INTRODUCTION:
Internal fixators are commonly used in the treatment of long bone fractures. The stability of a fracture, and hence movement of bone fragments is determined by the configuration of the device. The interfragmentary movement at the fracture site determines the fracture healing environment. Using less screws and a large working length (i.e. the distance between the innermost screws) produces a more flexible construct, which if excessive may lead to delayed healing or a non-union. However, increasing the working length reduces the stresses in the centre of the plate. Conversely, adding screws and reducing working length increases construct rigidity and in turn reduces interfragmentary movement. If the construct is overly stiff, insufficient micro-motion may occur to stimulate callus formation. In addition, bending of the plate is concentrated in the centre and increases stresses in the plate. Because the screw combination influences both the stresses in the plate as well as stability of the fracture, there is a need to find screw combinations that will firstly optimise interfragmentary movement to promote healing and secondly, limit stresses in the plate to prevent its failure. In engineering, optimisation algorithms have been widely used, e.g., in the design of truss structures, whose optimum design may be in terms of cost, weight, permissible stress and a number of other factors. Therefore, the goal of this study is to investigate the application of an optimisation algorithm to configure the optimal screw configuration that enhances bone healing but avoids mechanical failure of the plate in internal fixation.

METHODS:
Using the programming language, Fortran 90/95, an interface between the optimisation algorithm (Powell’s method) and the finite element software (ABAQUS) was established. Figure 1 shows the flow of data between the optimisation method and the finite element software.

Powell’s method is an optimisation algorithm that uses coupled vectors to form a search direction, which in this case is a screw combination (position and number), according to the 6 screw variables, shown in Figure 2. Each variable represented a screw material, which in turn implied its position. For example, a screw with its Young’s modulus as 20 MPa represented the absence of a screw, while a screw with E = 200 GPa represented a steel screw to be present. Each screw combination was tested using Finite Element Analysis (FEA).

A mid-shaft osteotomy with an interfragmentary gap of 3 mm was simulated as a cylindrical pipe, with its Young’s modulus, 20 GPa, representing cortical bone. The osteotomy was stabilised by a 14-hole steel locking compression plate and locking screws (E = 200 GPa). A compressive load of 580 N and a torsional load of 3.5 Nm were applied to the bone cylinder.

Outputs from FEA included the calculation of displacements of bone fragments in the longitudinal direction as well as in a shear direction as well as the maximum von Mises stress in the plate. The range of optimal interfragmentary movements was derived from a number of animal studies. In addition to the restriction of displacements, it was required that the maximum von Mises stress be minimised. If a particular screw combination resulted in a high stress, but acceptable displacement, a penalty constant was added to the objective function, which penalised that screw configuration. This resulted in a search for a new combination of screws.

RESULTS:
The optimisation method determined that the screw configuration that satisfies the prescribed criteria, i.e. the range of displacements and the minimisation of stress in the plate, consists of placement of screws in the second holes of the plate, either side of the fracture gap (see Figure 3). In the axial direction and shear direction, displacement was 1.2 mm and 0.85 mm respectively. The highest von Mises stress in the plate occurred at the edges of the middle holes, with a peak stress value of 550 MPa.

DISCUSSION:
In this study an optimisation algorithm was combined with the finite element method to determine the optimum screw configuration of an internal fixator that promotes fracture healing and prevents implant failure. The approach taken automates the testing of various screw combinations. For the simplified input/boundary conditions, the optimisation methods implemented here found a solution that satisfies the optimisation criteria. The solution consisted of a moderate working length as shown in Figure 3, with spacing between the innermost and outermost screws. This configuration is in agreement with recommendations derived from the work of Stoffel et al (2003). Stoffel et al found that for small gap sizes omitting screws from the central two holes decreased the stresses in the centre of the plate by 10%. Furthermore, more than three screws on either side of the fracture did little to influence the axial stiffness of the construct, which is important for callus stimulus. A wider spacing of the screws allows the plate to bend more uniformly across its length, which reduces stress in the centre of the plate.

In conclusion, this study demonstrates that optimisation techniques used widely in engineering may be applied to the problem of optimising the screw configuration of internal fixation devices. With the development of more representative models, i.e. including bone and callus geometry and their respective material properties and the introduction of physiologic-like loading conditions, this method may be used to find appropriate screw combinations for different types and positions of long bone fractures. Screw combinations can be optimised for the competing demands of interfragmentary motion at the fracture site, as well as the alleviation of stress in the plate.

REFERENCES:

Figure 1 Data flow between optimisation method and finite element software.

Figure 2 Showing the screw variables to be used in the optimisation algorithm. The positions of the screws are shown in the boxes.