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Modelling of Multilayered Foams for Universal Seat Design

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Abstract. Patients with chronic disability, or in a transient disability state post-surgery may require a mobility device for their safety and convenience. Patients with a low to mid-level severe mobility impairment are mostly comfortable to leave hospital in a factory wheelchair without further modifications, however in particular chronically disabled wheelchair bound patients require wheelchair cushion modifications specifically designed for their condition. Such personalized cushions minimise pain from sitting, avoid pressure ulcers, and correct patient posture to prevent musculoskeletal and spinal damage. To identify physical properties of a complex seat cushion design with multiple layers, for the simulation of optimum seat cushions for mobility impaired users, long-term testing was undertaken with multiples of different layer combination samples. Physical indentation results for reorganised cushions were obtained and further evaluated. We present the first study where a complex, multi-layered foam cushion structure is cycle-tested using a custom-specific human-shape indenter, derived from 3-D body scanning of a 95th percentile stature subject. The test provides physical material properties of the complex foam structure under realistic human shape indentation for the selected anthropometry. The test results feed and validate a realistic material model, and confirm durability and stability over time of the complex foam.

Keywords. Rehabilitation, Wheelchair, Seat Cushion, Pressure Ulcer

1. Introduction

In 2018, 4.4 million or 17.7% of Australians had a disability; 47.8% of the disabled in working age were employed, compared to 80.3% of people without disability. Only 28.3% of the disabled working population worked full-time, showing how people with disability experienced employment restrictions [1]. Overall, 4.4% of disabled used a wheelchair in Australia in 2015-16, and 189,200 Australians were wheelchair bound. In 2011, between 11,300 and 19,000 Australians lived with a spinal cord injury [2]. People with a physical disability or patients after spinal surgery may require a mobility device for their mobility, safety and convenience. According to the level of medical condition, health practitioners can suggest wheelchairs for early patient discharge post-surgery to return to normal lifestyle. This practice increases patient turnover and thus capacity at hospitals. Chronically disabled people are often fully dependent on a wheelchair for good. Wheelchairs come in different sizes and are mostly customizable to cover a larger range

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of patient anthropometry. Patients with mid-level severity conditions are mostly comfortable with an off-the-shelf factory wheelchair without further modifications, but others with more severe conditions require modifications specifically designed for the patients' condition to minimize pain from sitting, correct their posture to prevent spinal damage, and prevent pressure ulcers [3]. In 2015-16, 4,313 pressure injuries were reported by Australian public hospitals as hospital acquired, at a rate of 9.7 per 10,000 hospitalisations, causing significant cost [4]. Pressure ulcers are a medically critical complications as they are likely to cause further infections, abscess, sepsis and cancer after onset. The focus in this study was to assess cushion performance for severely affected patients.

PU foams are elastic materials that allow easy structural deformation however they eventually return to their initial shape [5]. The downside of repeated loading is loss of elasticity over time, which then causes a change in geometry and hardness.

A large proportion of patients visiting the Queensland Health Rehabilitation Engineering Centre (REC) have difficulty controlling body functions or have lost sensation below their waist. While in a healthy body the brain naturally senses build-up of pressure about the buttocks and lower limb area, and relieves pressure by changing posture or through micromotion, a significant proportion of these patients cannot independently correct their posture or sense pain from hazardous seating conditions. One solution to mitigate this problem are pressure relieving cushions which optimize distribution of pressure across weight bearing body parts.

To prevent such injuries and improve patients' quality of life, a pressure relieving cushion was formerly designed based on experience, trial and error [6]. While this design had been successfully used over the past decade, durability remained a problem to solve. Moreover, increasingly complex surgery required more intricate cushion solutions to prevent pressure injuries. The original design consisted of a simple cushion with three layers of foams with the hardness increasing from top to bottom so that the top layer provided high elasticity to deform and an even distribution of pressure over the contact area. With the aim to minimize pressure discomfort, a similar combination of foams with alternating hardness was then layered into cushions of high geometric complexity to provide both softness for comfort and hardness for durability [7], where the expectation from increased durability is to reduce instances of patients having to re-visit REC for a replacement.

