Mechanical description and engineering analysis of cutting and (sterile) needle insertion into Human skin

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ABSTRACT

Understanding the total complexity of biomechanical/mechanical properties of the human skin and developing an advance computational model (e.g. the Finite element skin models) that do not differ (or not so much differ!) from experimental data would provide information which could be very useful for surgical training and practical use (special in this project, the goal is to inform the development of optimized device which can be used for effective and reproducible skin penetration in the clinical setting. This project will also provide clear definition of underlying mechanisms of penetration and cutting and make it possible of generating a robust computational and physical model and an excellent technique for measuring skin deformation and in combination with advanced computational/mechanical methods it will offer many possibilities for in vivo measurements).

Difficulties and solutions related to the experience of developing this project beside the fundamental limitation of the finite element method for solving fracture mechanics problem, were dealing with the complicated multilayer structures and strong non-linearity in human skin which make the computational model difficult to create and analyse. However, to overcome the difficulties with fracture mechanical part the Theoretical and Computational Aspects of Cohesive Zone Modelling has been adapted to make it suitable for(Frictional and Thermodynamically coupled Frictional) modelling of cutting and needle insertion by using a modified version of Contact-Fracture formulation (a specific implementation of a mesh independence method for straightforward controlling of (non-linear) fracture mechanical processes using Mixed Mode Cohesive-Zone method). To successfully deal with the problem or difficulty with the modelling of human skin for fracture mechanical analysis, because of its complexity, the problem has been subdivided into simpler problems and analysed.

Keywords: *Fracture Mechanics; Cohesive Zone Method; Cutting; Needle insertion; Contact Mechanics*

1. Introduction

Various theoretical and numerical formulation of the Cutting and needle insertion have been widely studied and applied for the different problem classes using the (traditional) finite element methods.

Using a combination of digital image correlation and advanced Finite element modelling and explicitly taken into consideration the complexities of the algorithms due to the complexity of non-linear mechanical behaviour of human skin, after a series of Experimental Measurements on human skin and related computational modelling, S Evans and C A Holt [4] found evidence to suggest the application of stochastic optimization algorithms (due to the reduction of the errors).

In other study, in order to design optimised micro-needle device which completely depends on understanding of human skin biomechanics under small deformations, after doing a series of optimized laboratory developed tests and using much more precise model (considering the skin as a multilayer composite) by applying multilayer finite element model (with the results of which show a remarkable degree of success), R.B. Grovesa, S.A. Coulmanb, J.C. Birchallb and S.L. Evans[2,3] argue that, the problem with the precise approach and optimum development of numerical-experimental procedure and modelling of very complex mechanical behaviour of human skin would require first the perfect understanding of dependency and in-dependency of parts or elements of skin combined with mechanical description which can be used later for computational modelling.

At this point it is worth adding that, there were two main studies which aim to help us develop this project. The first one was the study by Oliver A.Shergold and Norman A. Fleck[1] about the development of the deep penetration of a soft solid by a flat-bottomed and by a sharp-tipped cylindrical punch with application of one term Ogden strain energy function and consideration the skin as an incompressible hyper-elastic isotropic solid. The second one was the study by Vincent Hayward and Mohsen Mahvash[5] about the development of the haptic-rendering of cutting with the clarification of the geometry and the mechanism of the interaction of the tools and the sample.

Without being affected by the complex nature of soft solid penetration, it is worth noting that the existing literature unfortunately provides little insight into Underlying Mechanisms of the penetration and cutting. Generally they indicate the deep penetration involves deformation and cracks and in most case without taking the existence of (sliding) friction into account. Therefore, this Project goals keep the focus on what is most important; namely mathematical and physical clarification of the mechanisms of the penetration and cutting processes following the related algorithms and computational implementation of the theory.

2. Methodology

In order to process the development of this project, the first step was the classification of computational and mechanical-mathematical problems related to modelling which were clearly separated into those with the implementation of the clarified underlying theory and those problems with optimization using advanced computational and mechanical optimization algorithms and methods. Then the accuracy of the implemented algorithms has been practically and experimentally verified.

