Original Article

Evaluating compressive properties and morphology of expandable polyurethane foam for use in a synthetic paediatric spine

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ABSTRACT

An expandable rigid PU foam can turn into complex shapes, with a shell like structure on the outside and honeycomb structure on the inside, which can be easily shaped to a vertebra form. The present study aims to determine whether expandable rigid polyurethane foam was an appropriate substitute for rigid block polyurethane foam to model the trabecular bone. Static compression tests were performed to determine compressive moduli and yield stresses on three polyurethane foam densities namely 0.16 g/cm³, 0.24 g/cm³ and 0.42 g/cm³. Morphology of the PU foams for all densities was also observed. The compressive modulus for 0.16 g/cm³ and 0.24 g/cm³ were found varied from 40 to 43 MPa and 83 to 92 MPa while yield stress ranged from 2.1 to 2.3 MPa and 3.4 to 4.8 MPa respectively. As for 0.42 g/cm³, the compressive modulus and yield stress varied from 240 to 256 MPa and 38 to 40 MPa. Based on these results, the compressive modulus and yield stress of 0.24 g/cm³ compared favourably with rigid block PU foam and human cadavers presented in the literatures. Hence, the findings of this study could potentially be used in developing a synthetic vertebral trabecular bone of paediatric spine for biomechanical testing.

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1. Introduction

It is a common practice to use human adult and animal cadaveric spine in biomechanical investigation for both adult and paediatric cases [1–3]. However, the animal cadaveric spines are best to represent adult spine because the mechanical properties, morphology and range of motion (ROM) are closer to adult spine as compared to paediatric spine. Ideally, human paediatric cadaver spine is the best specimen to be used in investigating paediatric cases [2]. However, the accessibility to obtain human paediatric cadaver spine is very rare and limited, therefore a synthetic spine can be considered as a good alternative [4]. The main advantages in using synthetic materials to model paediatric spine is that they can be tai-
lored to a specific requirements and offered constant material properties.

The vertebra is composed of trabecular bone surrounded by a thin shell of compact (cortical) bone. Trabecular bone structure is highly porous; similar to a sponge or foam while cortical bone has a very dense solid structure. The trabecular bone is the main element in the vertebra body and the key component of vertebra strength as it carries majority of the load. There are varieties of material that can be used as synthetic bone such as polymer form, polyvinyl chloride (PVC) foam and polyurethane (PU) foam of both open and closed cells [5–6,7,8]. Rigid PU foam is widely known as a great insulator with strong mechanical characteristics including its compression modulus and yield stress. The advantages of PU foam in comparison with other composite materials are its low cost and easy to handle [9–11]. Thus, rigid PU foams are widely used in biomechanical testing to replicate bone in favour of cadaveric specimens as they have similar mechanical properties to human bone. Extensive studies to investigate the effect of orthopaedic devices and instrumentation on the bone using both closed and open PU foams has also been increased dramatically especially once the American Society for Testing and Materials (ASTM) developed ASTM F1839-97, which is to provide a standard method to classify PU foam based on the mechanical behaviour of different densities [7,12–15].

Commercial closed cell rigid PU foam in block has the static and elastic mechanical properties similar to a human trabecular bone but not the failure properties of trabecular bone as the natural structure of trabecular bone itself is an open cell foams [6,16–18]. Hence, an open cell rigid PU foam can be used as an alternative for static or fatigue studies of human vertebrae [18]. However, recent study showed that commercial open cell PU foam do not reproduce the anisotropic microstructure of natural bone, thus its suitability to be used in in-vitro cases such as bone cement is limited [19]. Patel et al. [8] suggested that the rigid block PU foam with density of 0.16 g/cm³ can be used as a model to represent the osteoporotic bone in compression. Furst et al. [20] recently presented that their self-developed synthetic foam using different mineral filler and blowing agent mimicked the compressive behaviour of vertebral trabecular bone. However, there are no studies that stated a specific PU foam density to be used as an alternative for paediatric trabecular bone as most study focuses on adult trabecular bone and their specific applications.