As a result of the evolved structural complexity of such new pressure optimized cushions (Figure 1), purely physical development and testing is now uncommon. New designs are developed in analytical dynamic models [8] which represent both the cushion and human subject for testing in CAE [9]. However, to determine mechanical properties of multi-layered foam materials under realistic human like indentation, and in order to validate analytical modelling, physical studies are still required. The physical testing described here is a novel approach and deviates from standardised material testing, which measures indentation force/load deflection (IFD/ILD) with an indenter foot according ASTM D3574 [10], ISO 2439 [11] or DIN 53579-1 [12]. The purpose of this study is to inform future FEM analytical models with relevant material parameters.

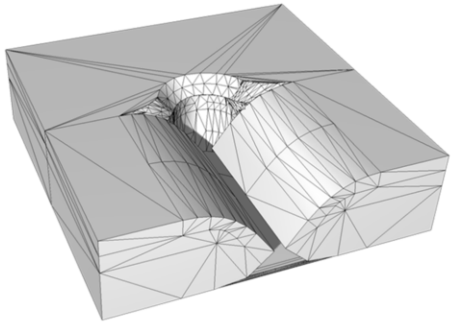

Figure 1. Complex multi-layered pressure optimizing cushion, see [6].

2. Methods

This physical study required multiple repetitive tests being conducted on three differently configured cushion PU foam samples. Initially a controller was programmed for a previously developed indentation rig [13] to perform a cycled loading test on cushion samples. Fatigue loading response of the three foam samples was compared, and the effect of fluid on the mechanical properties of different types of cushion was investigated.

2.1. Foam specification

Three different foams were used, with their hardness indicated by colour from light green to pink. The numbering for each foam type is indicative of the foam density and hardness, where the first number after the letters represents density and the following value indicates hardness. Foams were sourced from Dunlop (Table 1). Green and pink foams (Figure 2) have similar density, while the hardness of the pink foam is about 5 times stiffer than green. Yellow foam has the highest density, while providing a mid-range hardness within the types of foams used. Hardness values are measurements determined by Dunlop using the industry standard ASTM D3574 indentation force deflection (IFD) method with a standard probe. This involves compression of a given thickness and size foam sample block to a deflection of X percent of its initial height, using an indenter of 200 mm diameter [10]. IFD values differ depending on foam sample height, size, and the compression factor. Common sample heights are 50-100 mm [14]; common sample sizes are 380x380 mm and 500x500 mm; and common compression factors are X=25%, X=40% and X=65%. Lower hardness foam has a better capability to recover from deformation caused by a load. All foams used were premium quality, flame retarded and with antimicrobial protection, and came in four different thicknesses, 10 mm, 25 mm, 50 mm, and 75 mm. This made it possible to test cushions of 150 mm total thickness composed of different foam layers. Length and width of each foam layer block was 600 mm x 460 mm.

Table 1. Standard foam density and IFD hardness specification for each type of foam used.

Foam type	Colour	Density [kg/m³]	IFD hardness [N]	Resilience	Grade description
EN36-90	Green (G)	36 -1/+1.5kg	90 -10/+30N	50%	Soft cushioning foam
EN40-230	Yellow (Y)	40 -1/+2kg	230 ± 20N	45%	Firm cushioning foam
MA35-600	Pink (P)	35.0 +2kg	600 ± 50N	30%	Extra firm impact cushioning foam

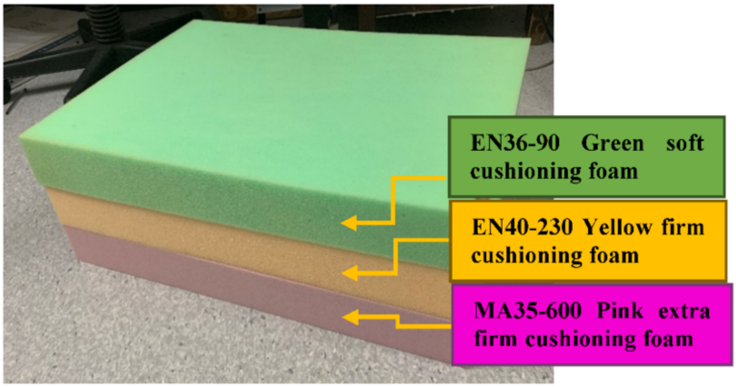

Figure 2. Three different foams piled in order of increasing hardness from top to bottom.

