INTRODUCTION

A novel method of bone fracture fixation has been proposed in which small-diameter bioresorbable nails/pins are inserted across the fracture site using a device similar to that of a pneumatic nail gun [1]. Multiple nails inserted at varying angles can prevent translation and rotation of any bone fragments allowing healing to progress uninhibited. High velocity insertion would reduce surgical time; the nail would create its own entry incision so a drilled pilot hole would be unnecessary. A self-contained nailer, preloaded with sterile nail cartridges, could improve surgical outcomes in non-ideal operating conditions such as those encountered in military field hospitals. The bioresorbable nature of the pins would also mitigate the need for potentially risky removal surgery [1].

Candidate bioresorbable nail materials, like magnesium and polylactide (PLA), are of similar strength to bone [2,3]. Thus, it is hypothesized that the nail tip geometry will be influential in determining if a nail can successfully penetrate the relatively hard cortical shell. Unsuccessful penetration may involve excessive deformation of the nail tip which could be detrimental to the resulting fixation. Also, certain tip geometries may require less energy to penetrate a given cortical shell. Minimizing the actuation energy will help extend the life of a portable power supply and reduce the chance of damaging surrounding bone. A numerical approach was chosen to explore nail tip design since it was capable of handling the high strain rate effects expected in high-velocity penetration [4]. And unlike physical prototypes, it allowed for quick parameterization.

METHODS

A 3D finite element model was constructed in Abaqus/CAE and solved using Abaqus/Explicit. The geometry consisted of a 2.5 cm long, 1.5 mm diameter nail, constrained by a nozzle, which was driven by a needle traveling at 15 m/s. The nail penetrated a 1.0 mm thick cortical bone shell backed by a cancellous bone substrate. Components were meshed with first order reduced integration brick (C3D8R) elements. In some cases the nail tip was meshed with second order tetrahedral elements (C3D10) to improve mesh quality. These element types were shown to be interchangeable for refined meshes. A more refined mesh was assigned to the nail tip and to the small section of cortical bone involved with impact. For the initial simulations, pointed, round, and blunt tip geometries were considered [Figure 1].

Both magnesium and PLA were considered as nail materials. The material model allowed for elastic and plastic deformation. Strain rate dependent yielding was considered. The cortical and cancellous bone also had an elastic and plastic response, again with the plastic response being rate dependent. A progressive damage model was employed to model failure of the bone. Failure initiated at a given level of plastic strain (rate dependent). Subsequent degradation in stiffness of an element was governed by the failure energy of the respective bone type.
Upon final failure, an element was removed from the mesh and its mass was assigned to its freed nodes [4].

RESULTS

Inspection of the deformation patterns from the initial simulations showed that tip geometry is extremely influential for the softer nail material (PLA). The round tip suffered very slight levels of deformation. The blunt tip mushroomed against the hard cortical shell before the material was folded back along the nail shaft during penetration. The pointed tip was crushed inside the nozzle (not shown), essentially creating a blunt tip, before mushrooming against the cortical surface. Tip mushrooming consequently led to a larger damaged volume of bone. For magnesium, none of the candidate geometries suffered much visible deformation, though the volume of damaged bone differed slightly [Figure 2].

To quantitatively assess which tip was the most ‘efficient’, the kinetic energy of the system was tracked. The largest combined drop in kinetic energy corresponded to the highest level of plastic deformation of the dart tip and damaged volume of bone elements. For PLA, the round tip nails had the lowest drop in kinetic energy, followed by the blunt and pointed. For magnesium, the pointed tip nails saw the lowest drop, followed by the pointed and blunt.

DISCUSSION

The results of these initial simulations have shown that the effectiveness of a certain nail tip design will be highly dependent on the strength of the nail material relative to cortical bone. A round geometry will likely be best for soft materials, while a pointed geometry may be best for harder materials. With hard materials, the tip design will change the required actuation energy slightly but could be considered relatively unimportant with regards to deformation. However with soft materials, an incorrect tip design could lead to tip mushrooming and subsequent plowing of the cancellous bone which could prevent penetration or compromise resulting fixation. In the future the numerical model will be useful in screening potential nail materials. Some materials may be too soft to avoid excessive deformation even with an ideal tip design. The finite element model gives insight into the small-scale interaction between the cortical bone and nail tip which is a phenomenon that would be difficult to visualize even with high speed photography. Next steps for the model will include analyzing the stress state in the surrounding bone during penetration to ascertain whether certain tip geometries might cause cracking in the cortical shell upon entry. This may place further limitations on the nail design.

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REFERENCES