Since there is no study investigates the human paediatric trabecular bone to date, the relationship between age with ash density demonstrated by Moskilde et al. [21] was taken into consideration in the present study. Younger bone has a higher modulus when compared to adult as based on equation derived by Moskilde’s [21], as shown in eq. (1).

$$E = -1.7 \times \alpha + 160 \text{ [MPa]}$$  \hspace{1cm} (1)

where $E$ is the elastic modulus and $\alpha$ is human’s age. Whereas ash density (AD) decreases from young to adult based eq. (2). This was demonstrated from the variation of the apparent bone density varies from 0.05 g/cm³ to 0.30 g/cm³ between range of individuals, levels and age.

$$AD = -0.0017 \times \alpha + 0.23 \left(\frac{g}{cm^3}\right)$$  \hspace{1cm} (2)

The main challenges in developing a synthetic spine are to match the biological spine in terms of kinematic, physical and mechanical behaviours. Most of the commercial rigid PU foams are available in blocks and long bone shapes like femur and tibia. Although synthetic vertebrae are available, it is mostly used as a teaching purpose. Anthony et al. [14] used commercially available synthetic vertebrae comprised of PU foam enclosed in a short-glass-fiber-reinforced epoxy resin to study the inter body device subsidence. The results showed that synthetic vertebrae did not accurately capture the subsidence in comparison with block PU foam and human cadaveric vertebrae.

The first synthetic spine developed by the author was too rigid and did not mimic the motion range of a natural spine [22]. An alternate solution was to use expandable PU to replace the rigid block PU where the foam once expands it turns into complex shapes, with a shell like structure on the outside and honeycomb structure on the inside. There have been no apparent studies focused on using expandable foams as a substitute for trabecular bone. Therefore, this study aimed to determine whether the expandable PU foam was an appropriate material to replace trabecular bone for biomechanical testing by comparing the compressive moduli and yield stresses of the expandable PU foam with block rigid PU foam and human data.

2. Materials and methods

Commercial expanding PU foams are available in a range of densities from 0.048 g/cm³ to 0.42 g/cm³. For this study, three different densities of expandable rigid PU foams were supplied by Smooth On, Inc. The densities selected were 0.16 g/cm³, 0.24 g/cm³ and 0.42 g/cm³. The first two densities fall under ASTM F 1839 (Standard Specification for Rigid Polyurethane Foam for Use as a Standard Material for Testing Orthopaedic Devices and Instruments) grade 10 and 15.

An animal trabecular core was also tested as a comparison with the expandable PU foams. In this research, porcine spines at the age of 5–6 months were selected. The vertebrae used were from T9 to T12 from three different spines. The cores were mechanically tested to determine the material properties.

2.1. Expandable PU preparations

The expandable PU foams were supplied in the form of two-component water blown rigid foams. The mixing ratio for all the foams was 1 to 1 in volume with 4–5 min of mixing time. The apparent density of the foams was measured in accordance with ASTM D 1622 (Standard Test Method for Apparent Density of Rigid Cellular Plastics). Apparent density was important in this study to justify the technique used to ensure that the density for the end product matched to the density provided by the supplier. The cube shaped foam sam-
amples were $25.4 \times 25.4 \times 25.4 \text{ mm}^3$ in volume. The density was calculated to three significant figures by dividing the mass of the foam with their respective volumes.

The results of apparent density according to ASTM D1622 for five specimens were found to be similar to the density presented in the manufacturing MDS (Materials Data Sheet) given by the manufacturer, Smooth On, Inc.