2.2. Indenter rig

The axial indenter rig had been previously developed [13]. It consists of a vertically mounted worm drive actuator, driven by a stepper motor that allows precise control of the rod movement along the vertical axis, allowing a precise specific load to be generated and held still at any given position. The rotation and torque created by the servo motor is fed to the worm drive supported by ball bearings. A strain gauge load cell (Honeywell, 500lbsf/227kgf range; accuracy 0.05%) is mounted between indenter and actuator (Figure 3) for the precise measurement of the three-dimensional indentation force. Weight plates are used to prevent cushion movement. The indenter mechanism was designed to apply high loads with low internal friction, permitting high precision and stabilised movements, and reducing power requirements to allow loads of over 80 kg.

2.3. Indenter probe

The indenter probe form was derived from 3D scans of a 95th percentile stature (2011), median corpulence healthy Australian young man [9] (Figure 4). This same indenter form had been previously used in investigating automotive seat pressure comfort, both in physical and virtual environments as a model in ANSYS [15]. In this study, a simplified physical model was used with identical geometry, however as rigid form with hard surface (Figure 5).

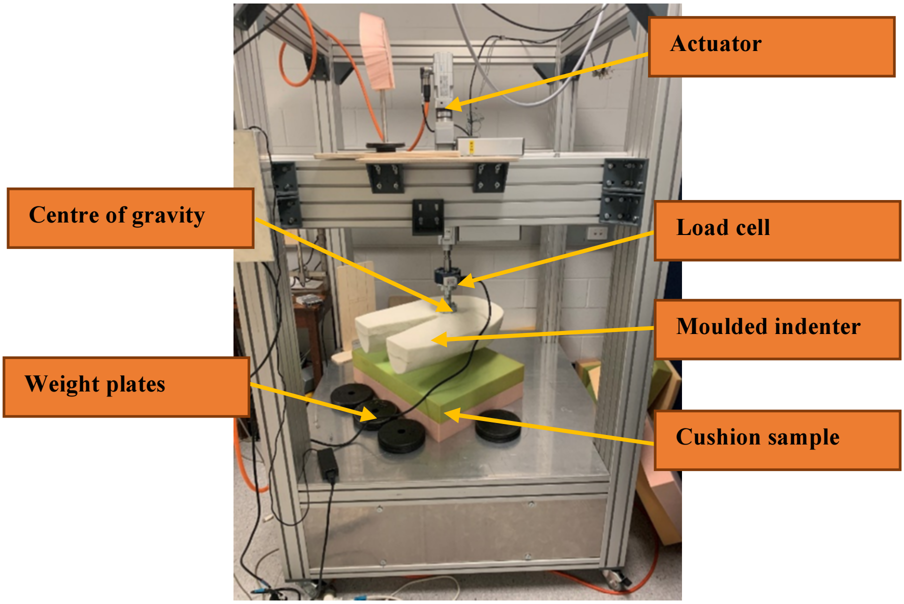

Figure 3. Setup of the axial indenter rig, consisting of actuator, load cell, moulded indenter and cushion sample.

Figure 4. Indenter shell. This picture shows a shell version with a surface layer of soft neoprene, however using the same geometry as the indenter shell in the experiment.

Figure 5. Hard surface indenter shell, from [6].

2.4. Software

The software to control the indenter rig was programmed using C# on Visual Studio. Two test features were implemented, normal and fatigue test. For a normal test, the cycle time is selected in minutes and the total run time in hours. For fatigue testing, instead of selecting a total run time, the number of cycles is chosen, and delays between each cycle if a resting period is required. The software provides a live graph feature to observe real-time results. At the end of each test all recorded data (time, force and indenter position) are saved in an Excel file.

2.5. Procedure

Multiple layered foam cushions have mechanical properties which deviate from the material data sheets. In addition to testing hardness change over normal use, a wet cushion test was implemented to further understand effects of incontinence on cushion durability for each foam type.

