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Research Paper

Predictive model of the prostate motion in the context of radiotherapy: A biomechanical approach relying on urodynamic data and mechanical testing

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ABSTRACT

In this paper, a biomechanical approach relying on urodynamic data and mechanical tests is proposed for an accurate prediction of the motion of the pelvic organs in the context of the prostate radiotherapy. As a first step, an experimental protocol is elaborated to characterize the mechanical properties of the bladder and rectum wall tissues; uniaxial tensile tests are performed on porcine substrates.

In a second step, the parameters of Ogden-type hyperelastic constitutive models are identified; their relevance in the context of the implementation of a human biomechanical model is verified by means of preliminary Finite Elements (FE) simulations against human urodynamic data.

In a third step, the identified constitutive equations are employed for the simulations of the motion and interactions of the pelvic organs due to concomitant changes of the distension volumes of the urinary bladder and rectum. The effectiveness of the developed biomechanical model is demonstrated in investigating the motion of the bladder, rectum and prostate organs; the results in terms of displacements are shown to be in good agreement with measurements inherent to a deceased person, with a relative error close to 6%.

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1. Introduction

In the treatment of prostate cancer based on conformational radiotherapy, safety margins surrounding the volume of the prostate are considered accounting for the complexity of the surrounding anatomy and its motion during irradiation (van Herk, 2004; Kragelj, 2005). Zelefsky et al. (1999) carried out an experimental work in order to assess the margins to be applied during the radiotherapy sessions around the clinical target volume (CTV; here the prostate); fifty patients were subjected to four CT scans during their course of radiotherapy. The margins are calculated on the basis of the inter-subjects standard deviations of the prostate displacements found experimentally. Considering large margins around the CTV may lead to harmful irradiations to the healthy surrounding organs, in particular the bladder and the rectum (Voyant et al., 2011). Consequently, reducing these margins around CTV is the main concern for radiophysicists (Artignan et al., 2006). In this respect, a biomechanical approach that predicts the prostate motion is especially important to understand the pelvic iterations and helps to calculate the merely enough values of margins around the CTV.

From an anatomical point of view, the prostate is located in the center of the pelvic area, the lower part of the man's abdominal cavity, as shown in Fig. 1. The organ lies between the bladder and the urogenital diaphragm, and is anterior to the rectum. Its anterior surface is adjacent to the pubic symphysis (the midline cartilaginous joint holding together the left and right pubic bones). The urinary bladder funnels into the prostate gland through the prostatic Urethra. Its posterior side is in contact with the Denonvilliers' fascia and the seminal vesicles which are confined in the rectovesical pouch. As to the rectum, its lower part, the anorectal ring is embedded in the pelvic floor. Its posterior surface is adjacent to the sacrum (posterior pubic bones). The puboprostatic ligament, which makes the upper fascia of the pelvic diaphragm in the male larger, extends laterally from the prostate and provides attachment to the bony pelvis.

The prostate motion is due to a number of factors, and partly to the distension of the urinary bladder and rectum.

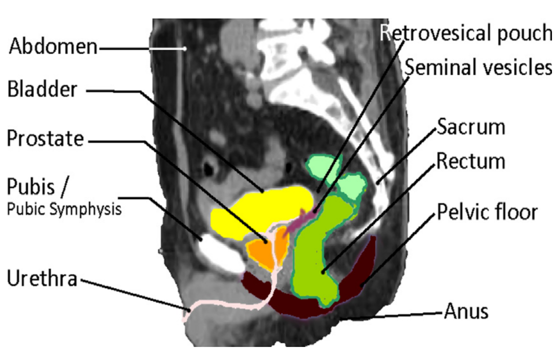

Fig. 1 – Overview of the pelvic anatomy. Scan acquired on a patient at C.A.V. Center at University Hospital (CHU-Brabois, Nancy), segmented and colored at L.E.M.T.A. Laboratory (Nancy, France). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

According to the reviews of Artignan et al. (2006) and Marchal et al. (2006), the rectum is the anatomical entity having the largest influence on the shape and motion of the prostate, but this organ is also influenced by the bladder and from its top by the lungs. Accordingly, the prostate displacements are mostly oriented in the anteroposterior direction. The displacements in this direction due to the rectal repletion are about 5 mm, with a maximum up to 20 mm according to patient and to the filling state of the prostate (for a prostate of a size of about 4–5 cm) (Marchal et al., 2006, p. 47). Similarly, the rectum motion involves a gland motion of 3 mm in the craniocaudal direction. The displacements of the prostate in the lateral direction are lower than 1 mm, a motion which is nearly not noticeable. The displacements of the prostate due to the bladder are principally oriented in the anteroposterior direction, with a tendency to move in the superoanterior direction. Globally, the bladder seems to less influence the prostate position than the rectum position. In order to quantify the prostate motion due to concomitant volume changes of bladder, rectum and the lungs, Keros et al. (2006) have carried out a series of measurements on a fresh human cadaver; a series of CT scans were acquired at each volume change of one of the aforementioned organs. A number of the quantified displacements are reported in Table 1.

A biomechanical model that aims at predicting the motion and interactions of the pelvic organs due to vesical and rectal distensions has been developed by Boubaker et al. (2009). An elastic modulus, equal to 60 kPa, was attributed to the prostate, whereas hyperelastic constitutive models were used for the urinary bladder and rectum wall tissues, assuming tissue homogeneity and isotropy. Material parameters in a first-order Ogden strain–energy model were first determined by fitting tensile data from Rubod et al. (2007) and then adjusted, in an iterative manner, in order to obtain a satisfactory agreement between the numerical simulations and anatomical measurements and observations of prostate displacements recorded by Keros et al. (2006): the errors resulting from this methodology were about 13%.

The relevance of adjusting the constitutive model coefficients, in the frame of a biomechanical model implementation, can, however, be questionable. As a perspective of our previous contribution, an independent measurement protocol of the organs' mechanical properties was suggested.

In this study, motivated by the need for improving the existing biomechanical approach of pelvic organs motion, the mechanical behavior of rectum and urinary bladder wall tissues is investigated and constitutive models are identified. Further changes are also brought to our previous approach so that the FE simulations are able to better reproduce the anatomical observations of the pelvic organ motion. In fact, urodynamic data from the urology service at the University Hospital Center (CHU-Brabois, Nancy, France) are exploited, firstly, to identify the values of the inflation pressures for the urinary bladder and rectum organs. Secondly, these data are also used to verify the relevance of the constitutive models before being implemented in the finite element model of the pelvic area. The exploitation of the urodynamic data is therefore an original feature in our biomechanical approach. In addition to the previous