Title: Comparative study of the strength characteristics of a novel wood-plastic composite and commonly used synthetic casting materials

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Abstract:

Background: Woodcast® is a wood-plastic composite casting material that becomes pliable and self-adhesive when heated to 65ºC and returns to being weightbearing as it cools down. The present study aims to test whether this novel non-toxic casting material is strong enough for clinical use by comparing its strength against materials that are already used in weightbearing casting applications such as total contact casts.

Methods: The strength of Woodcast® samples was compared against the strength of two commonly used synthetic casting materials (Delta-Cast®, OrthoTape). The effect of environmental factors such as cooling, prolonged heating and exposure to water was also assessed.

Findings: The results of this study indicated that Woodcast® is stronger than the synthetic casting materials in compression but weaker in tension. The flexural strength of Woodcast® was 14.24 MPa (±1.25MPa) while the respective strength of Delta-Cast® and OrthoTape was 18.96 MPa (±7.46MPa) and 12.93 MPa (±1.93MPa). Independent samples t-test indicated that the difference between Woodcast® and the other two materials was not statistically significant (P>0.05). Woodcast® recovered 90% and 78% and its tensile or flexural strength respectively after 15 minutes of cooling at ambient temperature and its strength was not reduced by prolonged heating. On average, exposure to water reduced the flexural strength of Delta-Cast® by 6% and of OrthoTape by 44%. The strength of Woodcast® was not affected by exposure to water.

Interpretation: The comparison between Woodcast® and commonly used synthetic casting materials indicated that Woodcast® is indeed strong enough to be safely used in weightbearing casting applications.

Keywords: Fracture fixation, mechanical testing, total contact cast, bending strength, tensile strength

1. Introduction

Casts or splints are commonly used to promote bone healing, after a fracture or orthopaedic surgery. In the case of diabetic foot management total contact casts are also used in the management of diabetic foot ulcers and Charcot foot osteoarthropathy(Armstrong et al., 2001). A total contact cast (TCC) is a padded cast that is well-moulded around the surface of the foot and the lower leg. Its role is to offload the foot by transferring plantar load to its side walls (Armstrong et al., 2001; Begg et al., 2016).

Traditionally casting has been performed using plaster of Paris (PoP). PoP casts were relatively thick and heavy but they were strong enough to support at least semi weightbearing activities (Bowker and Powell, 1992). However, PoP was brittle and could not tolerate water. A significant improvement has been the introduction of synthetic casting materials. These materials comprise a bandage impregnated with a water activated polymer and are stronger and at the same time lighter than PoP(Berman and Parks, 1990). In most synthetic casting materials, the bandage is made out of fibreglass fibres however other materials such as polyester have also been used. Synthetic casting materials can tolerate water, but their strength can be compromised when they get wet (Berman and Parks, 1990).

One of the disadvantages of synthetic casting materials is that they contain isocyanates which are among the leading causes of occupational asthma internationally (Stenton, 2010). Even though the risk of exposure to isocyanates during casting is considered to be relatively low (Pearson et al., 2013) there is a number of case studies where the use of synthetic casting materials has been linked to the development of asthma (Donnelly et al., 2004; Lefkowitz et al., 2015; Sommer et al., 2000; Suojalehto et al., 2011; Tanaka et al., 1994).

Woodcast® (Onbone Oy,Espoo, Finland) is a novel non-toxic material made from woodchips embedded in a biodegradable thermoplastic polymer (Lindfors and Salo, 2012) (figure 1a). This material becomes pliable and self-adhesive when heated to 65^{o}C and gradually hardens as it cools down. According to the manufacturer the material becomes loadbearing after only 5-15 minutes (Lindfors and Salo, 2012). Previous research has shown that this material has equally high stiffness as commonly used fibreglass materials (Pirhonen et al., 2013) and has successfully being used for the treatment of fractures both in the upper (Lindfors and Salo, 2014) and lower limbs (Hirsimäki et al., 2014). In the case of lower limb fractures the affected limb is subjected only to partial weightbearing. However, in applications like TCC substantial loading is expected to be developed in the cast which can significantly increase the risk of failure in the cast (Begg et al., 2016). In this case, a thorough investigation of strength and not just of stiffness is needed to tell whether this new material can be a safe and effective replacement for currently used casting materials.

In this context, the purpose of this study is to compare the strength on Woodcast® material against commonly used synthetic casting materials. The effect of humidity, cooling time and exposure to heat will also be assessed.

