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EFFECTS OF AGE AND LOADING VELOCITY ON THE DELAMINATION STRENGTH OF THE HUMAN AORTA

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Abstract. Arterial Dissection is a life threating disease which manifests as a process of delamination. It occurs most frequently in the thoracic aorta but it can spread along the entire length of the aorta. The crack that separates arterial wall layers may create a rupture of the wall itself, with often fatal consequences. The mechanical conditions at which the human aorta delaminates are the subject of the research presented here. Our study employs both experimental and computational approaches. The delamination strength is investigated in the peeling experiments, which were carried out with samples of the human aorta obtained from three different locations – ascending thoracic aorta, descending thoracic aorta, and abdominal aorta. Peeling experiments were designed to take into account the possible effects of arterial anisotropy and a rate-dependent mechanical response. The computational branch of our study is based on the XFEM model of the peeling experiment built in Abaqus, and on attempts to find the age- and location-dependent parameters of the traction-separation law. Our preliminary results suggest that there is a strong correlation between age and delamination strength. Furthermore, the delamination properties of the descending thoracic aorta seem to be rate-dependent, which is in contrast to the results observed in other aortic locations.

1 INTRODUCTION

Arterial dissection is a life-threatening disease manifested by a separation of the layers of an artery wall [1–3]. It occurs most frequently in the thoracic part of the aorta, but it can spread along its entire length. The dissections of other arteries, like the carotid artery or vertebral artery, are also described in the literature. Although one could consider aortic dissection to be a relatively rare disease, the rate of incidence is typically reported as ranging from 3 to 6 cases per 100 000 per year, nevertheless the lethality of dissection is rather high. According to [4], 37% of patients who reach the hospital alive die within the next 30 days, and approximately 20% of patients die before they receive medical intervention [5].

During dissection, blood enters the wall and causes the delamination of its layers. Further separation often leads to the creation of a new false lumen which can extend longitudinally. The dissection tear may run along an artery, along with some radial inclination, and reach the external surface of the artery. In such a case, internal hemorrhage follows. Another kind of failure induced by the dissection is a rupture of the weakened cross-section of the dissected artery wall.

Thus far, the exact dissection-initiation mechanism has not been definitively established and a detailed description of dissection propagation is a subject of current research. Our study tries to extend the knowledge of the biomechanics of aortic delamination by means of both experimental and computational approaches. The peeling experiment is the basic instrument utilized to show how the delamination strength depends on the anatomical site, loading velocity, and crack tip direction. The computational branch of our study is based on the XFEM model of the delamination test built in Abaqus, and attempts to find the age and location-dependent parameters of the traction-separation law of a cohesive zone.

2 METHODS

2.1 Samples

Segments of human aortas were obtained during regular autopsies conducted in the Department of Forensic Medicine and Toxicology at the Regional Hospital Liberec. The post-mortem use of human tissue was approved by the Ethics Committee of the Regional Hospital Liberec. Highly calcified segments, and tissues from cadavers exhibiting putrefaction changes were not included in the study. Any possible bias in the results due to post-mortem changes was ruled out by post-hoc statistical analysis.

Rectangular samples, approx. 8 x 40 mm, were cut from aortic segments. These segments were excised from the ascending as well as descending thoracic aorta, and from the abdominal aorta. Rectangular samples were cut, aligned with both the longitudinal and circumferential direction of the vessel.

2.2 Peeling experiment

A method adopted to characterize the delamination properties of the aorta is the so-called peeling test. This experimental protocol was, in the context of the biomechanics of the aortic dissection, introduced by Sommer in 2008 [1] and has been used in further studies focused on the delamination properties of arteries [6–12]. It resembles the mode I crack opening that is widely used in fracture mechanics, see Figure 1. The main advantage of this experimental technique lies in the controllable crack propagation, which allows for the quantification of fracture energy.

As indicated in Figure 1, when the clamps move apart, forces induced by them open the crack front and delamination takes place. The intact portion of the sample shortens as the clamps continue in their movement. In the final stage of the experiment, the tested sample falls apart into two separate sections.

The experiments were carried out with the help of the multipurpose tensile testing machine, Zwick/Roell (Messphysik). Both the delamination force *F* (the force that is necessary to increase a tear length) and the tear length were recorded on a PC. The delamination force was measured by HBM U9C +/- 25N force transducers. The tear length was determined from the movement of the clamps, which was recorded at 1 μm resolution. This data was complemented with the recordings carried out by a built-in video-extensometer, which measured the distance between the marks made on the surface of the samples. In order to determine whether delamination strength depends on loading rate, the experiments were carried out with clamps' velocity set to 0.1, 1, 10, 50 mms^{-1}.