2.2. Specimens preparation

Keaveny et al. suggested that a 2:1 cylinder aspect ratio is the best specimen size to determine the uniaxial compressive modulus and strength of biological trabecular bone [23]. As foam material density was generally 40 % lower than biological trabecular bone, it resulted in lower modulus and strength compared to human bone [18]. Twenty cylinders of foams with large dimension (25 diameter x 50 height mm) and a 2:1 aspect ratio for each density were manufactured. It was manufactured on separate days to evaluate the properties and inter-batch repeatability. Ten specimens were core drilled for each density to form small cylinders cores (9 mm) with average height of 7.7 mm to enable direct comparison with to enable direct comparison with a published study of rigid block PU foam [8,24]. The average diameters were then measured for all specimens using the a digital vernier calliper and the specimens were filed with fine and very fine sandpapers (grade 100 and 150) to obtain approximately 7.7 mm in height as presented in Fig. 1.

The porcine spines assigned to this research were dissected into individual vertebrae. The specimens were stored at $-20 \degree \text{C}$ and thawed out for 24 h at 4 $\degree \text{C}$ before testing. Each vertebra was core drilled on the drill press platen such that the longitudinal axis of the core was parallel with the orientation of the longitudinal trabecular struts as suggested by Keaveny et al. [25] as shown in Fig. 2. Five samples were drilled with 1:1 ratio (8 mm x 8 mm) and 2:1 aspect ratio (7 mm x 14 mm). The ends of the cores were machined using diamond precision annular saw. The cores were wrapped in hydrated gauze with saline to prevent drying prior to testing.

2.3. Compression test

The uniaxial compression tests were conducted using an Instron 3343 materials testing machine (Norwood, MA, USA). The machine is ideal for tension and compression applications as it is fitted with a 1 kN load cell and 1067 mm vertical test space. No preloads were applied to the specimens and they were compressed in between two steel plates as shown in Fig. 1(b). Normally preload is necessary for compression test to ensure the upper plate makes contact with the specimen to remove any ‘toe’ region in the graph. However, due to the size and structure of the specimens, no preload was applied and the upper plates were aligned close to make contact directly with the specimens instantly reducing the chance of the ‘toe’ region in the results The tests were performed at a strain rate of 0.5 % under displacement control up to 20 % of the total strain to observe post-yielding behaviour. The specimens were placed such that the axis of the compressive load applied was parallel to the expandable foam rise direction. The same set up was applied to the porcine specimens, where it was placed such that longitudinal axis of the core was parallel with the orientation of the longitudinal trabecular struts.

2.4. Microstructure observation

The expandable PU foams morphology for all three densities (0.16 g/cm$^3$, 0.24 g/cm$^3$ and 0.42 g/cm$^3$) was observed using a JEOL (JSM-6390LV) Scanning Electron Microscope (SEM) on small rectangular sections. A standard stereological method was performed on the SEM images with 500 μm scale bar to measure the average cell size and the mean intercept length. The mean intercept length was calculated by dividing the $L_{c}$ (total length of cells intercepted by the lines divided with total length of the lines) over $N_{c}$ (number of cells intercepted in length of the lines). Average cell size was calculated by the total length intercepted by the lines divided by the number of cells intercepted by the lines.

2.5. Statistical analysis

Statistical analysis was conducted using MINITAB Release 16.0 Statistical Software (Minitab Inc., Pennsylvania, USA). Data was analysed using one sample t-test with the significance level at 0.05 to compare the results with literatures. Normality distribution was evaluated using the Anderson-Darling test. Comparison between literature [8] and the current study was made at the approximate ranges of 95 % confidence intervals for all values.

3. Results

3.1. Compressive properties of expandable rigid PU foam

The results were presented as force-displacement curves and engineering stress-strain curves. The engineering stress was calculated by dividing the force at every data point with the cross-sectional area of the PU foams while the engineering strain was determined by dividing the displacement at each point with the original height of the PU foams. The stress values for both specimen sizes were in good agreement for all densities while the modulus values for smaller specimens were significantly lower in respect to the larger specimens as shown in Tables 1 and 2. This made the strain values for smaller specimens higher than the larger specimens. The measured values were different, most likely due

