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Mixed-mode crack propagation during needle penetration for surgical interventions

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Abstract

An accurate description of the penetration mechanics of flexible needles into target soft tissues is a complex task, including friction at the needle-tissue interface, large strains, non-predetermined penetration trajectories, fracture under mixed-mode loading and so on. In the present work, a finite element algorithm is employed to simulate the two-dimensional deep penetration of a flexible needle in a soft elastic material. The fracture process of the target material during penetration is described by means of a cohesive zone model, with a suitable mixed-mode criterion for determining the propagation direction of the crack. To illustrate the potential of the numerical algorithm, we have performed some simulations of the insertion of a flexible needle with an asymmetric tip, and the results are presented in terms of force-penetration curves as well as of the obtained penetration paths in the target tissue.

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Keywords: Needle penetration; Needle steering; Cohesive elements; Soft tissue; Mixed-mode crack propagation.

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1. Introduction

The controlled insertion of needles is a largely applied technique in the field of minimally-invasive and robotically-assisted surgery. Specifically, high precision interventions in delicate organs use thin flexible needles, which are capable to follow curved trajectories, in order to reach a precise location and avoid possible obstacles (van Gerwen et al., 2012). Needle steering can be achieved with different mechanisms: for instance, in needles with an asymmetric bevelled tip, steering results from a non-symmetric distribution of the tip forces, which cause the needle to steer while it is inserted (Misra et al., 2010; Burrows et al., 2013). A key aspect in the design of such devices is the accurate description of the interactions between the tool and the target tissue, so that not only the penetration forces but also the steering capability of the needle can be predicted. However, highly detailed models of the insertion process remain a challenging task, in large part due to the complex and heterogeneous nature of biological tissues (Forte et al., 2017).

The fracture process at the tip of a needle or a cutting tool can be described using a cohesive zone approach, where the energy for crack propagation comes from both the elastic strain energy of the substrate and the external work

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performed by the tool which is pushed during the insertion. Relevant applications of the cohesive model to penetration processes include simulations of wire-cutting of foods (Goh et al., 2005) and straight insertions of a needle into soft tissues (Oldfield et al., 2013). Cohesive zone-based models applied to mixed-mode fracture propagation problems are also available in the literature (see, for instance, Geißler et al. (2010); Oldfield et al. (2012)).

The present paper is focussed on the application of a numerical finite element (FE) model to describe the deep penetration of a needle with an asymmetric tip, inserted into a soft phantom tissue. Based on the cohesive zone approach to describe the fracture process, a mixed mode criterion is combined with an adaptive remeshing algorithm to model crack propagation along non-predetermined failure paths (Terzano et al., 2019). The algorithm is here applied to describe the trajectories and the force-displacement profiles during the penetration of the needle in the target tissue, which is modelled as a nearly-incompressible elastic material. Some results are presented to highlight the influence of relevant material and geometrical parameters on the fracture process occurring at the tip, and hence on the resulting penetration paths.

2. Description of needle penetration

During the penetration of a cutting tool into a target tissue, a complex mechanical interaction between needle and target tissue occurs. The energy balance for an elastic material under quasi-static penetration rate is given by the following equation

$$W_{\text{ext}} = U_S + U_f + U_G \tag{1}$$

where W_{ext} is the external work generated by the force applied to the needle, U_S is the strain energy in the material, U_f is the energy dissipated due to friction and U_G is the energy spent to cut the tissue. Different stages during the penetration can be identified as follows, where all or some of the contributions are involved: (i) Initial indentation (no cutting): $W_{\text{ext}} = U_S$; (ii) Cut propagation until full penetration: $W_{\text{ext}} = U_S + U_f + U_G$; (iii) Sliding after full penetration: $W_{\text{ext}} = U_f$. This last stage will not be modelled in the present work.

