INTRODUCTION
Joint replacement at the shoulder is now an established operation for pain relief and restoration of function in the arthritic shoulder. However, because of the complexity of the shoulder mechanism and the variety of pathologies, there are many available designs of prosthesis. Reverse anatomy shoulder replacements have become a popular choice for patients with rotator cuff arthropathy – arthritis associated with large or massive rotator cuff tears. However, despite acknowledged clinical effectiveness, the biomechanical rationale of these designs has not been fully explored. This paper addresses the use of biomechanical modelling techniques to support the design of reverse anatomy designs and presents the application to a novel prosthesis.

Arthritis with massive rotator cuff tear is combined with severe loss of humeral range of motion and is one of the most challenging pathologies to restore functionality. While reverse anatomy prostheses have been demonstrated to be effective for these patients, there are no significant studies investigating the associated biomechanics in order to quantify the advantages or disadvantages or to evaluate new designs.

METHODS
a) Biomechanical
In this study, a biomechanical model of the shoulder (Newcastle shoulder model) has been used to evaluate a novel reverse anatomy prosthesis. The model contains representation of 31 shoulder muscles (87 fascicles) using data from Johnson et al. (1996). The skeletal data are taken from the Visible Human Project. The necessary wrapping of the muscles around the skeleton is modelled using techniques developed by Charlton and Johnson (2001). Scapula motion accompanying glenohumeral motion is included in the model using data from Barnett et al. (1999). The model simulates a range of 10 daily activities using data from Johnson and Murray (2004). Visual display is achieved using SIMM software and all of the necessary calculations are performed by custom written MATLAB routines. When simulating ADL activities the model can be used to predict both muscle and resultant joint forces.

In this study the model has been further developed to allow simulation of one established reverse anatomy prosthesis (DELTA III). It has further been used to study the biomechanics of a new mobile bearing prosthesis – the NGR-i prosthesis having a half sphere attached to the glenoid and a unique mobile bearing in the humeral stem. Initially, the implantation has been simulated according to descriptions of the surgical technique and clinical photographs of the implantation procedure. The representation of muscles has then been modified to simulate a patient with rotator cuff arthropathy.

The model has been used to predict the biomechanical behaviour of this prosthesis by calculating muscle and joint forces. Comparisons between the normal shoulder having intact musculature and having the reverse design with absent rotator cuff muscles demonstrated great differences in joint and muscle forces when performing standardised and ADL tasks.

b) Clinical Pilot Studies
Ten patients with either Rotator Cuff Arthropathy or arthritis associated with non-reconstructable deformity were treated with an NGR-i total shoulder arthroplasty. Patients were aged from 69 to 77 years (m=73) except for one 33 year old man treated for a severe fracture malunion with OA. One patient had an incorrectly assembled prosthesis and required revision. 8 patients have been adequately followed up two of which have been assessed over 12 months after insertion. Follow-up assessments have been carried out using the Constant-Murley Shoulder Function Score. In addition the majority of patients had a video-recording of their movements in abduction, flexion, internal and external rotation from which a truly functional analysis could be assessed.

RESULTS
a) Biomechanical
The modelling technique has demonstrated the ability to predict shoulder muscle and joint forces. The maximum joint force at the natural shoulder is predicted to be 0.8 BW during abduction and 0.5 BW in forward flexion. Simulation of the normal shoulder with the rotator cuff muscles absent demonstrates the large upward force from deltoid associated with clinically observed impingement. When the reverse anatomy design is used, then there is an increase in the deltoid moment arm of over 50%. This result in a corresponding reduction in both muscle and joint force during abduction. The reverse design also transmits the joint reaction force in a different direction. In particular, it allows the reaction to the upward deltoid force and so prevents coraco-acromial impingement. The resultant joint force during abduction is reduced to 0.5 BW. A further interesting prediction concerns the ability to rotate externally in abduction. It has been observed clinically (in the pilot study below) that this movement is possible for patients having a reverse anatomy prosthesis. The model predicts that this can be achieved by a combination of teres minor (if present) and the posterior fibres of deltoid.

In comparison with the normal shoulder, in the reverse design the direction of the shear forces on the glenoid site was reversed, the compressive forces were decreased and the joint contact vectors were always within the humeral cup providing joint stability for all simulated activities. The most affected muscle is the deltoid group that becomes able to compensate for the dysfunctional rotator cuff muscles providing also ability for extended humeral rotation.

b) Clinical Pilot study
One patient had an incorrectly assembled prosthesis and required revision. 8 patients (7/10) have been adequately followed up two of whom have been assessed over 12 months after insertion. Their Constant Scores before surgery have ranged from 18 to 47 (m=29.8) and at follow-up from 55 to 81 (m=64.6) – a 35 point improvement. However the most interesting finding was a return to near normal flexion of the arm and an improvement in external rotation which has been recorded as often deficient after the alternative Delta III shoulder. Further work on a more detailed analysis of scapular movements is being carried out.

DISCUSSION
This work has demonstrated the application of biomechanical modelling techniques to the development of new designs of shoulder replacement. In particular, it has been possible to demonstrate the important biomechanical features of the reverse design approach. First, the great stability of the reverse design is an important finding. This results from the reversed envelope of the joint contact forces and increases also the muscle moment arms crossing the GH joint. The clinical results in the short term have been encouraging but medium term follow-up studies are now under way.

REFERENCES