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Research Paper

Strong similarities in the creep and damage behaviour of a synthetic bone model compared to human trabecular bone under compressive cyclic loading

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ABSTRACT

Understanding the failure modes which instigate vertebral collapse requires the determination of trabecular bone fatigue properties, since many of these fractures are observed clinically without any preceding overload event. Alternatives to biological bone tissue for *in-vitro* fatigue studies are available in the form of commercially available open cell polyurethane foams. These test surrogates offer particular advantages compared to biological tissue such as a controllable architecture and greater uniformity. The present study provides a critical evaluation of these models as a surrogate to human trabecular bone tissue for the study of vertebral augmentation treatments such as balloon kyphoplasty. The results of this study show that while statistically significant differences were observed for the damage response of the two materials, both share a similar three phase modulus reduction over their life span with complete failure rapidly ensuing at damage levels above 30%. No significant differences were observed for creep accumulation properties, with greater than 50% of creep strains being accumulated during the first quarter of the life span for both materials. A significant power law relationship was identified between damage accumulation rate and cycles to failure for the synthetic bone model along with comparable microarchitectural features and a hierarchical composite structure consistent with biological bone. These findings illustrate that synthetic bone models offer potential as a surrogate for trabecular bone to an extent that warrants a full validation study to define boundaries of use which compliment traditional tests using biological bone.

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1. Introduction

With an estimated 1.4 million fractures annually, vertebral compression fractures comprise one of the most prevalent injuries to the musculoskeletal system (Johnell and Kanis, 2006). Vertebral fractures are particularly frequent in the female patient demographic, where osteoporosis has diminished the ability of bone to sustain loads induced by daily activities (Felsenberg, 2002). The cyclic nature of spinal loads can accumulate damage and creep strains in the vertebrae which are composed predominantly of trabecular bone (Burr et al., 1997; Pollintine et al., 2009). Clinical observations have illustrated accumulation of damage and creep strains, which lead to the progressive collapse of the vertebrae (Qasem et al., 2014). Attempts to understand this type of failure mode have been pursued using *in-vitro* tests on trabecular bone extracted from human vertebra (Haddock et al., 2004; Lambers et al., 2013; Rapillard et al., 2006) and through computational means (Kosmopoulos and Keller, 2008; Kosmopoulos et al., 2008; Makiyama et al., 2002). An ongoing challenge for *in-vitro* tests remains the inherent variability present in biological tissue and the availability of sufficient sample numbers to achieve statistical significance. Fatigue testing poses particular challenges due to the limited test life of specimens resulting from biological degradation and dehydration which can influence the mechanical properties (Linde and Sørensen, 1993).

Alternative test media to bone tissue are available in the form of commercially available open cell polyurethane foams, which offer greater uniformity and longer shelf lives among their advantages. The absence of a comprehensive validation for these materials has rightly caused the biomechanics community to be somewhat sceptical of results obtained using them until sufficient data is available to give confidence in their validity. The present study compares mechanical and morphological properties of one such synthetic model with human bone as a first step in evaluating whether their advantages can be utilised in vertebral augmentation studies, once their limitations and subsequent effects on findings are adequately understood. The first study to suggest the use of open cell bone models was completed more than 20 years ago (Szivek et al., 1995). More recent studies of open cell synthetic bone models have also been supportive of their use in terms of static properties, notwithstanding the need to acknowledge that elastic properties are at the lower end of the spectrum for real trabecular bone (Patel et al., 2008; Thompson et al., 2003). Closed cell type foams have also been shown to exhibit comparable elastic properties and similar pressure dependant yielding mechanisms to bone tissue (Kelly and McGarry, 2012; Rincon-Kohli and Zysset, 2009, Calvert et al., 2010). Another study investigated fatigue properties of closed cell foam compared to trabecular bone and found a much lower level of damage and creep strain accumulation (Palissery et al., 2004). This stems from a fundamental difference in the failure mechanisms of an open cell structure where cell edges can bend and buckle, leading to a gradually localising crush band, similar to trabecular bone (Gibson, 2005). Meanwhile in closed cell structures, deformation of cell faces causes formation of a localised crush band that expands to the surrounding regions unlike trabecular bone.

Open cell models have proven popular in cement augmentation studies where the porous structure is important to replicate infiltration of cement into the inter-trabecular spaces (Bohner et al., 2003; Loeffel et al., 2008; Mohamed et al., 2010). These models have been further utilised to study the micromechanics of the bone cement interface, which is an important feature for augmentation outcomes (Purcell et al., 2014, 2013; Zhao et al., 2012). Many of these studies utilise an aluminium based open cell structure, which have been found to exhibit favourable properties for the study of cement injection micromechanics in terms of damage evolution and distribution (Guillén et al., 2011). To the author's knowledge only one previous study has examined the fatigue properties of a commercial polyurethane open cell bone model, albeit encapsulated within a fibreglass cortex, and found similar cyclic damage accumulation compared to human vertebral bodies (Johnson and Keller, 2008).

Previous fatigue studies of human vertebral trabecular bone have found creep contributes to a significant proportion of the overall deformation compared to damage induced strains which can typically reduce stiffness by up to 40% at failure (Haddock et al., 2004; Lambers et al., 2013; Rapillard et al., 2006). These findings reiterate the potential importance of fatigue related creep in instigating vertebral collapse commonly observed clinically. Architecture has also been found to be an important factor in fatigue properties of vertebral bone, where any applied loads oblique to the principal material direction can drastically reduce fatigue life (Dendorfer et al., 2008). Inclusion of fabric property measures into fatigue life predictions of trabecular bone has also been shown to strengthen prediction power (Rapillard et al., 2006). Open cell polyurethane foams are known to have a principal material orientation in the rise direction of the foam during manufacturing, which given the apparent importance of bone architecture on both static and fatigue properties (Charlebois et al., 2010; Moesen et al., 2012; Wolfram et al., 2012) makes them particularly comparable in morphological terms to vertebral trabecular bone (Gómez et al., 2013).

Given the lack of previous studies directly comparing synthetic open cell bone models with human data, the present study provides a critical evaluation of their suitability as a surrogate to human trabecular bone tissue in terms of both fatigue and morphological properties. This initial investigation further aims to determine whether a full validation study of synthetic models is warranted to enable their use as a surrogate to human bone within carefully defined boundaries of use for *in-vitro* mechanical studies.

2. Materials and methods

Two main methodologies were utilised to evaluate the suitability of the open cell foam as a surrogate for human trabecular bone. The first of these methodologies comprised a series of static and cyclic loading tests to characterise the mechanical properties of the foam compared to published data for human bone (Haddock et al., 2004; Lambers et al., 2013; Rapillard et al., 2006). Subsequently a microcomputed tomography study was also conducted to evaluate the morphological properties of the foam compared to a freely