2. Methods

Woodcast® and two different synthetic casting materials (figure 1b,c) that are commonly used by the National Health Service (NHS) in the UK were used in this study: Delta-cast®

Elite (BSN medical Inc., Rutherford college, USA) and OrthoTape (K10 Medical Supply, Ridgeland, USA). Both casting materials have reinforcing fibres oriented along two axes which are perpendicular to each other; namely in the direction of bandage role (0^{o}) and along the width of the bandage (90^{o}) (figure 1b,c). In Orthotape, these fibres were made of fibreglass while in Delta-cast® out of polyester.

The capacity of these materials to carry load without failure was assessed for three different loading scenarios: a) a loading scenario that simulated heel strike (i.e. the instance of gait when heel comes in contact with the ground), b) in tension, and c) in three-point bending (3PB). Tension and 3PB were performed using a 3kN INSTRON ElectroPuls^{TM} E3000 load frame while heel strike was simulated using a 30 kN Lloyds electromechanical load frame (NexiGen Plus 3.0). All samples were prepared in accordance to the recommendations of the respective manufacturer.

2.1 Simulated heel strike

A 3D anatomically accurate geometrical model of a human foot (Behforootan et al., 2017) was modified to design and to 3D-print a mould of the foot hitting the ground at an angle of 14 deg during heel strike (figure 2a,b). This mould was used to produce geometrically similar samples made from the three materials. For each material, varying thicknesses were employed within the experiments to account for the range of different construct thicknesses used in clinical practice. In the case of Woodcast®, casting was performed using three different thicknesses; namely 4mm, 6mm and 8mm. In the case of the synthetic casting materials, casting was performed using four or six layers (Berman and Parks, 1990). Seven samples were tested for each condition (49 samples in total).

During testing the heel samples were placed on a rigid flat surface on the base of the load frame and were compressed with a help of a compression plate which simulated the ground (Figure 2c). Loading was applied at the heel at 20mm/sec until the failure of the sample. During testing, force was sampled at 100Hz using a 30kN load cell (XLC Series, Lloyd Instruments, accuracy 0.5% of reading) and the force – displacement curve was drawn. The failure load of each sample was measured as the maximum force value in the force – deformation graph.

2.2 Tension

Woodcast® samples for tensile testing were cut from 6 mm thick rectangular sheets (length: 800mm, Width: 145mm) with the help of a laser cutting machine. The dimensions of the samples were decided based on the limitations imposed by the available Woodcast® material sheets. More specifically, the Woodcast® material sheets were filled with circular holes (diameter≈9mm) arranged in parallel rows to improve the breathability of the cast. As a result, the maximum width of the samples was restricted to the distance between consecutive rows of holes which was 17mm. The dimensions of the samples are shown in figure 3.

Synthetic casting materials were dipped in water at a room temperature (ranging between 20 and 25 ^{o}C) and then were wrapped around a flat wooden plank (≈400cm long and ≈1cm thick) until there were six layers of material at each site (Berman and Parks, 1990). Six layers were used because this is the most commonly used thickness in weightbearing casts (Berman and Parks, 1990). Special care was given to ensure that there was good bonding between layers. To achieve that, the layers were kept under constant compression until they cured. Synthetic casting materials were left to dry for two days before using them to cut samples using a hand saw. All samples were cut with their testing axis along the bandage role direction (Mihalko et al., 1989).

The samples were fixed on the load frame using conventional tension grips (initial grip-to-grip distance: 70mm) and then they were stretched until failure at 0.5mm/min (Figure 3). Force was recorded at 100Hz using a 5kN load cell (Dynacell, INSTRON, accuracy 0.5% of reading) to draw the force – elongation graph of each test and to identify the failure load (i.e. peak force). Ultimate engineering tensile stress (σ_T) was calculated by dividing failure load (F) over cross-sectional area. To support a more reliable calculation of stress, the width and thickness of the central portion of each sample were averaged over three measurements: one at the sample’s centre and two more locations one cm distant to the centre (figure 3).

To assess the effect of water, Woodcast® and synthetic casting samples were tested dry and wet. More specifically a set of samples was kept in water for two hours and then immediately tested while they were still wet. The effect of cooling and heating time was also assessed in the case of Woodcast®. To this end, Woodcast® samples were heated to 65°C until they became pliable and then they were tested after cooling at ambient temperature (22°C ±1°C) for 15 or 30 minutes. The effect of heating time was assessed by leaving a set of samples in the heater at 65°C for 24 consecutive hours. These samples were then stored on a flat surface at ambient temperature for two days before testing. Five tests were performed for each condition.

