



Morsellised sawbones is an acceptable experimental substitute for the in vitro elastic and viscoelastic mechanical characterisation of morsellised cancellous bone undergoing impaction grafting

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ABSTRACT

Impaction grafting using morsellised bone chips is widely used during surgery to mitigate the effects of bone loss. The technique typically involves the packing of morsellised allograft cancellous bone into bone defects, and has found extensive application in revision hip and knee surgery. In the ideal situation, the presence of the bone graft prevents subsidence of the revised prosthesis in the short term, and integrates with the host bone in the longer term. However, the configuration of particles within the graft remains to be optimised, and is highly likely to vary across potential sites and loading conditions. Human bone, for use in experimental investigation, is often difficult to obtain with properties that are relevant from a clinical point of view. This study, therefore, has explored the mechanical response of a Sawbones based experimental substitute. An established confined compression technique was used to characterise the morsellised Sawbones material. Comparison of the results with published values for bovine and human bone indicate that the mechanical response of the morsellised Sawbones material map well onto the elastic and viscoelastic response of bone of a biological origin.

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1. Introduction

Knee and hip replacements are very widely performed procedures: The UK National Joint Registry (NJR) reports 80,314 hip replacements and 84,653 knee replacements for 2011 in England and Wales alone: The ratio of primary to revision procedures is reported as 6.1% for knees and 11% for hips [1]. Younger patients are more likely to need revision surgery [2]. Patients who have had a revision are more than five times more likely to need a re-revision, compared with a primary arthroplasty [3]. Worldwide the figures are expected to increase substantially over the next few years [4].

Patients frequently present for revision with a significant loss of bone stock, and this can be exacerbated during the removal of the old prosthesis [5]. Stabilisation of the revision implant may well require that bone stock is enhanced in key areas, leading to the use of techniques such as allograft bone impaction grafting. The technique was first developed in 1984 by Slooff et al. [26] to improve bone stock deficiency in protusio acetabuli and, in 1991, it was adapted by the Exeter group to address femoral bone deficiency [27]. Impaction grafting essentially involves using packed chips of cancellous bone to mitigate the effects of bone loss in revision hip or knee surgery whereby the graft surrounds the revision implant

granting it immediate post-operative stability. It has been demonstrated that, when appropriate conditions are met, bone stock can be restored in the long term with the graft being incorporated into the host [28]. Reported clinical outcomes are generally good, however the success rates achieved by the developers of the technique appear to be largely unmatched by other centres [29]. There is long established general agreement that success in allograft impaction grafting is strongly linked to the creation of a favourable mechanical environment, hence the surgical technique and the care with which it is adopted are paramount [30,31]. Future improvement depends upon further understanding of the mechanics of the bone construct and the factors that affect its consolidation and, eventually, remodelling and incorporation into the patient's own tissue.

Impaction grafting has been demonstrated to be a successful and progressively improving surgical technique at its best producing good long term bony support [6]. However, availability of human allograft bone is an issue, with demand exceeding supply [7,8]. Transmission of disease is also a significant concern [9], as is the degradation of longer term mechanical performance associated with sterilisation techniques such as irradiation [32].

Clinically, this has led to an interest in synthetic graft extenders e.g. hydroxyapatite [10,11] which may also change to the mechanical environment [12].

The level of availability of human allograft bone has had a significant impact on biomechanical studies exploring impaction grafting. Bovine, porcine and ovine bone have all been investigated as

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substitutes that can potentially be used in experimental investigations of the mechanical response of morsellised cancellous bone (MCB) [13]. The challenge in mechanical characterisation of morsellised bone is to devise an experimental protocol which separates out the pressure dependent elastic properties from the time dependent viscoelastic and the plastic properties. Methodologies to do this, based on a confined compression testing procedure originating in soil mechanics, have been presented most recently by Phillips et al. [14,15] and Lunde et al. [16]. In this study, we have used the methodology of Phillips et al. [15] and postulate that a synthetic “Sawbones” morsellised bone substitute (Solid Rigid PU Foam, code 30pcf) will exhibit similar mechanical behaviour to the biological based alternatives. 30pcf was chosen as it readily available and falls in the mid-range of the different densities of solid rigid polyurethane foam testing blocks produced by Sawbones and conforming to ASTM F-1839-08 “Standard specification for Rigid Polyurethane Foam for Use as a Standard Material for Testing Orthopaedic Devices and Instruments”.

Experimental investigations into the primary stability of impacted bone graft use variants of the confined compression test to represent physiological loading constraints. Many studies have focussed on the comparison of the effect of a particular parameter, e.g. hydraulic and manual driven impactation loading protocols [33] and size of the morsellised bone particles [34–39]. Unfortunately, direct comparison of findings across different experimental studies is problematic due to the lack of standardisation in (i) the test configuration (e.g. [33,40–43]); (ii) the magnitude and frequency of loading [18,19,23,22]; (iv) the origin and treatment of the bone chips [13,20,44]. One approach that potentially alleviates the difficulties of comparison across studies is to use experimental protocols which enable the bone graft material to be characterised using consolidation models from soil mechanics, such as the Drucker–Prager and Mohr–Coulomb yield criteria. This then offers the possibility of employing computer based stress analysis techniques to help inform experimental and clinical observations (e.g. [25,45,46]).