2.1. The bevelled tip needle

The present investigation is focused on a programmable bevel tipped needle proposed by Ko and Rodriguez y Baena (2013). This needle is composed of a multi-segment flexible shaft, a bevelled tip and allows a programmable offset between the segments. A two-dimensional sketch of the probe is shown in Fig. 1a. In the present two-dimensional simulation of the needle penetration, only two interlocked segments are considered: the relevant sizes are the needle diameter b, the tip angle α and the programmable offset c. In general, needles advance into the target material propagating a crack under a combination of mode I and mode II, with the tangential contribution coming from the sliding forces due to friction. When the tip is symmetric, the opening mode I is predominant and the needle follows an approximately straight path. On the contrary, the distribution of the resultant forces at the tip-tissue interface is asymmetric in bevelled tip needles (Fig. 1b), and the penetration follows a curved path.

2.2. The fracture of the target tissue

When needles are inserted into soft materials, a crack is formed following the point of failure in the target tissue. Among the amenable numerical methods to describe failure and crack propagation, the Cohesive Zone Model (CZM) has the capability of accounting for the non-linear behaviour of soft tissues, and allows the inclusion of the contact constraints imposed by the needle penetration (Geißler et al., 2010). In the CZM, the fracture process zone is lumped into a line ahead of the crack tip and the crack surfaces interaction is defined through a traction-separation relationship describing the damaging mechanisms taking place in the process zone. We assume a triangular traction-separation law for the cohesive zone, where the area underneath the traction-separation curve represents the fracture energy G_C of the material. The cohesive law is assumed to be valid for both normal and shear tractions, without considering any coupling between them. In the FE implementation of the cohesive model, an additional compliance zone develops due to the finite stiffness of the cohesive elements prior to rupture.

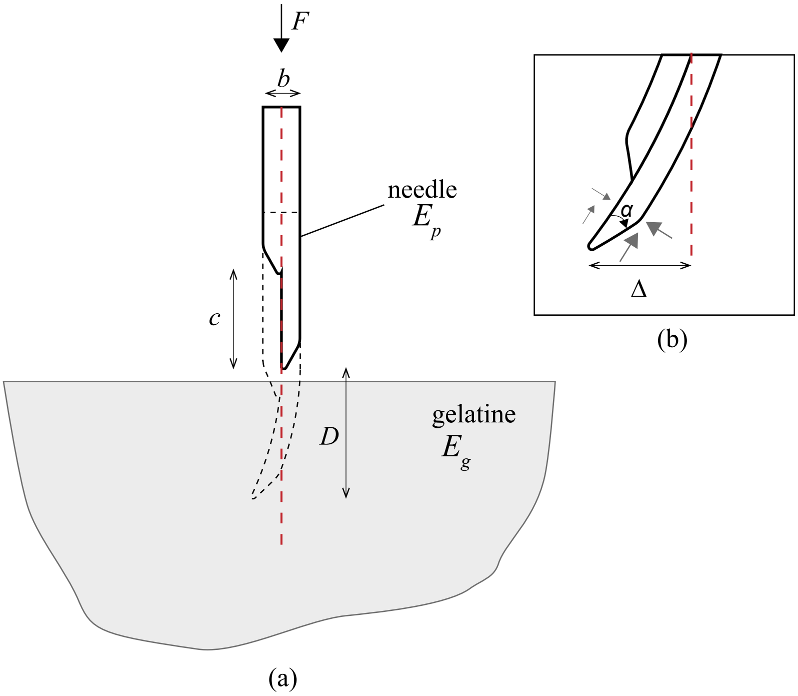

Fig. 1. (a) Two-dimensional sketch of the flexible needle, inserted in a block of gelatine phantom tissue. c is the length of the initial offset and D is the penetration depth. (b) Enlarged view of the bevelled-tip region, with a schematic illustration of the asymmetric tip forces. Δ is the deflection of the tip with respect to the insertion axis.

In the present study, interface cohesive elements are included in the FE mesh to model the penetration path followed by the asymmetric needle. Usually, cohesive elements are either pre-inserted along the propagation path, in case it is known in advance, or included in a larger area when such path is unknown. Here, an alternative approach is followed, where the cohesive elements are inserted into the finite element model iteratively and the complete penetration path is obtained as part of the solution. A mixed-mode fracture criterion is implemented to define the critical condition for propagation and the kinking angle. The Minimum Strain Energy Density (MSED) criterion (Sih, 1974), which defines the direction of propagation as the one that minimises the strain energy density, is adopted.

