiación.	1	Statement of purpose letter for cooperation GIPSA-LAB-UNIVALLE-ANSYS Inc (France). Proposal does not presented. Prof N. Hermant is incapacitated by illness. Prof. Alexander Ladino is at PhD studies

Tabla No. 2. Detalle de productos

Tipo de producto:	Paper Q1 – Book chapter (for equivalence) Filename: 01a - 2017 - Biomechanics of living organs FrontMatter.pdf 01b - 2017 - Chapter-19 Hermant et.al Human-Tongue-Biomechanical-Modeling.
Nombre General:	Hermant, N., Perrier P., Payan Y. Chapter 19 – Human Tongue Biomechanical Modeling. Biomechanics of Living Organs. Academic Press Series in Biomedical Engineering. Editors Elsevier. Academic Press. June June 2017. ISBN: 9780128040607.

Tipo de producto:	Paper Q2 Filename: 02a - 2019 - Ramirez et.al Physiological accurate deglutition - submission letter. 02b - 2019 - Ramirez et.al Physiological accurate deglutition - paper - MBEC-D-19-00307

Nombre General:	"Physiological accurate numerical simulation of the propulsive phase of deglutition" Medical and Biological Engineering and Computing. Submitted May 2019. ISSN: 01400118.

Tipo de producto:	National conference Filename: 03a - 2017 - Ramirez - Simulation of the Human Swallowing Process from the Geometry of a Healthy Adult - Certification XI CCMN 2018.pdf 03b - 2017 - Ramirez et. al Simulation of the human swallowing from the geometry of a healthy adult – extended.pdf
Nombre General:	Ramirez N., Ladino J., Casanova F., Hermant N. Simulation of Human swallowing process from the geometry of a healthy adult. XI Congreso Colombiano de Métodos Numéricos 2017. UIS Bucaramanga, Colombia. Agosto 16-18 2017. ISBN: 978-958-48-5477-3

Tipo de producto:	International Conference. Filename: 04a - 2016 - Simplified numerical model of the oral phase of swallowing - PMHA-2016-Attendance.pdf 04b - 2016 - Simplified numerical model of the oral phase of swallowing - PHMA-2016 Proceedings short.pdf
Nombre General:	Ramirez, N., Ladino J.A, Casanova F, Hermant N. Simplified models of oral swallowing. International Workshop on Biomechanical and Parametric Modeling of Human Anatomy (PMHA2016). University of British Columbia, Vancouver, Canada.

Tipo de producto:	Undergraduate thesis. Filename: 05 - 2018 - Undergraduate thesis evaluation letter.pdf
Nombre General:	García, Mauricio. Blandón, Juan Camilo. Análisis numérico y validación experimental de un modelo simplificado de deglución en seres humanos. Pregrado en ingeniería mecánica. II-2017. Acta de sustentación.

Tipo de producto:	Masters Thesis. Filename: 06 - 2018 - Masters thesis evaluation letter 20180905134748.pdf
Nombre General:	Ramírez Nicolás. Biomechanical Modeling of Deglutition. Maestría en ingeniería mecánica. I-2018.

Tipo de producto:	Undergraduated/Graduted* elective course Filename 07b - 2017 - Elective course syllabus - Fundamentals of Biomechanics.pdf Elective course defined for undergraduate students and also for master students
Nombre General:	Fundamentals of Biomechanics. Cod. Programa de curso. Desarrollado el II-semestre de 2017.

Tipo de producto:	Semillero de investigación. Filename 08 - 2016 - Blandón - research hotbed certify.pdf

Nombre General:	Certificado de terminación del programa de Semilleros de Investigación - Juan Camilo Blandón.

Tipo de producto:	PhD student enrolment. Leonel Terán c-PhD Filename 09 - 2017 - Intellectual property enrollment act pHD student Leonel Teran.pdf
Nombre General:	Intellectual property act – Biomode.

Tipo de producto:	Intention letter for collaboration GIPSA-LAB School of Mechanical Engineering and ANSYS Inc. Filename 10 - 2018 - Attestation de collaborations 3D tongue biomechanics.pdf
Nombre General:	Statement of purpose letter for cooperation GIPSA-LAB-UNIVALLE-ANSYS Inc (France). January 2018.

Firma del investigador principal

Vo. Bo. Vicedecano Investigaciones