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► **To cite this version:**

Clément de Loubens, Faisal Ahmad, Guillaume Maîtrejean, Stéphane Tanguy. Investigating human defecation by coupling fluid mechanical modeling and X-ray video-defecography. 48th Congress of the Society of Biomechanics, Oct 2023, Grenoble, France. pp.S60-S62, 10.1080/10255842.2023.2246304 . hal-04272594

HAL Id: hal-04272594

<https://hal.science/hal-04272594v1>

Submitted on 6 Nov 2023

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Investigating human defecation by coupling fluid mechanical modeling and X-ray video-defecography

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1. Introduction

Defecation is a complex physiological process involving multiple systems, including neural, muscular, hormonal, and cognitive functions (Heitmann et al., 2021). Abdominal and rectal contractions trigger defecation, which is followed by rectal evacuation through the anal canal. Defecation disorders, such as constipation or incontinence, affect approximately 15% of the global population (Higgins et al., 2004). Because of limited understanding of defecation, it is challenging for physicians to distinguish aetiologies from symptoms (Scott et al., 2008).

There are many possible causes of defecation disorders, including slow bowel transit, structural obstructive phenomena, anal sphincter injuries. However a significant proportion of patients with impaired defecation do not have a well-defined anatomic disorder (Faucheron and Dubreuil, 2000). Although many testing tools are available to diagnose anorectal function (e.g., manometry, video defecography, MRI), methodologic issues limit physicians' understanding of pathophysiological defecation (Carrington et al., 2018).

To gain new insights on the biomechanics of human defaecation, we developed patient-specific simulations of rectal evacuation of yield stress fluids based on X-ray video-defecographies with a neostool. First, we segmented automatically X-ray videos with a Convolutional Neural Network. Then, flow, pressure and stress fields were simulated by lattice-Boltzmann methods for yield stress fluids. Lastly, we applied the model to simulate normal defecation, and impaired defecations in absence or in presence of obstructive phenomena (rectocele).

2. Methods

2.1 Video defecographies

X-ray video-defecographies were carried out with the patient in sitting position, Fig. 1. The rectum was filled with a standardized radio-opaque neostool (Faucheron and Dubreuil, 2000). The neostool was prepared by mixing barium sulfate with a suspension of potato starch and cooked to obtain a paste with a yield stress

τ_0 of 350 Pa, which matched to the yield stress of soft regular human feces (de Loubens et al., 2020). All the patients underwent X-ray defecographies during their health care pathways. The procedures performed in this study complied with the requirements of the ethical standards research committee and with the Helsinki declaration. Ethics approval is not required for this retrospective study.

2.2 Image segmentation

The RCNN (Region-based Convolutional Neural Network) architecture, and specifically the R50-FPN Mask R-CNN variant, was utilized for the automatic segmentation of X-ray defecography images, Figure 1. R-CNN works by generating region proposals, extracting features using a convolutional neural network, and then classifying the proposed regions and refining their bounding boxes if necessary. Despite the limited dataset of only 200 manually segmented rectum instances, the R50-FPN Mask R-CNN model achieved impressive results with an average precision of 83%.

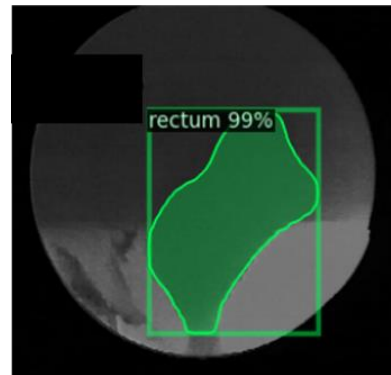


Figure 1: Automatic segmentation of the rectum from X-ray video defecography by a Region-based Convolutional Neural Network (RCNN).

2.3 Lattice-Boltzmann solver

As the neostool was very viscous and the Reynolds number very small, the flow was modelled using the incompressible Stokes equations in 2D for Herschel-Bulkley fluid (with $\tau_0 = 350$ Pa, $n = 0.42$, $k = 1000$ Pa.s^{0.42}). The smoothed position of boundary nodes extracted from the video and their velocity were used as boundary conditions along the moving wall of the rectum. The set of equations was solved by lattice-Boltzmann methods for yield stress fluids and moving boundary conditions, see details in Ahmad et al., 2022. We computed flow, pressure and stress fields and also the stress applied in the normal direction by the fluid over the boundaries of the rectum, i.e the wall normal stress (WNS). By integrating the WNS along the boundaries of the rectum, we calculated also the effective evacuation force F .

3. Results and discussion

We calculated flow, pressure, and stress in the rectum for three types of patients: (i) normal evacuation, (ii) impaired defecation without obstruction, and (iii) anatomical obstruction. In Fig. 2, we provide an example of the rectum's squeezing action during defecation. The WNS was highest at the proximal moving part and decreased at the static anorectal junction. Similarly to high resolution manometry (Scott et al. 2008), the spatio-temporal evolution of the pressure along a mid-line going from the anal to the proximal ends is shown for one example in Fig. 2. In this example, the pressure dropped from 15 to 0 kPa between 5 cm and 0 cm, and increased up to 10 s towards the ano-rectal junction.

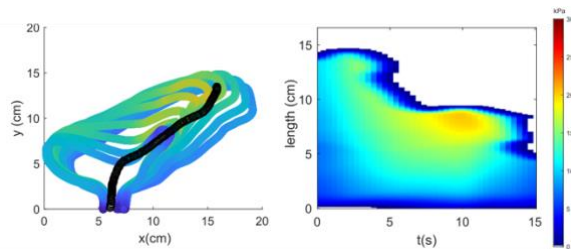


Figure 2: Example of Wall Normal Stress during the defecation of patient with a rectocele (left) and spatio-temporal map of the pressure along the black line (right).

For normal patients, we found that viscous stress was significantly higher than the yield stress of the neostool in the anal canal and the anorectal junction. The flow of the neostool was restricted by these anatomical parts and governed by its shear-thinning properties (see Ahmad et al. 2022 for details). The relationship between the outlet velocity through the anal canal and the evacuation force was strongly non-linear due to the shear-thinning properties of the neostool. In patients with impaired defecation without any obvious anatomical disorder, the WNS and the applied force were only half of what they were in normal patients. This led to a dominance of the yield stress on the flow of the neostool, resulting in a flow rate that was 10 times smaller than for normal patients. Lastly, in patients with an anatomical disorder such as rectocele (Fig. 2), the initial phase of defecation had a normal development of the WNS. However, it was unable to sustain the maximum force (pressure) during the second phase of defecation, leading to partial evacuation. Furthermore, while the force applied to the rectum in normal patients was oriented along the mid-axis, it exhibited a different orientation in cases of rectocele.

4. Conclusions

In this study, a fluid mechanics analysis of video defecography was introduced as a potential tool to

complement clinical investigations of anorectal function. This approach could help better understand normal and pathologic defecation, and identify the origin of disorders such as rectoanal discoordination. By combining medical imaging and fluid dynamics, a new pathophysiological classification of evacuation disorders could be established.

Acknowledgements

The authors thank Agence Nationale de la Recherche for its financial support of the TransportGut project, ANR-21-CE45-0015. The authors would also like to thank Prof. Jean-Luc Faucheron and Dr. Alain Dubreuil for all the data and in-depth discussions.

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Keywords: Rectum; Motility; Rheology

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