Influence of fracture type and thickness of intramedullary nails on fracture healing – A numerical study

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INTRODUCTION:
It is common knowledge that the fracture healing process is strongly influenced by the mechanical behaviour of the bone implant complex (BIC) due to the resulting interfragmentsary movement (IFM) of the bone fragments at the fracture site. Unreamed intramedullary nailing reduces the disturbance of blood supply in comparison to reamed nailing but leads to a more flexible stabilization due to the distance between nail and endosteal surface. Therefore high interfragmentsary movements (IFM) may occur under low shear loads which could result in a delayed fracture healing. To identify the mechanical key factors influencing the healing outcome of intramedullary nailing, we simulated the fracture healing process for typical types of diaphyseal fractures treated with intramedullary nails of various diameters.

METHODS:
To simulate the fracture healing process, the 3D flexibility behaviour of the BIC has to be known, which in the case of intramedullary nailing is very complex due to nonlinearity, especially under shear loads. To simulate this complex flexibility behaviour, we created a finite-element (FE) model with contact elements based on an in vitro tested BIC (transverse osteotomized human cadaver tibia, stabilized with Stryker T2 intramedullary nailing system) out of CT data. This FE contact model was validated using the in vitro measured flexibility behaviour for different loading conditions.

After this validation, the FE contact model was adapted to three idealized fracture types (transverse, oblique, bending wedge). To mimic the 3D flexibility behaviour of the specific BIC during the healing simulation, a simplified FE model with beam and spring elements was used, which was validated through the FE contact model.

In addition to the flexibility behaviour of the BIC, an appropriate 3D load case for the healing simulation has to be defined. Therefore, an inverse dynamic muskuloskeletal model, which was developed and provided under public domain by the “AnyBody research group” (www.anybody.aau.dk), was modified to determine the internal forces and moments in the human tibia during gait.

The simulation of the healing process was done with a numerical model, which was validated for the healing process in sheep and corroborated for humans [Simon et al., 2003; Wehner et al., 2008]. In this model, the three idealized fracture types and a healing region, i.e. where the tissue differentiation could takes place, were modeled as FE. For each FE in the healing region, the mechanical stimulus, i.e. the deviatoric and the distortional strain, was calculated under the estimated 3D load case with the highest shear loads during gait and the specific flexibility behaviour of the BIC. Based on these strains as well as the local tissue distribution and vascularisation, the tissue differentiation was predicted using a rule based fuzzy logic approach with the fuzzy toolbox of Matlab (www.mathworks.com). The healing simulation was done for the three fracture types with fracture gap sizes of \( fr = 3-7 \) mm combined with nail diameters of \( d = 9-11 \) mm.

RESULTS:
The highest IFM occurred in the sheaf direction in the sagittal plane. With increasing healing time these movements decreased due to bone formation in the healing region. This bone formation starts on the surface of the bone fragments, propagates into the lateral healing region where the bony bridging occurs if the mechanical strains are at a suitable level (Figure 1).

Thin intramedullary nails, which were used in unreamed intramedullary nailing, as well as large fracture gaps led to a prolonged healing time. This effect was pronounced for oblique & transverse fractures, which led to a significantly delayed union for a transverse fracture with a large fracture gap treated with a thin intramedullary nail (Figure 2).

DISCUSSION:
Using three numerical models we identified large fracture gaps and small nail diameters as the two mechanical key factors potentially leading to a biomechanically weak situation and therefore to delayed healing. Transverse fractures seemed to be most critical for the healing outcome in these situations. These results were corroborated by clinical observations [Bhandari et al. 2000 & 2003; Larsen et al., 2004]. The safest way to avoid a delayed healing from the mechanical point of view is the use of thick intramedullary nails, i.e. the reamed technique of intramedullary nailing. These methods will be used to optimize current designs of nailing systems to reduce the healing time.

REFERENCES:
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Figure 1: Bone concentration (red = 100%, blue = 0%) in the healing region over the healing time for transverse fractures with a gap size of \( fr = 7 \) mm, stabilized with a \( d = 9 \) mm (top) and a \( d = 11 \) mm (bottom) intramedullary nail. The thinner intramedullary nail led to a delayed healing in comparison to the thicker nail.

Figure 2: Healing time related to the fracture type, the fracture gap size \( (fr) \) and the nail diameter \( (d) \).