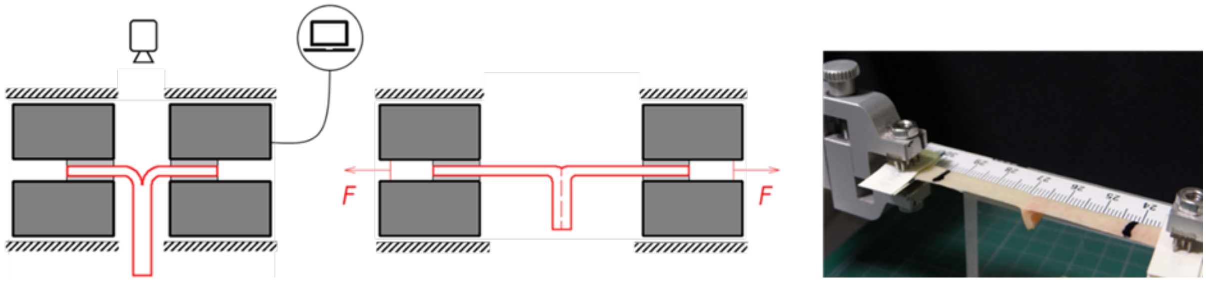

Figure 1: Scheme of the peeling experiment.

2.3 Statistical evaluation

As mentioned above, to study site-specific differences in the delamination strength, our study included experiments with strips obtained from the ascending and descending thoracic aorta, and the abdominal aorta. Anisotropy of the delamination strength was studied by means of employing samples oriented in the longitudinal and circumferential direction of the aorta. Finally, dependence on loading velocity was also investigated. All these properties were studied by means of Kruskal-Wallis tests, complemented with the Dunn test to determine which particular groups significantly differed from each other. The hypothesis that the delamination properties depend on age was evaluated in the post-hoc correlation analysis. In all statistical evaluations, results were considered to be significant at the level, $\alpha = 0.05$.

2.4 Outline of the regression analysis of the traction-separation law

The principle idea is to simulate the peeling experiments by means of FEM, with XFEM employed to capture discontinuity propagation. When the geometrical and bulk properties of arterial strips are known from experiments, the only unknowns that remain to be determined are the parameters of the traction-separation law. Our FEM model is built in Abaqus (v. 2019, [13]) and the Gasser-Ogden-Holzapfel strain energy density function [14] is used to capture the elastic behavior of the aorta. The linear traction-separation law adopted from [15] is used to describe local damage, eq. (1). The damage is introduced into the cohesive zone when the maximum principle stress reaches the threshold T_c. When Δu reaches Δu_c, the tear propagates. T_c and Δu_c are the material parameters which will be determined by means of the minimization of the differences between the reaction force computed in the FEM model of the peeling experiment and the observed delaminating force.

$$T = \begin{cases} T_c\left(1-\dfrac{\Delta u}{\Delta u_c}\right) & 0 \le \Delta u < \Delta u_c \\ 0 & \Delta u_c \le \Delta u \end{cases} \tag{1}$$

3 RESULTS AND DISCUSSION

3.1 Delamination experiments

Experiments with tissues obtained from 11 donors were carried out from November 2020 to April 2021. Figure 2 shows the typical recordings obtained in these experiments. In this particular case, it can be seen that the delamination force is dependent on the loading velocity observed in the descending thoracic aorta in experiments conducted with samples delaminated in the longitudinal direction of the vessel. Each curve was sampled at 20 frames per second, which explains why the curves corresponding to a high velocity seem to be smoother than the curves recorded in a slow movement.