| Table 1 - Mechanical properties for 0.16 g/cm$^3$ and 0.24 g/cm$^3$ for 25 mm diameter and 50 mm height of expandable PU foam specimens. |
|-----------------|-----------------|-------------------|
| Mechanical Properties | Density (g/cm$^3$) | Average[Stddev](MPa) |
| Compression | 0.16 | 134.39[28.94] |
| Modulus, $E$ | 0.24 | 227.08[8.21] |
| Compressive Stress, $\sigma_{\text{UC}}$ | 0.16 | 3.29[0.2] |
| Yield Stress, $\sigma_{\text{yield}}$ | 0.16 | 4.29[0.4] |
| | 0.24 | 2.39[0.18] |
| | 0.24 | 3.14[0.59] |
to the fact that smaller specimens compressed easier compared to the larger specimens because of the quantity of cells within the specimens. However, the smaller specimens were tested only to enable a direct comparison with published results.

3.2. Compressive properties of porcine

In this research, porcine spines were selected as the biological specimens to conduct an analytical comparison with synthetic PU foam. This research tested cylindrical shaped specimens of the porcine trabecular bone using two different size specimens, 1 to 1 ratio (8 height x 8 diameter) and 2 to 1 ratio (14 height x 7 diameter) cm and the results were shown in Table 3. Teo et al. conducted a compression test on 10 cube specimens of porcine trabecular bone with (1: 1: 1) ratio specimen’s sizes (5 × 5 x 5) cm instead of 2:1 ratios as suggested by Keaveny et al. [26,27]. The results from this study were compared with Teo et al. and summarised in Table 6.
3.3. **Microstructure characterization**

SEM microstructure images were taken which displayed the closed cell PU foam for three different densities. The image showed in Fig. 3 displayed a uniform distribution of cells (pores) across the surface image when the foam expanded. It was expected that the higher density foam would have a larger value of cell size since there was an inverse relationship between density and cell size of the foam. Table 1 summarised the density and cell size measurements for each density.

From Table 4, with 500 μm scale bar as reference, 0.24 g/cm$^3$ foam has smaller average cell size than 0.16 g/cm$^3$ foam, showing that there was an inverse relationship between density and cell size. However, for the highest density foam, 0.42 g/cm$^3$, this relationship did not hold true, as the distributed cells were more distinct and larger. However, for the highest density foam, 0.42 g/cm$^3$, this relationship did not hold true, as the distributed cells were more distinct and larger and it can be seen that were more solid PU materials in between cells.

**4. Statistical analysis**

Table 3 summarised the values for compressive moduli and yield stresses between the present study and Patel et al. [4] for 0.16, 0.24, 0.32 and 0.42 g/cm$^3$. No direct comparison could be made for 0.24 and 0.42 g/cm$^3$, therefore a linear interpolation and extrapolation graph was plotted to show the expected value for 0.24 and 0.42 g/cm$^3$ PU foam by adapting Patel et al. [4] 0.16 and 0.32 g/cm$^3$ average value as a reference. The equation of the linear slope between the reference points were measured for both compressive modulus and yield stress. The value for 0.24 and 0.42 g/cm$^3$ was approximated to 93 and 201 MPa for compressive modulus and 2.2 and 4.7 MPa for yield stress, respectively.

The true statement was assumed when the null hypothesis ($H_0$) is equal to the average values from the literature.

**Fig. 3 – SEM images of expandable rigid PU foam of three different densities at 500 μm scale bar (a) 0.16 g/cm$^3$ (b) 0.24 g/cm$^3$ and (c) 0.42 g/cm$^3$.**

The tests were carried out to observe whether the statement was likely true or not. According to the t-test, for 0.16 and 0.24 g/cm$^3$ PU foam, no significant differences were detected for the compressive modulus ($p > 0.05$) but there was significant difference for the yield stress ($p < 0.05$). Compressive modulus data failed to reject $H_0$ but yield stress data clearly

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**Table 3 – Mechanical properties of porcine trabecular core specimens.**