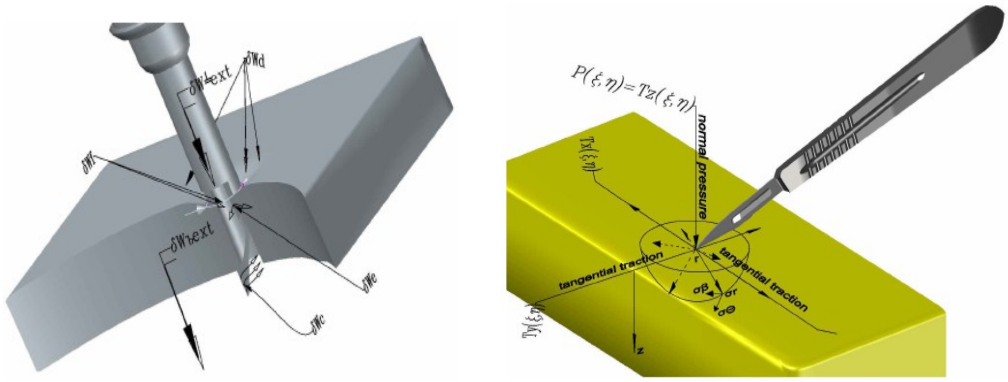

Figure 1: Geometrical description of cutting and needle insertion

Following Equation represents the underlying mathematical concepts(total energy functional-energy conservation law):

$$\frac{DE_{total}}{Dt} = \frac{D}{Dt}\{ \underbrace{\sum_{\forall i}(\int_{\Omega} U_i^t d_{\Omega}}_{Totalstrainenergy} \underbrace{- \int_{\Omega} b.u_i d_{\Omega} - \int_{\partial\Omega_\sigma} t_\sigma.u_i d_{\partial\Omega_\sigma})}_{Appliedenergy} -$$

$$- \underbrace{\sum_{\forall s,m} \int_{\partial\Omega_\Gamma} (q_c^s + q_c^m)_t d_{\partial\Omega_\Gamma}}_{FractureSurface-Thermodynamicenergy} + \underbrace{\sum_{\forall i,j,\beta} \int_{\partial\Omega_\Gamma} t_f^i.\tau^\beta (u_j^\beta - u_i^\beta) d_{\partial\Omega_\Gamma}}_{FractureSurface-Frictionenergy} +$$

$$\underbrace{\sum_{\forall\partial\Omega_\Gamma} \int_{\partial\Omega_\Gamma} G_c[G_{Ic} \mid G_{IIc}] d_{\partial\Omega_\Gamma}}_{Fractureenergy} + \sum_{\forall\Omega}(\underbrace{\int_{\Omega} C(T_{current} - T_{initial})\rho d_{\Omega}}_{Heatenergy}$$

$$-\underbrace{\sum_{\forall\partial\Omega_\Gamma}(\int_{\partial\Omega_\Gamma} T_x\{u_i\}d_{\partial\Omega_\Gamma}+\int_{\partial\Omega_\Gamma} T_y\{u_i\}d_{\partial\Omega_\Gamma}+\int_{\partial\Omega_\Gamma}[P=T_z]\{u_i\}d_{\partial\Omega_\Gamma})}_{\iint_s Tx(\xi,\eta)\phi d\xi d\eta+\iint_s Ty(\xi,\eta)\phi d\xi d\eta+\iint_s[P(\xi,\eta)=Tz(\xi,\eta)]\phi d\xi d\eta}+$$

$$\underbrace{\int_\Omega \frac{1}{2}\rho(\frac{\partial u_i}{\partial t})(\frac{\partial u_i}{\partial t})d_\Omega}_{Kineticenergy}-\underbrace{\int_\Omega R^t d_\Omega+\int_{\partial\Omega} Q^t N d_{\partial\Omega})}_{AppliedThermalenergy}\}=0 \tag{1}$$

The algorithm proceed with the adaptation of the definition and the algorithm of the modified contact[additionally thermodynamically coupled friction concept](in the previous study has been practically and analytically verified), optimized with inequality constraints: the Kuhn-Tucker conditions which enforces the contact constrains within a strong Mixed Mode Cohesive Law formulation by clearly taking the place of the classical contact constrains formulation and in the case of the physical requirement of impenetrability and compressive interaction between two bodies, enforces the classical contact constrains.