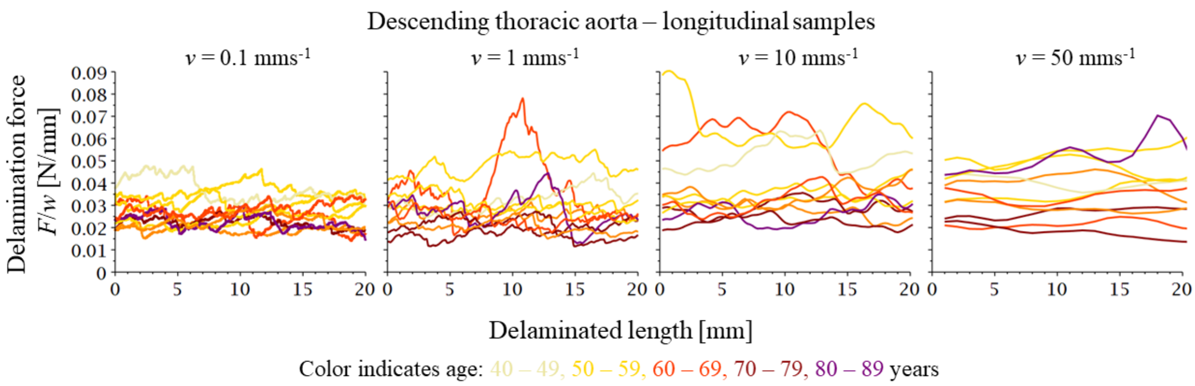

Figure 2: Examples of the recorded force plotted as a function of increasing crack length. In this particular case, the Kruskal-Wallis test and the Dunn test identified significant differences between groups of samples loaded at different loading rates; see Figure 4 (second panel form left). In all panels, axes have the same scaling.

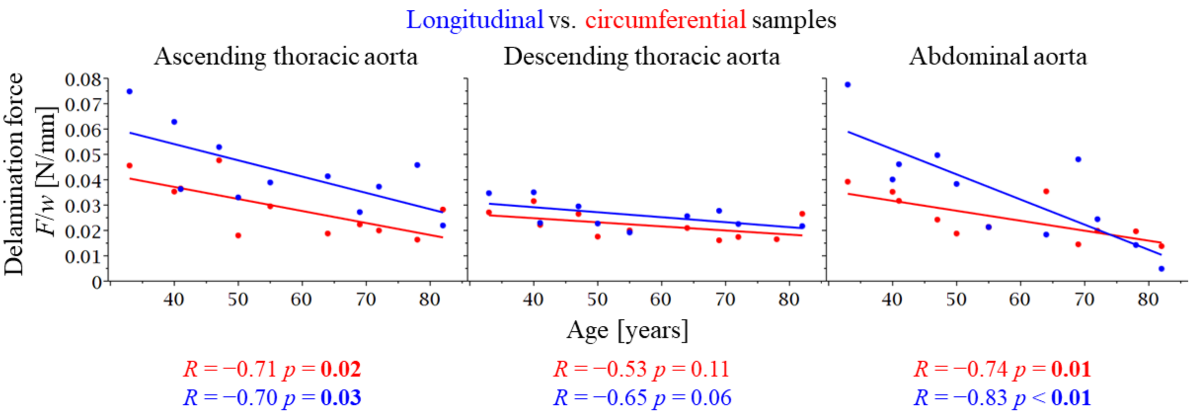

Figure 3: Correlation between age and delamination strength at 0.1 mms^{-1}. Points were obtained as medians of recorded forces. The correlation is tight in the ascending thoracic and abdominal aorta. The delamination strength in the descending thoracic aorta is rather smaller than in the ascending and abdominal parts of the aorta.