A creep compression test (one cycle loading of 60 kg load for one hour; 1.5 m/min), which was also used to calculate stiffness ilo IFD and durability test (0.2 Hz; 15,000 cycles; 80 kg maximum load) were conducted on each foam type. Durability testing was also performed on wet cushions to determine the impact. The creep test was run for the cushions to obtain their intended property, as foam requires conditioning before it reaches its nominal strength. Durability testing for wet cushions was run for 8 hours, and 5 days for normal cushions. Standardised wet set testing has shown good correlation with fatigue and is thus predictive of durability [16]. Hysteresis was not tested. All tests were performed according to the aims of the study:

Experiment 1: Creep test and stiffness calculation of multilayered foams with different ratios of each foam type.
Experiment 2: Durability test on normal cushion.
Experiment 3: Durability test on wet cushion.

Each foam combination was tested so that the cushion front edge was placed at 300 mm distance from the centre of gravity (Figure 6). The ratio of foam types in each sample varied, with a total cushion thickness of 150 mm. The samples tested in this experiment were according to Table 2.

Table 2. Foam combinations used as study samples. Numbers next to the colour indicate the ratio of foam types used in each sample, for example: pink2:yellow1:green3 indicates the use of 50 mm pink, 25 mm yellow and 75 mm green foam.

Number	Foam combination and ratio
1	green
2	green1:pink5
3	green2:pink4
4	green2:pink4
5	green3:pink3
6	green4:pink2
7	green: yellow
8	yellow
9	yellow1:pink5
10	yellow2:pink4
11	yellow3:pink3
12	yellow4:pink2
13	pink
14	pink2:yellow1:green3
15	pink2:yellow2:green2
16	pink2:yellow3:green1
17	pink3:yellow1:green2
18	pink3:yellow2:green1

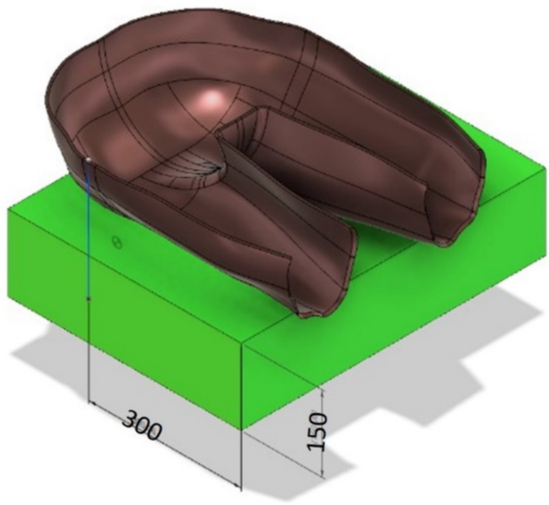

Figure 6. Indenter placement.

The wet test experiment followed the same procedure as outlined for the fatigue test. Each cushion sample was treated with 800 ml of room temperature tap water. An average person urinates between 800 ml to 2 l per day, however foams will not absorb more than 1 l of water without expelling. The foams had hydrophobic surface characteristic due to their antimicrobial protectant treatment, therefore 1/3 cup of water was added during the experiment every 10 cycles for 10 times. This test ran with reduced cycles for 8 hours on a single day.

3. Results

3.1. Creep test

Creep for various foam and layered cushion configurations is shown in Figure 7. Green and pink foam cushions settled and reached equilibrium in hardness within 20 minutes of creep testing, whereas the yellow cushion showed an ongoing and continuous change in hardness. Creep for the green foam was over 100 mm, while yellow foam creep was about 40 mm and pink foam creep was less than 20 mm. It can be seen that while the P2:Y3:G1 or P3:Y1:G2 configurations achieved a creep reduction to about 55 mm, **P3:Y2:G1** yielded a significantly better creep of about 45 mm, similar to the two layer configuration P2:Y4. The two latter ones appear as a reasonable compromise between hardness and creep behaviour.