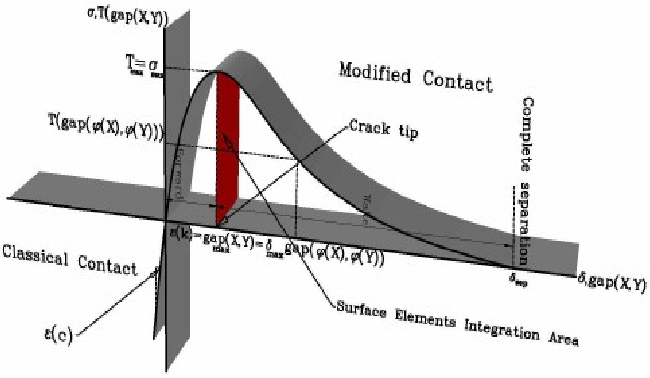

Figure 2: Definition of the Modified Contact combined with Classical Contact Mechanics

After applying this definition to the finite element discretisation of global variation equation(1), summarized, we obtain a non-linear ordinary differential equation (the Discrete Momentum Balance equation) expressed as (by using the residual vector concept and appropriated boundary conditions):

$$R(d_{n+1})=F^{mech}_{ext}(t_{n+1})+F^{ther}_{ext}(t_{n+1})-M[\frac{4d_{n+1}}{(t_{n+1}-t_n)^2}]$$

$$+M(a_n+\frac{4d_n}{(t_{n+1}-t_n)^2}+\frac{4v_n}{(t_{n+1}-t_n)})-\{C\dot{d}_{n+1}+F^{mech}_{int}[d_{n+1}]+$$

$$F^{ther}_{int}[d_{n+1}]+\underbrace{F_{Fst}[d_{n+1}]+F_{fric}[d_{n+1}]+F_{frac}[d_{n+1}]+F_{trac}[d_{n+1}]}_{F_{contact}[d_{n+1}]}\}=0 \tag{2}$$

$$(a_n, d_n, v_n, acceleration, displacement, velocity\ vectors)$$

Where commonly, $Given\ [\ddot{d}_n \mid a_n], d_n, v_n \quad \overrightarrow{Find} \quad [\ddot{d}_{n+1} \mid a_{n+1}], d_{n+1}, v_{n+1}.$

Then the numerical implementation of the explained theories has been performed in the open source code FEBio (Non-linear finite element solver for biomechanical applications http://febio.org/febio/) by the modification of the existing contact algorithm.

3. Computational Model/Result/Discussion

Based on the collected experimental data[cutting test on silicon rubber type material (E=0.77 MPa, v=0.48) by using Zwick universal testing machine] and practicing the advantage of FEBio package (PreView, PostView, FEBio) the computational model has been created and analysed. Beside issues related to computational model, an interesting issue had been examined was the sensitivity of the experimental result to the acceleration and velocity of the cutting tool during testing would have a direct effect on the under-resolving some local details.

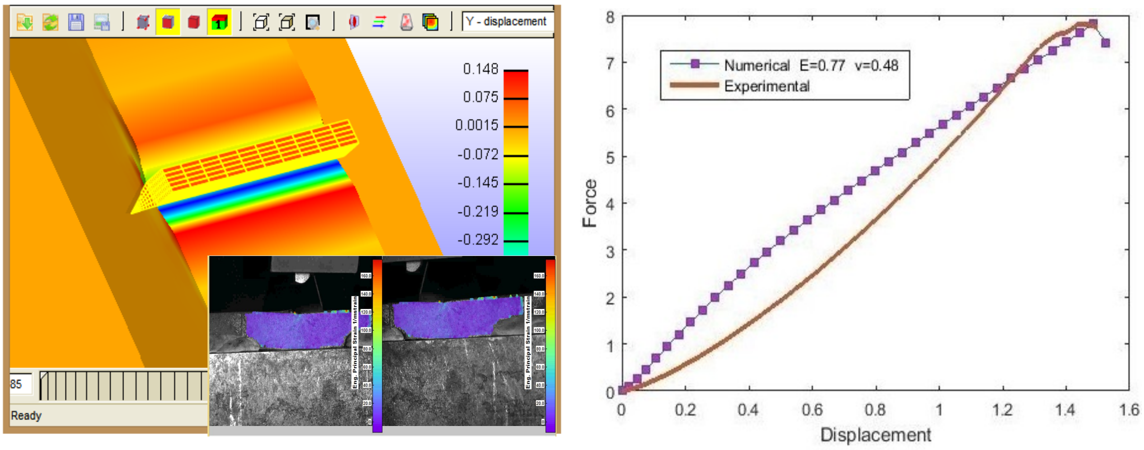

Figure 3: Computational versus Experimental results

However, comparison Computational with Experimental results reveals that using the modified contact algorithm in such a way can significantly increase the chances of success and will contribute to the achievement of desired results.

4. Conclusions

In this study it has been shown that the development of computation model, in this way, by using the Modified Contact fulfils the strong condition of the cohesive zone law and additionally supports the physical ideas and mathematical structures of the Classical Contact, allowing us a significant degree of flexibility and success in the deployment of robust models for engineering analysis.

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