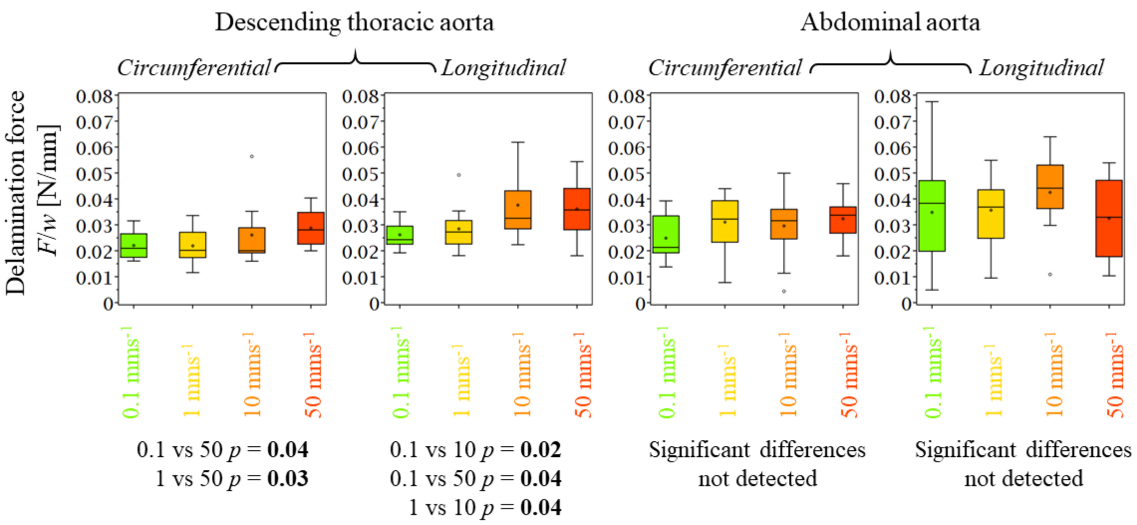

Figure 4: Effect of loading rate. Groups of medians of observed delamination strength. In contrast to the ascending and abdominal parts of the aorta, data obtained for the descending thoracic aorta suggest that delamination strength could depend on the loading velocity. Significantly different pairs of groups were identified by means of the Dunn test.

The colors used in Figure 2 indicate the age of the donor, the darker the older. Perfectly arranged shades would suggest a strong correlation of the delamination force with age. However, the correlation analysis revealed that samples from the thoracic aorta do not exhibit so tight correlation with age, contrary to the remaining two locations as shown in Figure 3.

Each point in Figure 3 was obtained as a median of the corresponding experimental record. This figure also offers an easy comparison of site-specific differences. The data shows that the descending thoracic aorta exhibits the lowest delamination strength, which is in accordance with clinical observations characterizing this part of the aorta as highly susceptible to dissection. The fact that regression lines in the thoracic aorta do not mutually intersect suggests that delamination strength should be an anisotropic property and resistance to crack propagation is higher in the longitudinal direction. This result is also in accordance with clinical observations and with results known from biomechanical literature [1,9,16].

Our preliminary results also suggest that rate-dependent phenomena could play a role in the delamination failure of the aorta. This can be observed for the descending thoracic aorta, as one can see in Figure 4 (first and second panel from left). On the other hand, experiments carried out with samples obtained from the ascending part of the thoracic aorta and from the abdominal aorta did not show this property. Eleven donors, which is the number of experiments which were processed by the spring of 2021, cannot be considered to be final. Our experiments will run at least until this autumn and we expect that the final count will be double the current one. Final conclusions with regards to the effect of loading rate are left to that time.

3.2 FEM simulations

Currently we are at the point of debugging the FEM model, therefore results obtained up to now cannot be considered as final. A 2D model is ready to be used but exhibits discrepancies rising from an out-of-plane orientation of reinforcing fibers. A 3D model exhibits certain issues related to convergence. Thus, FEM-based regression analysis for the traction-separation law parameters is a task that remains to be completed in our study. Figure 5 shows an example comparing measured and predicted delamination force.

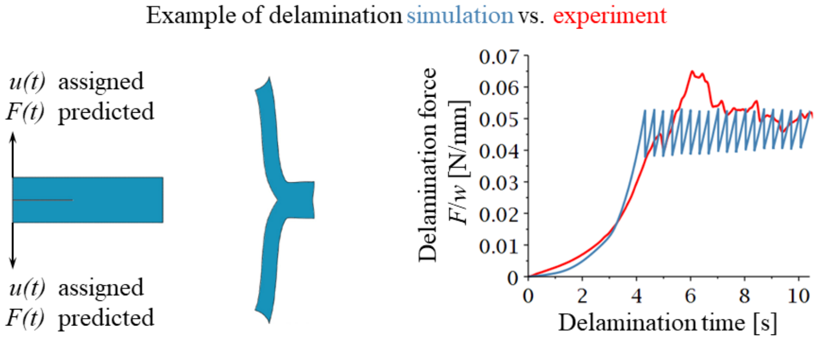

Figure 5: Comparison between FEM computed and measured force.

4 CONCLUSIONS

Our paper reports the preliminary results of our project, dealing with the delamination properties of the human aorta. Experiments carried out with samples from eleven donors have suggested that there is a strong correlation between age and delamination strength; that delamination strength depends on anatomical location, and that it is an anisotropic property. It also seems that the descending thoracic aorta could exhibit rate-dependent delamination strength. Regression analysis of the traction-separation law is planned to be carried out with the help of the FEM/XFEM model, but at this time it is still at the debugging phase.

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