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>Specimen size(mm)</th>
<th>Average<a href="MPa">Stddev</a></th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>8 D x 8 H</td>
<td>188.04 [79.78]</td>
</tr>
<tr>
<td>Modulus, E</td>
<td>7 D x 14 H</td>
<td>308.89 [127.82]</td>
</tr>
<tr>
<td>Compressive Stress, $\sigma_{ult}$</td>
<td>8 D x 8 H</td>
<td>12.99 [3.00]</td>
</tr>
<tr>
<td>Yield Stress, $\sigma_{yield}$</td>
<td>8 D x 8 H</td>
<td>9.13 [2.18]</td>
</tr>
<tr>
<td></td>
<td>7 D x 14 H</td>
<td>11.18 [2.52]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.35 [1.53]</td>
</tr>
</tbody>
</table>

**Table 4 – Summary of apparent density, average cell size and mean intercept length of three different densities (0.16 g/cm$^3$, 0.24 g/cm$^3$ and 0.42 g/cm$^3$).**

<table>
<thead>
<tr>
<th>Foam Type</th>
<th>Apparent Density (g/cm$^3$)</th>
<th>Average cell size [Std Dev] (μm)</th>
<th>Mean Intercept Length [Std Dev] (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foam it 16</td>
<td>0.16</td>
<td>408.51 [93.10]</td>
<td>388.54 [72.11]</td>
</tr>
<tr>
<td>Foam it 24</td>
<td>0.24</td>
<td>261.57 [55.86]</td>
<td>258.52 [62.16]</td>
</tr>
<tr>
<td>Foam it 42</td>
<td>0.42</td>
<td>422.56 [138.89]</td>
<td>387.13 [181.90]</td>
</tr>
</tbody>
</table>
rejected the H₀. As for 0.42 g/cm³, both compressive modulus and yield stress rejected H₀ with α-level at 0.05. The normality test and the time series plot indicated that the data met the t-test’s assumptions of normality and randomness. By using α-level at 0.05, all p values were greater than α value on Anderson-Darling test for normality distribution, suggesting that all data was normally distributed.

The 95% confidence interval indicated the true value of the current study for 0.16 g/cm³ was within 40.90–43.48 MPa for compressive modulus and 2.09–2.32 MPa for yield stress. As for 0.24 and 0.42 g/cm³, the true value was within the range of 84.53–95.24 and 240.30–255.70 MPa for compressive modulus and for yield stress, the values range from 3.63 to 4.92 and 38.40–40.30 MPa respectively. On the other hand, Table 4 shows the comparison between the results of current study and other research works that used human or porcine trabecular as specimens.

5. Discussion

The main motivation in selecting the material for paediatric synthetic spine was to ensure that the materials mimicked the biological material. Therefore, the next step was to evaluate the results against the human trabecular bone. Human trabecular bone moduli vary widely from 90 to 875 MPa. This variation is due to several diverse factors such as the age, cause of death, bone density, and the methods used to calculate the compressive modulus. Keaveny et al. and Banse et al. calculated the compressive modulus using the slope of the best-fit straight line within different ranges of strain, while others calculated within the maximum slope of the stress-strain curve [23,27,28]. This study calculated the compressive modulus as the maximum slope within the elastic region of the stress-strain curves. The average compressive modulus for both densities (0.16 and 0.24 g/cm³) that were used in this study were 134.49 and 227.08 MPa, which fell within the range of human vertebra trabecular bone based from literature as shown in Table 6.

The yield stress of human vertebra trabecular bone varied from 0.5 to 4.6 MPa using 0.2% offset. Keaveny et al. suggested that yield stress depended on the direction of testing and tended to overestimate if the platens used were not fixed properly [25]. In the current study, the specimens were positioned as recommended by ASTM F1839, which required the axis of the compressive load applied to be parallel to the foam rise direction. The average yield stress for both densities (0.16 and 0.24 g/cm³) in this study were 2.37 and 3.14 MPa, which are slightly higher compared to the human vertebra trabecular bone but it still fell within the range given by the literature as presented in Table 6. Although both densities fell within the range of human trabecular bone, the PU foam with 0.24 g/cm³ density was the best fit compared to 0.16 g/cm³ because the modulus percentage difference between 0.24 g/cm³ and human trabecular bone was smaller compared to the 0.16 g/cm³.