2.3. The finite element algorithm

A specific algorithm has been designed to simulate the insertion and complete penetration of the needle into the target soft elastic material. As explained in the previous section, the penetration path is not pre-determined, hence an iterative approach is used, which consists of two main parts: (i) a complete non-linear FE analysis, which in particular provides the stress and strain fields in the tip zone; and (ii) the post-processing part, which implements the fracture criterium.

Part (i) has been carried out with a static non-linear analysis using the implicit solver of the commercial software Abaqus, under plain strain conditions and accounting for geometric non-linearity. Each iteration describes the penetration of the probe from the initial configuration down to a certain depth, until the critical condition for propagation is attained. Part (ii) of the algorithm is developed within Matlab environment. The local tip fields are employed to implement the fracture criterion and establish the new direction of propagation; then, the mesh is updated to include the new cohesive interfaces along the determined direction. For details of the complete algorithm, the reader should refer to the work by Terzano et al. (2019).

3. Results

The model used here is based on the experiments in Burrows et al. (2013), where two adjacent segments of the programmable bevelled tip needle were advanced equally to create a fixed offset that was maintained throughout the physical experiment. This configuration restricts needle steering to a single plane and so a 2D plane-strain simulation is used. The substrate consists of a block of gelatine, with a concentration of 10% w/w, having dimensions 235mm × 245mm. The gelatine material is modelled as linear-elastic, with a Young modulus $E_g = 14.8$kPa and a Poisson coefficient $\nu = 0.475$. The value of the fracture energy G_C for the gelatine is equal to $1.1 \mathrm{J/m^2}$. The probe has a diameter of b=8mm, a total included angle at the tip of $\alpha = 20°$ and tip radius equal to $\rho_{\mathrm{tip}} = 0.5$ mm. The probe material is modelled as linear-elastic, with a Poisson coefficient equal to $\nu = 0.475$, whereas the Young modulus E_{p} is varied in the simulations, in the range between 117-940 kPa.

Boundary conditions are applied to reply the experimental set-up as closely as possible. The lateral surfaces of the substrate are pinned and the bottom nodes are also prevented from normal motion. The needle is prevented from buckling by moving between two rigid vertical surfaces, which are frictionless and fixed. Contact is defined with a frictional interaction between the probe and the substrate, described by the Coulomb law with coefficient of friction $f = 0.3$.

A series of simulations were run, changing the stiffness ratio between probe and gelatine, as well as the initial offset between the segments. Separately, a symmetrical needle configuration, equivalent to zero offset, was also simulated to test whether a straight path could be achieved with the proposed procedure. Each simulation was run sufficiently far to establish a reliable curvature of the penetration path for comparison with experimentally observed behaviour.

The results of the simulations are reported in Fig. 2. In particular, the force vs penetration depth is plotted in Fig. 2a-b, where the needle-gelatine stiffness ratio and the initial offset are varied. The corresponding penetration paths are illustrated in Fig. 2c-d, in terms of tip deflection vs penetration. Overall, the results suggest that the numerical model is capable of capturing with great accuracy the effect of different parameters, either related to the material or to the geometry. In particular, it is of major concern the role played by such parameters in affecting the fracture process at the tip.

4. Conclusions

This paper presents some relevant results obtained from numerical simulations of the deep penetration of a flexible needle in a gelatine phantom tissue. In particular, the focus is on the fracture process occurring at the asymmetric bevelled tip of a multi-segment needle with a programmable offset. A realistic model is considered to describe the tool-tissue interaction, included frictional contact, needle bending and large deformations in the substrate. Damage and fracture of the soft tissue are incorporated through a cohesive zone model. Following the initial puncture, crack propagation proceeds under mixed-mode conditions, caused by the asymmetric distribution of the forces at the tip. A finite element model is enriched with a modification of the mesh topology, in order to implement a mixed-mode fracture criterion capable of defining the critical condition and the direction of propagation. Such an approach allowed us to obtain also the penetration path as part of the solution, and explore the influence of relevant analysis parameters. In particular, in this work we have considered the influence of the tool-tissue stiffness ratio and of the initial tip offset.