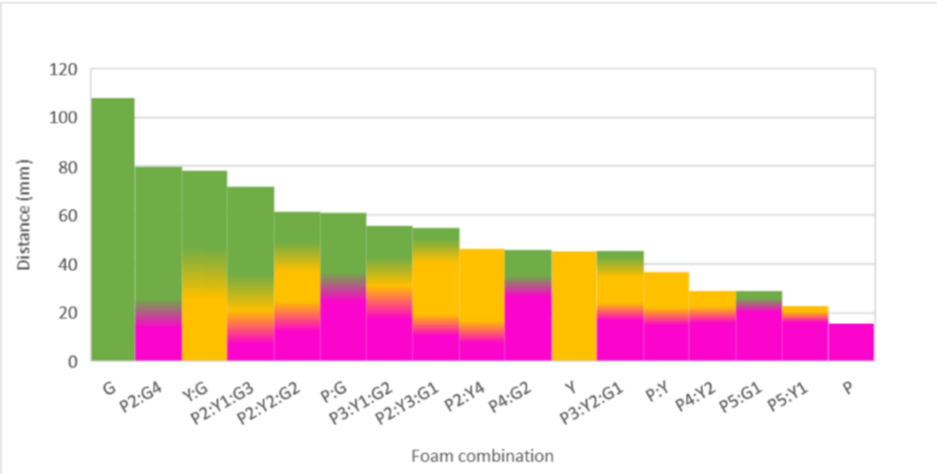

Figure 7. Creep under 60 kg load over 1 hour. 150 mm total height of cushion layered with different hardness, indicated by P (pink), Y (yellow) and G (green). Numbers represent the thickness ratio of each foam used.

3.2. Stiffness

Stiffness as a comparison value to indentation hardness (IFD) of different cushion configurations was calculated from creep test measurements with new foams; results are shown in Figure 8.

The common configuration used for average patients at REC is P2:Y2:G2. This configuration has a good low overall stiffness of about 10 N/mm, similar to P3:Y1:G2 and P2:Y3:G1. It is however inferior to **P3:Y2:G1** which provided a similar stiffness, yet yielded significantly better creep. The two-layer configuration P2:Y4 is slightly harder, however performs better in creep and appears to be a good low-cost alternative to the three-layer configurations.

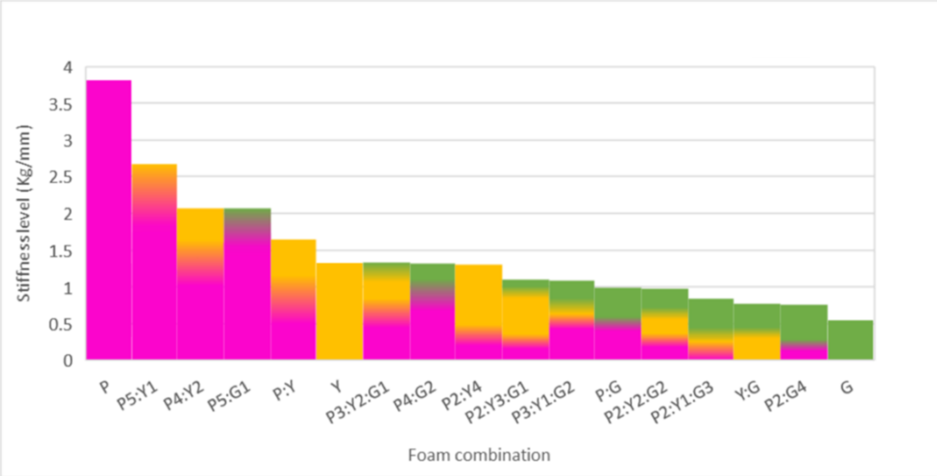

Figure 8. Stiffness as calculated from creep test measurements with a human form indenter probe at 60 kg load. 150 mm total height of cushion layered with different hardness, indicated by P (pink), Y (yellow) and G (green). Numbers represent the thickness ratio of each foam used.

3.3. Durability test

Foam cushion combinations were tested as green on pink (G:P), yellow on pink (Y:P), and pink (P) (all 1:1 ratio). While G:P and P achieved a settled state on the first day after start of the experiment, Y:P settled after 5 days (Figure 9). No fatigue was recorded after 15,000 cycles.