Since this research investigates paediatric cases, it was necessary to select the expandable rigid PU foam closest to human paediatric trabecular bone. Mosekilde et al. [21] demonstrated the relationship between age with ash density (bone mass) and modulus of elasticity of human cadavers. However, it only valid for samples between 20–80 years. Based on eq. (1), for 20 years old trabecular bone, the expected modulus was 126 MPa and for 30 years old, the modulus decreased to 109 MPa. Although the equation valid for samples between 20–80 years old, the pattern emerged can be used as a guideline for paediatric bones. In consideration of a 20 years old trabecular bone based on eq. (1), the modulus for paediatric bone was expected to be higher than 126 MPa. Both PU foams used in this study have a higher modulus than 126 MPa but if eq. (1) was applied to 9 years old (paediatric age), the modulus was calculated to be around 176 MPa. Therefore, the 0.24 g/cm³ PU foam was the better selection compared to 0.16 g/cm³ foam.

Other considerations are directly comparing the properties of the expandable PU foam used in this study with published results of PU foam commonly used as trabecular bone. To enable a direct comparison, the experimental procedures used in this research were setup according to those used by Patel et al. [8]. In Table 5, the mean compressive moduli for 0.16 g/cm³ and 0.24 g/cm³ were 42 MPa and 90 MPa respectively. This data was close to the mean compressive modulus found by Patel et al. These were shown using t-test as the F-values for both PU foams were statistically greater than 0.05. The values provided sufficient evidence to accept the null hypothesis that the mean values for both foams were equal to the mean value from Patel et al. [8].

Yield stress for all PU foams was neither equal to the mean figure found by Patel et al. according to the t-test (p > 0.05) nor within the approximate ranges when compared with the 95% confidence interval. However, Patel et al. [4] stated that for 0.16 g/cm³ and 0.32 g/cm³, the results were within the range from 0.9 to 4.5 MPa. If taking the latter factor into consideration, the yield stress values obtained in this study were still within the ranges presented in the literature as in Table 3. The denser PU foam used in this study demonstrated higher strength and stiffness as compared to Patel et al.

Although the compressive modulus of 0.42 g/cm³ (247.58 MPa) expandable rigid PU foam was closer to the human trabecular bone, the yield stress (39.44 MPa) was 20% higher than human trabecular bone. As in most cases for rigid materials, the stronger materials are brittle and could fracture easily and therefore do not replicate human trabecular bone. The structure of this foam was displayed in Fig. 2. In comparison with the other two foams, the 0.42 g/cm³ foam showed that it was less porous; this could explain why the yield stress was higher than human trabecular bone. Therefore, 0.42 g/cm³ PU foam was eliminated from as an alternative to replicate the synthetic vertebrae for paediatric spine.

In addition, porcine spines were used as the biological specimens to conduct an analysis comparison with the expandable PU foam. Teo et al. [29] conducted a study to investigate the relationship between CT intensity, micro-architecture and mechanical properties of porcine vertebral trabecular bone. Although Teo et al. used cube shaped specimens as compared to cylindrical specimens, the ratio used were similar which is 1:1. The different percentage between the same specimen size ratio (1 to 1) was lower for all mechanical properties compared with 2 to 1 ratio. As expected, the range between similar
specimen size ratios was approximately 20% or less for all properties, while the 2:1 ratio range in comparison with Teo et al. was within 30–40%. In line with Keaveny et al., the results of porcine spine indicated that the ratio and specimen size used in testing trabecular bone affect the final result. Therefore, the results of the porcine spine with a 2:1 size ratio as suggested by Keaveny et al. were used to compare with research on human trabecular bone. As shown in Table 6, the different percentage of compression modulus between porcine spine and human trabecular bone for various studies was within 15%. The compression modulus of porcine spine conducted by Teo et al. was in good agreement with synthetic PU foam (0.24 g/cm³) under 2:1 ratio.