2.3 Bending

Rectangular 140mm long Woodcast® samples were cut from a 6mm thick material sheet using a circular saw. Rectangular synthetic casting material samples were prepared in a similar way as tensile samples and cut with their long dimension aligned with the direction of bandage role (Berman and Parks, 1990; Mihalko et al., 1989) (Figure 4). To assess flexural strength, the samples were loaded in 3PB at 0.5mm/s with a supported length of 90mm (Berman and Parks, 1990). Force was recorded at 100Hz and the failure load (F) of each test was calculated as the peak of the force – deflection graph. Ultimate flexural stress (σ_{3PB}) was calculated using the following formula from the classical Bernoulli-Euler technical bending theory: $\sigma_{3PB}=(3FL)/(2wt^2)$, where L is the supported length of the sample during testing (L=90mm), w the width of the samples and t their thickness. Width and thickness were averaged over three measurements at the central portion of the sample.

Similar to tension, the effect of water was assessed for both Woodcast® and synthetic casting samples, while the effect of cooling and heating time was assessed for Woodcast®. The width of the samples used in these tests was 17mm which enabled cutting them between the rows of holes in the Woodcast® material sheet. To assess the effect this dense pattern of holes can have on flexural strength an additional set of tests was performed for Woodcast® samples that were 90mm wide and included ten holes in total in three parallel rows (figure 4). Five tests were performed for each condition.

3. Results

3.1 Simulated heel strike

All samples failed in a similar way. The failure mode can be described as a complete collapse of the heel causing a drop in the sample's resistance to compression (figure 5). Failure load was significantly higher for Woodcast® compared to the other two materials. As shown in figure 6 the force that the Woodcast samples were able to carry without collapsing increased linearly with thickness from 6.22kN(±0.35kN) to 15.3kN(±1.2kN) for thickness of 4mm and 8mm respectively. At the same time, the average force the thickest synthetic casting samples (i.e. 6 layers) were able to carry without collapsing was only 2.11kN(±0.19kN) and 3.1kN(±1.2kN) for Delta-Cast® and OrthTape respectively.

3.2 Tension

The average thickness of the Woodcast®, Delta-cast® and OrthoTape samples was 6.90mm(±0.07mm), 4.88mm(±0.37mm) and 3.71mm(±0.20mm) respectively. In qualitative terms, ultimate stress was reached at relatively lower elongations for Woodcast® and Orthotape relative to Delta-cast® (figure 7a). The strength in tension for Woodcast® was significantly lower than Delta-cast® and OrthoTape. More specifically, ultimate tensile stress was equal to 8.71MPa(±0.30MPa) for Woodcast® and 17.6MPa(± 1.0MPa) and 26.0MPa(±2.7MPa) for Delta-cast® and OrthoTape respectively (figure 8a).

Only the synthetic casting materials appeared to be affected by water. Two hours in water reduced Delta-cast® and OrthoTape's ultimate stress by 16% and 27% of their original respective values. The average ultimate strength of the Woodcast® samples that were allowed to cool only for 15 or 30 minutes was 7.87MPa(±0.12MPa) and 8.08MPa(±0.13MPa) respectively; namely 90% and 93% of the reference strength. Exposure to 24 h of continuous heating increased the ultimate stress of Woodcast® samples to 9.43MPa(±0.40MPa); an increase of 8%.

3.3 Bending

Characteristic 3PB stress – flexion graphs for the three materials can be seen in figure 7b. Similar to tension, Delta-cast® samples appear to reach their ultimate 3PB load for higher deformations compared to the other two materials (figure 7b). Regardless of the difference in the level of deflexion between the two synthetic casting materials they both appeared to fail in a similar way which was distinctively different to Woodcast® (figure 9). Woodcast® samples' failure started at the bottom surface where tensile stress was maximum. On the contrary Delta-cast® and Orthotape samples failed due to delamination close to the top surface; namely where compressive stress is maximum (figure 9).