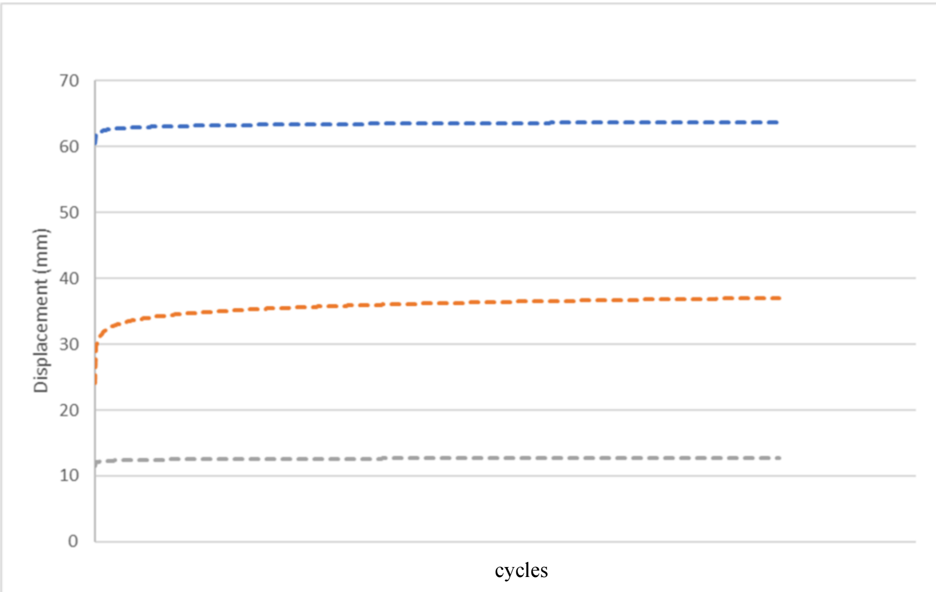

Figure 9. Foam cushion durability test over 5 days and 15,000 cycles on three different samples. Blue line: G:P; Orange line: Y:P; Grey line: P. Measured with human indenter form under 80 kg cycled.

3.4. Wet compression test

The tests showed a continuous increase in compression rate for all three water treated samples P, Y and G, while P and G dry/unconditioned samples had reached a settled state, and dry Y increased at a much smaller rate. Exemplary results are shown for Y (Figure 10). Wet Y reached 40 mm compression after 2:45 hrs, which was not reached after 5 days in a dry condition; at the same time, dry Y reached 33 mm compression.

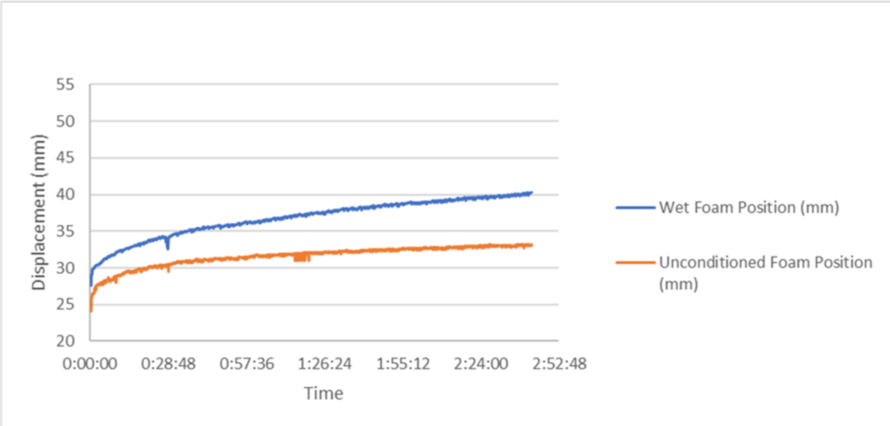

Figure 10. Foam cushion ageing/fatigue test over 1 day on wet (blue line) and dry (orange line) Y samples. Measured with human indenter form under 80 kg cycled.

