Computer-Integrated Surgery of the Human Brain, New Possibilities

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Abstract : The discipline of Computer-integrated surgery (CIS) will provide equipment able to improve the efficiency of healthcare systems and, which is more important, clinical results. Surgeons and machines will cooperate in new ways that will extend surgeons' ability to train, plan and carry out surgery. Patient specific CIS of the brain requires several steps: 1 - Fast generation of brain models. Based on image recognition of MR images and equipped with artificial intelligence, image recognition techniques should differentiate among all brain tissues and segment them. After that, automatic mesh generation should create the mathematical model of the brain in which the various tissues (white matter, grey matter, cerebrospinal fluid …) are clearly located in the correct positions. 2 – Reliable and fast simulation of the surgical process. Computational mechanics will be the crucial aspect of the entire procedure. New algorithms will be used to simulate the mechanical behaviour of cutting through cerebral tissues. 3 – Real time provision of visual and haptic feedback A sophisticated human-machine interface based on ergonomics and psychology will provide the feedback to the surgeon. The present work will address in particular point 2. Modelling the cutting of soft tissue in a structure as complex as the human brain is an extremely challenging problem in computational mechanics. The finite element method (FEM), that accurately represents complex geometries and accounts for material and geometrical nonlinearities, is the most used computational tool to simulate the mechanical response of soft tissues. However, the main drawback of FEM lies in the mechanics theory on which it is based, classical continuum Mechanics, which assumes matter is a continuum with no discontinuity. FEM must resort to complex tools such as pre-defined cohesive zones, external phase-field variables, and demanding remeshing techniques to include discontinuities. However, all approaches to equip FEM computational methods with the capability to describe material separation, such as interface elements with cohesive zone models, X-FEM, element erosion, phase-field, have some drawbacks that make them unsuitable for surgery simulation. Interface elements require a-priori knowledge of crack paths. The use of XFEM in 3D is cumbersome. Element erosion does not conserve mass. The Phase Field approach adopts a diffusive crack model instead of describing true tissue separation typical of surgical procedures. Modelling discontinuities, so difficult when using computational approaches based on classical continuum Mechanics, is instead easy for novel computational methods based on Peridynamics (PD). PD is a non-local theory of mechanics formulated with no use of spatial derivatives. Its governing equations are valid at points or surfaces of discontinuity, and it is, therefore especially suited to describe crack propagation and fragmentation problems. Moreover, PD does not require any criterium to decide the direction of crack propagation or the conditions for crack branching or coalescence; in the PD-based computational methods, cracks develop spontaneously in the way which is the most convenient from an energy point of view. Therefore, in PD computational methods, crack propagation in 3D is as easy as it is in 2D, with a remarkable advantage with respect to all other computational techniques.

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