The percentage difference between the 0.24 g/cm³ PU foam and various human trabecular bone data in this study was around 40%. This difference supported the observation found by Johnson and Keller where the foam material density was generally 40% lower than human trabecular bone [18]. The 0.24 g/cm³ expandable PU foam was the best foam to replicate trabecular bone when compared to other expandable PU foams tested in this study.

### 6. Conclusion

The results obtained in this study highlighted the challenges in determining which expandable PU foams could replicate the trabecular bone behaviour. This was due to the very wide range of data for human bone from literature. In this study, expandable rigid polyurethane foams with densities of 0.16 g/cm³, 0.24 g/cm³ and 0.42 g/cm³ were tested in uniaxial compression and the results showed that the 0.16 g/cm³ foam was too low to be used for trabecular bone testing. Although the compressive modulus of 0.42 g/cm³ was close to the literature, the yield stress for 0.42 g/cm³ foam was 20% higher than the ranges given in literature. Additionally, the structure of this foam was less porous and did not exhibit the structure expected for human trabecular bone therefore this foam was eliminated. On the other hand, the compressive modulus and the yield stress for 0.24 g/cm³ PU foam fell within the range given for human osteoporotic trabecular bone presented in literature. Hence, for paediatric, the compressive modulus was expected to be lower (126 MPa from eq. (1)) than for adult data used in literature. Therefore, the expandable PU foam 0.24 g/cm³ is believed to have the potential to replace the trabecular bone to model the paediatric synthetic spine. This study highlighted the difficulties in determining which expandable rigid PU foams could replicate the human trabecular bone as the range data of human bone were very wide. One of the main advantages of expandable PU foam is that it can be shaped into complex shape such as vertebra and at the same time minimalised the inter-specimen variables. A beneficial future study would be to perform confined compression tests to demonstrate post yield behaviour of PU foams and hence strengthen the case of using the selected PU foam as the synthetic bone.

### Table 5 – Current study versus Patel et al. [8] for 0.16, 0.24, 0.32 and 0.42 g/cm³ PU foams.

<table>
<thead>
<tr>
<th>Density (g/cm³)</th>
<th>Compression Modulus, E Average [Stddev] (MPa)</th>
<th>Yield stress, σ&lt;sub&gt;yield&lt;/sub&gt; Average [Stddev] (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current Study</td>
<td>Patel et al.</td>
</tr>
<tr>
<td>0.16</td>
<td>42.19 [1.04]</td>
<td>41 [3]</td>
</tr>
<tr>
<td>0.24</td>
<td>89.89 [4.31]</td>
<td>145 [6]</td>
</tr>
<tr>
<td>0.32</td>
<td>NA</td>
<td>93&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>0.42</td>
<td>247.58 [6.15]</td>
<td>201&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

* values based on linear interpolation value from 0.16 and 0.32 g/cm³.

### Table 6 – Current study versus human and porcine trabecular bone as presented in literature.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type (specimen ratio size)</td>
<td>PU F (2:1)</td>
<td>PV</td>
<td>HV (2:1)</td>
<td>HV (2:1)</td>
<td>HV (2:1)</td>
</tr>
<tr>
<td>Compression Modulus, E Average [Stddev] (MPa)</td>
<td>0.16 g/cm³</td>
<td>134.39 [28.94]</td>
<td>1.0 (1:1)</td>
<td>188.04 [79.78]</td>
<td>308.89 [127.82]</td>
</tr>
<tr>
<td>Yield stress, σ&lt;sub&gt;yield&lt;/sub&gt; Average [Stddev] (MPa)</td>
<td>2.39 [0.18]</td>
<td>3.14 [0.59]</td>
<td>11.18 [2.52]</td>
<td>7.35 [1.53]</td>
<td>2.02 [0.92]</td>
</tr>
</tbody>
</table>

<sup>a</sup> PU F- Polyurethane foams, HV-Human Vertebrae, PV-Porcine Vertebrae.
Conflict of interest statement

The authors do not have any conflict of interest that may affect the outcomes of this study.

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