4. Discussion

While cushion indentation hardness can be optimized to prevent pressure ulcers, pressure comfort may require more firmness which contributes to a feeling of support. Evaluating the perfect balance between firmness and softness was not an aim of this study and could not be determined in the evaluation. The use of pressure mapping is suggested for further analysis to find the cushion configuration that most evenly distributes pressure around areas of medical concern, such as the rectum.

Due to inaccuracies of the mechanical and servo motor control assembly, load accuracy at full load was 5% or ± 2 kg as each step of movement triggered by the motor created 4kg change in load. Due to its non-linear and time-dependent compression behaviour, indentation force changes at a set point over time. Therefore, the control program was set to step up the indenter rod when the load had eased to 2 kg below the intended load. For example, for a target of 80 kg, the motor was set to increase indentation when the load measured by the load cell decreased to 78 kg, to obtain 82 kg, therefore applying a load of between 78 kg to 82 kg. While this issue did not affect smaller indentation, load control became less accurate for higher loads. This could be improved by reducing the amount of worm drive rotation in each step; however, this will require a different drive gear or position control to be implemented on the worm drive.

While quasi-linearized stiffness measurements of single foam type cushions compare with standardised IFD indentation hardness values, more complex multilayer foam cushions show significant deviation from an averaged stiffness prediction in a linear model. For example, P5:Y1 was measured at 25.5 N/mm while P had a stiffness of 37.3 N/mm and Y had a stiffness of 12.7 N/mm. When predicting averaged stiffness of P (IFD 40% 600 N) and Y (IFD 40% 230 N) in a linear model however, combined averaged stiffness would be 33.2 N/mm, and combined averaged IFD would yield 538 N. The addition of a thin layer of softer foam to a layered cushion thus had a significantly over-proportional effect on overall stiffness. Similarly, in IFD hardness the 25 mm softer foam layer will contribute over-proportionally to a 40% compression of 60 mm. This was confirmed when comparing P4:Y2 to P5:G1. While measured stiffness of both samples was equally 20 N/mm, predicted stiffness (hardness) is 29.1 N/mm (IFD 40% 477 N) for P4:Y2, and 31.9 N/mm (IFD 515N) for P5:G1.

The ratios of stiffness, i.e. P:Y=2.937, P:G=7.612, Y:G=2.592, were found consistently larger (P:Y=+12.6%; P:G=+14.2%; Y:G=+1.4%) than the ratios of IFD hardness (P:Y=2.608; P:G=6.666; Y:G=2.555), indicating an increasing influence of foam IFD hardness on foam stiffness as measured with a human indenter form under quasi-static/quasi-linear conditions. Because harder foams cannot be avoided in cushions for a variety of reasons shown before, a key finding of this study is therefore the deduction that cushions must use a combination of at least one softer and one harder PU foam for comfort reasons. Findings are summarized in Table 3. Results from this study will be used to inform a finite element model, which will be used in combination with indenters modelled from patient specific 3D scans. The results are essential to provide realistic parameters for the wheelchair cushion FE model; these are currently unavailable, as neither dry nor wet stiffness of such wheelchair cushion foams have ever been established, and tabulated standardised data has been shown to be misleading. While durability was confirmed to be no issue in dry foams, it was shown that fatigue behaviour of the wet foams requires further study [17] to formulate time-dependent elasticity in the FE model.

Table 3. Summary of foam stiffness measurements using human form indenter vs IFD hardness specification for each type of foam used.

Foam type	Density [kg/m³]	IFD hardness [N]	Stiffness [N/mm]	Hardness ratio	Stiffness ratio
EN36-90 (G)	36 -1/+1.5kg	90 -10/+30N	4.9	2.555	2.592
EN40-230 (Y)	40 -1/+2kg	230 ± 20N	12.7	2.608	2.937
MA35-600 (P)	35.0 +2kg	600 ± 50N	37.3	6.666	7.612

The results show that medical device cushion foams are likely to lose their expected indentation hardness and durability under wet condition, and appropriate treatments are suggested to prevent contact with moisture. Climate chamber tests will be required to investigate this behaviour further.

Through experimental variation of geometric parameters in such a correctly parametrized wheelchair cushion FE model, we expect to optimize seat pressure of occupants, with a particular focus on medically relevant areas.

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