INTRODUCTION
Thin Ilizarov wires are commonly used to provide fixation to fractures of the tibia, corrective treatment of non-unions, misalignments and limb deformities [1]. Treatment using the Ilizarov technique has focused on younger patients [2]. However, as the mean age of the global population increases, greater numbers of elderly patients will indicate for Ilizarov fixation. Bone density, stiffness and strength reduce significantly with ageing. Under the high stress concentrations at the intersection with thin Ilizarov wires bone with reduced mechanical competence may suffer considerable yielding and lead to loss of fixator stability. In this study the yielding of peri-implant bone in Ilizarov fixation of tibial midshaft fractures across a range of age-groups was investigated using finite element analysis. Results were used to assess the effect of ageing on peri-implant bone yielding and identify strategies to minimize the associated loosening risk.

METHODS
Ilizarov fixation of the tibial midshaft was modelled using finite element analyses. Configurations of two (Figure 1) and four wires were modelled under single-legged-stance loading of 700N. Bone competence was varied to approximate three groups: a) healthy/young bone; b) osteoporotic/middle-aged bone and c) osteoporotic/old bone. The tibial cross-sections were varied to match reported age-related variations [3]. Orthotropic elastic constants of bone were assigned, including the variation of elastic constants with age/porosity and periosteal-endosteal position based on a recent study by the authors [4]. Implant-bone interactions were modelled with contact analysis, enabling realistic separation in regions of tension and slippage in shear. Bone damage was simulated using a bone-specific, strain-based yield criterion. To the knowledge of the authors this is the first time that all these key features of bone-implant interaction and bone properties have been included in a computational model. The effect of wire pre-tension was investigated by varying its value between 0N and 2000N. A constant wire pre-tension of 1000N was specified for most analyses.

RESULTS AND DISCUSSION
The pattern of yielded bone was compared between age-groups at the sites of wire-bone intersection. Close-up images are presented in Figure 2 for two-wire fixation. Peri-implant yielding occurred towards the periosteum on the superior (loaded) side and to a lesser extent towards the endosteum on the inferior side of the wires. The inferior region of yielded bone was induced by stresses resulting from the bending deformation of the wires under loading. This appeared to increase the loading and subsequent extent of bone yielding on the superior side of the wires. The two regions of yielded bone remained unconnected in all age-groups and a substantial region of cortex remained unyielded even in the old group.

Figure 1: Two-wire Ilizarov fracture fixation model geometry and applied loading. Wire tension ($T_o$) of 1000N was applied.

Figure 2: Regions of yielding bone (red) in the two-wire model for young (a), middle-aged (b) and old (c) groups. A similar pattern was observed with four wires. Images correspond to wire A-C (left-right) as illustrated in Figure 3.

The volume of yielded bone at wire entrance sites A-D for two-wire fixation is shown in Figure 3. The volume of yielded bone followed a hierarchy at all entrance sites such that it was greatest at A, intermediate at B and D, and minimum at C. It was observed that the largest volume of yielded bone occurred at the site with the smallest exposed wire length and vice-versa. The volume of yielded bone increased with ageing, approximately 1.7 and 2.2 times greater in old-aged bone than in young bone with two- and four-wire fixation respectively.
Increased wire pre-tension (results not shown) was found to reduce the volume of peri-implant yielded bone. An increase of 500N in wire pre-tension was associated with a 14% reduction of the volume of yielded bone at site A under a reference pre-tension of 1000N.

Figure 3: The volume of peri-implant yielded bone at the four wire-bone intersections (A-D) in two-wire fixation for all age-groups.

CONCLUSIONS

The volume of yielded bone and implied risk of loosening were seen to increase considerably with bone degradation associated with ageing/osteoporosis. Results indicate that to achieve stable fixation of older patients is a greater challenge than with younger groups.

A substantial variation of peri-implant yielded bone volume was observed between different wire entrance sites, associated with varied exposed lengths. Results therefore indicated that tibia should be placed centrally within Ilizarov rings minimised peri-implant bone damage.

Wire pre-tension was a key determinant of bone yielding around Ilizarov wires. This result emphasises the need to ensure wire pre-tension is maintained in patients with reduced bone competence.

ACKNOWLEDGEMENTS

The authors would like to thank the Carnegie Trust for the Universities of Scotland for supporting this study.

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