The average thickness of the Woodcast®, Delta-cast® and OrthoTape samples was 6.75mm(±0.16), 4.92mm(±0.53) and 3.66mm(±0.21) respectively. Woodcast® and OrthoTape exhibited similar strength under 3PB; 19.67MPa(±0.85MPa) and 18.96MPa(±7.46MPa) respectively. The strength of Delta-Cast® was significantly lower; 12.93MPa(± 1.93MPa). Two hours in water reduced Delta-cast® and OrthoTape's ultimate stress by 6% and 44%. The strength of Woodcast® was not affected by water (figure 8b). The ultimate strength of the Woodcast® samples that were allowed to cool only for 15 or 30 minutes was 15.30MPa(±0.98MPa) and 16.80MPa(±1.16MPa) respectively; namely 78% and 85% of their reference strength. Exposure to prolonged heating increased the ultimate stress of Woodcast® to 22.56MPa(±0.98MPa); an increase of 15%. On the contrary the inclusion of holes in the wider 3PB samples lead to a reduction in strength to 14.24MPa(±1.25MPa); a 28% reduction in strength (Figure 8b).

4. Discussion

The aim of this study was to test whether a new non-toxic casting material (Woodcast®) is strong enough for use in weightbearing casts and could therefore be considered as a replacement for existing casting materials that are linked to increased risk for developing occupational asthma (Donnelly et al., 2004; Lefkowitz et al., 2015; Sommer et al., 2000; Suojalehto et al., 2011; Tanaka et al., 1994). To this end, the strength of Woodcast® samples was compared against two synthetic casting materials that are commonly within the NHS (Delta-Cast®, OrthoTape).

To get a more complete view of the strength characteristics of these materials three different loading scenarios were tested: tension, bending and simulated heel strike. Simulating heel strike involved the production of cast samples with the help of a 3D printed heel model. These samples were then compressed until failure to provide an assessment of their ability to withstand compressive loads.

The results of this study indicated that Woodcast® was capable of carrying substantially more load in compression compared to the other two materials (figure 6) but at the same time it was also weaker in tension (figure 8a). Indicatively the failure load for the thinnest Woodcast® cast (i.e. 4mm) in simulated heel strike was two times higher than the respective value for the strongest synthetic casting material (i.e. OrthTape 6 layers). On the contrary the strength of Woodcast® in tension was two or three times lower compared to Delta-Cast® and OrthoTape respectively.

Casting materials are unlikely to be subjected to high tensile forces during real life loading scenarios but that does not reduce the importance of tensile strength. Weightbearing casts can be subjected to substantial bending moments which will also lead to the development of high tensile stresses. The assessment of tensile strength is therefore particularly important in interpreting possible differences in flexural strength.

The fact that Woodcast® was weaker in tension while the synthetic casting materials were weaker in compression can explain why these materials failed in different ways when subjected to 3PB; with Woodcast® failing on the surface of maximum tensile stress while Delta-cast® and Orthotape failing on the surface of maximum compression (figure 9). Even though the failure mechanism was significantly different between Woodcast® and the synthetic casting materials their flexural strength was relatively similar with Delta-cast® being the weakest of the three (figure 8b). More specifically, independent samples t-test indicated that the flexural strength of Woodcast® material was significantly higher than Delta-cast® (two tail, $t(8) = 14.909$, $P < .001$) but not significantly different to OrthoTape (two tail, $t(8) = 0.224$, $P = 0.827$).

These tests provide an assessment of the strength of Woodcast® as a material. One should note that when Woodcast® is used in clinical practice the casts will also be filled with a dense pattern of holes. The purpose of having these holes is to improve breathability but at the same time they will also reduce the cast's capacity to carry load without breaking. To assess the potential effect these holes can have on the strength of a Woodcast® cast a separate set of samples was prepared and tested. These samples were wide enough to include a number of holes and they provide a representative assessment of flexural strength of the actual Woodcast®cast. The results indicated that flexural strength was indeed significantly reduced (to 14.24MPa(±1.25MPa) from 19.67MPa(±0.85MPa)) but remained similar to that of the two synthetic casting materials. Independent samples t-test indicated that the difference between the strength of the Woodcast® samples with holes was not significantly different to Delta-Cast® (two tail, $t(8) = 1.281$, $P=0.236$) or to OrthoTape (two tail, $t(8) = -1.487$, $P= 0.168$).