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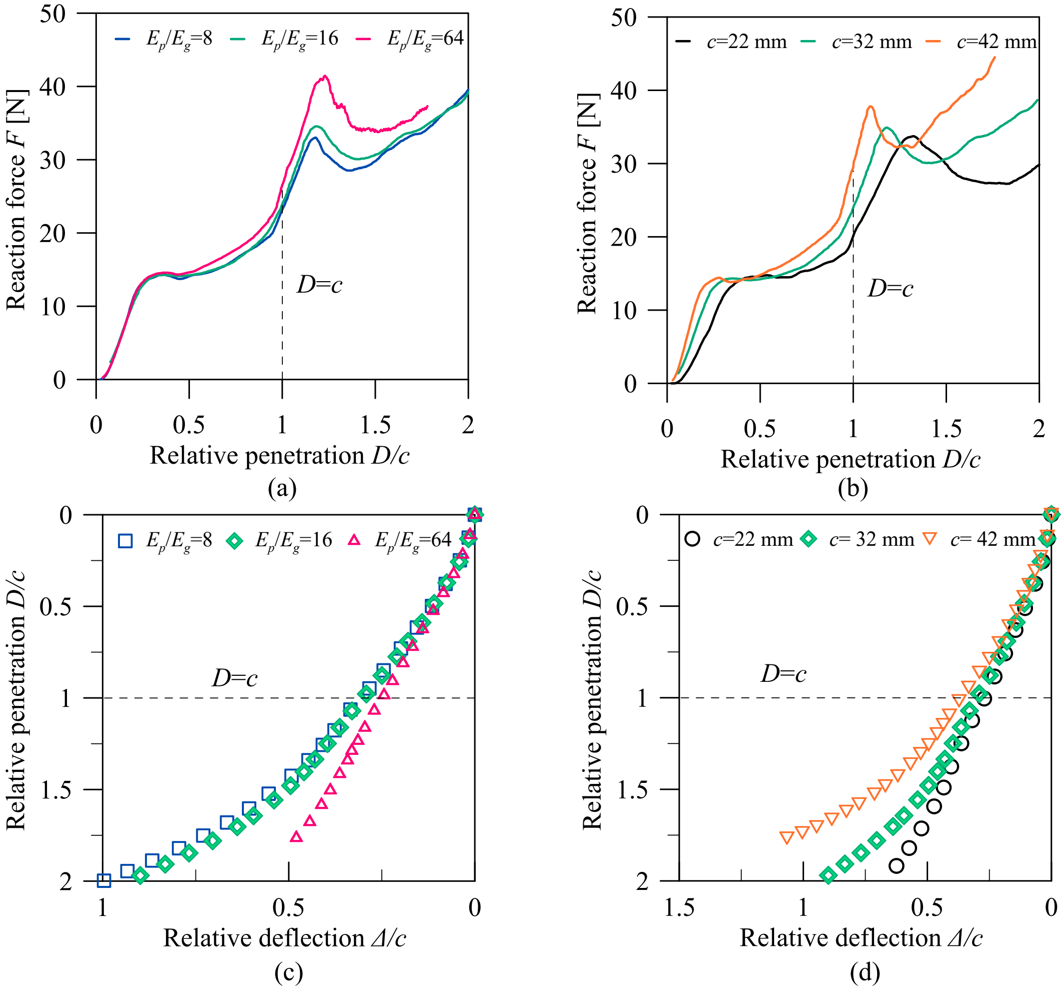

Fig. 2. Force-penetration curves of the bevel-tipped needle: (a) influence of the stiffness ratio $E_\mathrm{p}/E_\mathrm{g}$ and (b) influence of the initial offset c. Tip deflection vs penetration curves: (c) influence of the stiffness ratio $E_\mathrm{p}/E_\mathrm{g}$ and (d) influence of the initial offset c. In (a),(c) the offset is kept fixed at *c=32 mm*, while in (b),(d) the stiffness ratio is maintained constant at $E_\mathrm{p}/E_\mathrm{g} = 16$.

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