2. Materials and method

The testing procedure used in this study was similar to that developed by Phillips et al. [15] and subsequently adopted by Lunde et al. [16] with minor modifications. This allows for direct comparison with the results obtained in these previous studies.

2.1. Testing arrangement

Confined compression testing was used, where the samples were confined within a die produced from a cylindrical section of mild steel with an internal diameter of 51 mm, a wall thickness of 9 mm and a length of 100 mm (Fig. 1). The diameter of the die meant that the size of the bone graft particles would be small in comparison, minimising any interaction between the particles and the die [14,15]. The large wall thickness prevented radial strains from significantly altering the geometry of the cavity during testing. The die was secured to its base plate using three screws threaded through its wall, allowing easy removal of the samples following testing. Loading was applied to the samples through a plunger, rigidly attached to a materials testing machine (Instron, model no. 3360, High Wycombe). The plunger was a solid steel cylinder with a diameter of 50 mm. The 1 mm clearance allowed between die and plunger was small enough to ensure adequate constraint of the bone graft, whilst minimising interaction between both components.

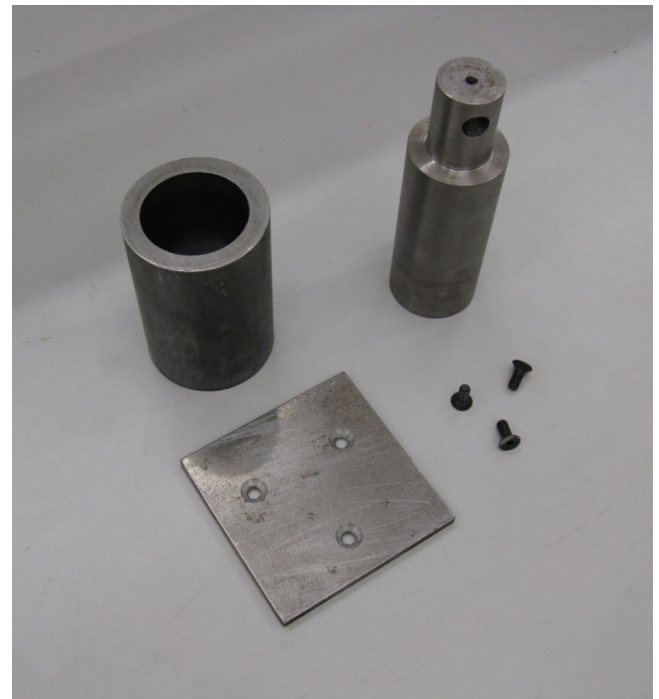


Fig. 1. Schematic/photo of test rig.

2.2. Specimen preparation

Polyurethane foam produced by Sawbones (Sawbones, product no. 1522-04, Malmö, Sweden) was used to create a dry morsellised bone substitute material. With a compressive strength of 18 MPa and a compressive modulus of 445 MPa, in its solid test block form, the material has mechanical properties that are within the range of human cancellous bone. A Norwich bone mill (Howmedica now Stryker, Mahwah, NJ, USA) was used to create synthetic MCB particles. The morsellised Sawbones particles were passed through a series of sieves to ensure their distribution ranged in size between 1 and 6 mm; visual inspection was used to remove particles larger than 6 mm. This size range is consistent with that of clinically used particles for femoral impactation grafting [29] and also reduced the risk of edge effects affecting the results. Particle size distribution was not recorded in this study.

2.3. Experimental procedure: Elastic and viscoelastic characterisation

Samples were introduced into the die in three roughly equal layers; a 20 N static load was applied to each layer for approximately 5 s in order to standardise the compression applied to each sample at the time of insertion into the die. A standardised loading profile was then applied to each sample in three stages: conditioning, re-loading and unloading. During the conditioning stage, samples were subject to 750 cycles, with each cycle loading the sample to a maximum nominal stress of 3.0 MPa and unloading to an minimum nominal stress of 0.01 MPa (close to zero). The load was applied at a constant displacement rate of 10 mm/min. Time, plunger displacement and load applied to the samples were continually recorded. The aim of this conditioning stage was to ensure that the specimen was very well packed so that subsequent testing at physiological stress level would produce a response which could be assumed completely elastic in nature. Following the conditioning cycles, the plunger was removed from the test chamber and the sample was left to rest for 16 h while still inside the die. Five samples were then re-loaded to each of six stress levels (0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 MPa), and were left to stress relax by for a period of 6 h. This was

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