In this study the samples from each material were cut in the same relative orientation. Considering the apparent random orientation of reinforcing woodchips in Woodcast® (figure 1a) its properties are unlikely to be affected by the orientation at which the samples were cut. However, this is not case for the synthetic casting materials. These materials have reinforcing fibres running along two perpendicular axes (figure 1b,c), thus generating an orthotropic mechanical behaviour. In one of the first studies on the mechanical properties of synthetic casting materials (Rowley et al., 1985), the tested fibreglass materials were found to be stiffer and stronger along their width (90^o) compared to the direction parallel to bandage role (0^o). On the contrary, a more recent study that included one fibreglass and one fibreglass-free synthetic casting material concluded that both materials were stiffer along the bandage role direction (Rizza et al., 2015). In this study all synthetic casting material samples were cut along the bandage role direction to enable direct comparison with relevant literature (Berman and Parks, 1990).

Previous experimental investigations on the mechanical behaviour of casting materials have showed that the strength of fibreglass materials can be significantly reduced by exposure to water. Berman and Parks (1990) found that submerging different fibreglass materials into water for two hours reduced their strength by a minimum 13.2% and a maximum of 58.6%. In this study, the same exposure to water reduced the flexural strength of the tested fibreglass casting material (Orthotape) by 44%. Delta-Cast® lost 6% of its strength due to exposure to water. At the same time exposure to water is also known to affect the mechanical properties of wood and of wood composites (Jay Chung and Yang Wang, 2019). However the results of the present study showed that the strength of Woodcast® was not affected at all by exposure to water. A possible explanation is that the polymer matrix in Woodcast® effectively shields the woodchips from water and prevents them from absorbing water.

Since heating and cooling play an integral role in the preparation of Woodcast® casts a more detailed investigation of their effect on strength was deemed important. According to the manufacturer, once Woodcast® has been heated to 65°C and has become fully pliable it should return to being weightbearing after 15 minutes of cooling. This claim is substantiated by the findings of this study where 15 minutes of cooling at ambient temperature enabled Woodcast® samples to regain 90% of their tensile strength and 78% of their flexural strength. Fifteen more minutes (i.e. 30 minute of cooling) increased strength to 93% and 85% of their respective tensile and flexural strength.

Although the effect of curing time on the strength of the two synthetic casting materials was not assessed within this study, previous studies highlight that they are able to attain most of their strength within the first 30 minutes following casting. More specifically, the experimental investigation by Berman and Parks (1990) reported that different fibreglass materials achieved between 66% and 88% of their full strength within half an hour since casting.

Polymeric materials are known to degrade due to exposure to various environmental factors including heat (Ray and Cooney, 2018). In the present study, the exposure to continuous heating (65^{o}C) for 24 hours had no negative effect on Woodcast®. On the contrary it appeared to lead to a relevant increase in strength. More specifically 24 hours of continuous heating increased tensile strength by 8% (two tail, $t(8) = -4.984$, P=0.001) and flexural strength by 15% (two tail, $t(8) = -3.204$, P=0.013); a statistically significant improvement according to independent samples t-test. This increase in strength could be the result of better bonding between the polymeric matrix and the wood reinforcement. Overall this finding indicates that it is safe to heat and reheat Woodcast® as deemed necessary.

In this study the ability of Woodcast® to be safely used in weightbearing applications, such as TCC, without the risk of material failure was assessed by comparing its strength to that of commonly used synthetic casting materials. Even though a direct measurement of cast loading was not performed as part of this study, the fact that these synthetic casting materials are already successfully used in similar applications allows using them as reference for defining a level of satisfactory strength.

In the case of simulated heel strike, relative capacity to carry loading without failure was assessed by comparing the failure load between materials measured in Newtons. Even though all samples had similar geometry (i.e. were made using the same heel model) their thickness was different. Indeed, fibreglass materials were consistently thinner than Woodcast®. This difference in thickness will also account for part of the observed difference in failure load.

On the contrary, the ability to carry load without failure in tension and bending was assessed using the ultimate stress (in Pascals) which is independent of sample dimensions. Even though there is a lack of set clinical guidelines on casting thickness it appears that Woodcast® casts are most likely to be thicker than fibreglass. This could mean that the actual failure forces are likely to be relatively higher for the Woodcast® cast reducing even further the risk of material failure. At the same time, the potential effect of increased weight (e.g. to perceived comfort(Hurst et al., 2017)) should also be further investigated.

In addition, it needs to be highlighted that the use of engineering stress for tension and of the stress equation from beam theory for bending are reliable estimations of true stress only for small deformations, which was not always the case here. The elongations and deflexions for Woodcast® and Orthotape appeared to be relatively low, but they were significantly higher for Delta-cast®. Indicatively for the samples in figure 7a, ultimate tensile stress was measured for an elongation that was equal to 2.3% and 2.1% of the initial grip-to-grip distance for Woodcast® and Orthotape respectively, but for 18.7% for Delta-cast®. Similarly, in the case of the 3PB samples of figure 7b, ultimate stress was measured for deflexion that was equal to 9.0% and 6.2% of the supported length for Woodcast® and Orthotape respectively but 19.2% for Delta-cast®. Finally, in the case of the wide Woodcast® samples for 3PB, the validity of the used formula for stress could also be undermined by the drilled holes. Overall, it can be concluded that the stresses presented in this study should be interpreted as indicative measurements of strength, meant to enable the comparison between the three materials, and not as assessments of the true stress developed in the samples.

5. Conclusions:

The results of this study indicated that Woodcast® is satisfactorily strong to be used in weightbearing casting applications without significant risk for material failure. Its strength was not affected by environmental factors that are known to weaken existing synthetic casts such as exposure to water. Woodcast® is also capable of regaining most of its strength after only 15 minutes of cooling and was not weakened by prolonged heating.

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References:

Armstrong, D.G., Nguyen, H.C., Lavery, L.A., Van Schie, C.H.M., Boulton, A.J.M., Harkless, L.B., 2001. Off-loading the diabetic foot wound: A randomized clinical trial. Diabetes Care 24, 1019–1022. https://doi.org/10.2337/diacare.24.6.1019

Begg, L., McLaughlin, P., Vicaretti, M., Fletcher, J., Burns, J., 2016. Total contact cast wall load in patients with a plantar forefoot ulcer and diabetes. J. Foot Ankle Res. 9, 1–8. https://doi.org/10.1186/s13047-015-0119-0

Behforootan, S., Chatzistergos, P., Chockalingam, N., Naemi, R., 2017. A clinically applicable non-invasive method to quantitatively assess the visco-hyperelastic properties of human heel pad, implications for assessing the risk of mechanical trauma. J. Mech. Behav. Biomed. Mater. 68, 287–295. https://doi.org/10.1016/j.jmbbm.2017.02.011

Berman, A.T., Parks, B.G., 1990. A comparison of the mechanical properties of fiberglass cast materials and their clinical relevance. J. Orthop. Trauma. https://doi.org/10.1097/00005131-199003000-00015

Bowker, P., Powell, E.S., 1992. A clinical evaluation of plaster-of-Paris and eight synthetic fracture splinting materials. Injury 23, 13–20. https://doi.org/10.1016/0020-1383(92)90118-C

Donnelly, R., Buick, J.B., Macmahon, J., 2004. Occupational asthma after exposure to plaster casts containing methylene diphenyl diisocyanate. Occup. Med. (Lond). 54, 432–4. https://doi.org/10.1093/occmed/kqg133

Hirsimäki, L., Lindfors, N., Salo, J., 2014. Novel ankle cast designs with non-toxic material. Foot Ankle Online J. 7, 1–5. https://doi.org/10.3827/faoj.2014.0704.0005

Hurst, B., Branthwaite, H., Greenhalgh, A., Chockalingam, N., 2017. Medical-grade footwear: The impact of fit and comfort. J. Foot Ankle Res. 10, 2. https://doi.org/10.1186/s13047-

016-0184-z

Jay Chung, M., Yang Wang, S., 2019. Physical and mechanical properties of composites made from bamboo and woody wastes in Taiwan 65, 57. https://doi.org/10.1186/s10086-019-1833-1

Lefkowitz, D., Pechter, E., Fitzsimmons, K., Lumia, M., Stephens, A.C., Davis, L., Flattery, J., Weinberg, J., Harrison, R.J., Reilly, M.J., Filios, M.S., White, G.E., Rosenman, K.D., 2015. Isocyanates and work-related asthma: Findings from California, Massachusetts, Michigan, and New Jersey, 1993-2008. Am. J. Ind. Med. 58, 1138–1149. https://doi.org/10.1002/ajim.22527

Lindfors, N., Salo, J., 2012. A Novel Nontoxic Wood-Plastic Composite Cast. Open Med. Devices J. 4, 1–5. https://doi.org/10.2174/1875181401204010001

Lindfors, N.C., Salo, J., 2014. New ecological wood–plastic composite materials for scaphoid-type casting: Material properties and clinical evaluation. Hand Ther. 19, 67–72. https://doi.org/10.1177/1758998314538241

Mihalko, W.M., Beaudoin, A.J., Krause, W.R., 1989. Mechanical properties and material characteristics of orthopaedic casting material. J. Orthop. Trauma 3, 57–63. https://doi.org/10.1097/00005131-198903010-00011

Pearson, R.L., Logan, P.W., Kore, A.M., Strom, C.M., Brosseau, L.M., Kingston, R.L., 2013. Isocyanate exposure assessment combining industrial hygiene methods with biomonitoring for end users of orthopedic casting products. Ann. Occup. Hyg. 57, 758–65. https://doi.org/10.1093/annhyg/mes110

Pirhonen, E., Pärssinen, A., Pelto, M., 2013. Comparative study on stiffness properties of WOODCAST and conventional casting materials. Prosthet. Orthot. Int. 37, 336–339. https://doi.org/10.1177/0309364612465885

Ray, S., Cooney, R.P., 2018. Thermal degradation of polymer and polymer composites, in: Handbook of Environmental Degradation Of Materials: Third Edition. Elsevier Inc., pp. 185–206. https://doi.org/10.1016/B978-0-323-52472-8.00009-5

Rizza, R., Liu, X., Thometz, J., Tassone, C., 2015. Comparison of biomechanical behavior between a cast material torso jacket and a polyethylene based jacket 10, 1–5.

Rowley, D.I., Pratt, D., Powell, E.S., Norris, S.H., Duckworth, T., 1985. The Comparative Properties of Plaster of Paris and Plaster of Paris Substitutes 402–407.

Sommer, B.G., Sherson, D.L., Kjøller, H., Hansen, I., Clausen, G., Jepsen, J.R., 2000. [Asthma caused by methylene-diphenyl-diisocyanate cast in a nurse]. Ugeskr. Laeger 162, 505–6.

Stenton, S.C., 2010. Occupational and environmental lung disease: occupational asthma. Chron. Respir. Dis. 7, 35–46. https://doi.org/10.1177/1479972309346757

Suojalehto, H., Linström, I., Henriks-Eckerman, M.-L., Jungewelter, S., Suuronen, K., 2011. Occupational asthma related to low levels of airborne methylene diphenyl diisocyanate (MDI) in orthopedic casting work. Am. J. Ind. Med. 54, 906–10. https://doi.org/10.1002/ajim.21010

Tanaka, Y., Satoh, F., Komatsu, T., Muto, H., Akiyama, N., Arai, Y., Miyamoto, Y., Sano, Y., 1994. [A case of suspected occupational asthma in an orthopedist, due to cast materials containing MDI]. Nihon Kyobu Shikkan Gakkai Zasshi 32, 606–9.

Figure legends:

Figure 1: A closeup of the Woodcast® structure (a) and of the fibre orientation in the Delta-cast® (b) and Orthotape (c) materials. In the case of the synthetic casting materials the direction of bandage role (0^{o}) and of the material width (90^{o}) is also shown.

Figure 2: The 3D model of the human foot during heel strike (a) and the mould that was 3D printed to support the production of geometrically similar samples (b). The testing set-up for simulated heel strike (c).

Figure 3: The geometry of the samples (left) and the testing set-up for tensile testing (right). The sites where width and thickness were measured are also shown (dotted lines).

Figure 4: The testing set-up (centre) and the two different sample geometries that were used for 3PB. (Left) the narrow sample design used for Woodcast® and fibreglass. (Right) the wide sample design used to assess the effect of circular holes in the Woodcast® material sheets. The sites where width and thickness were measured are also shown (dotted lines).

Figure 5: Typical force – deformation graphs for simulated heel strike. The respective samples are also shown following testing.

Figure 6: The failure load for different thickness Woodcast® and fibreglass materials.

Figure 7: Characteristic stress – elongation (a) and stress – flexion (b) graphs for tension and 3PB respectively. Elongation is calculated as the change in grip-to-grip distance. Flexion as the displacement of the 3PB punch from the point of first contact with the sample.

Figure 8: Comparison between the ultimate stress in tension (a) and 3PB (b) of the three casting materials when they were tested dry and after been submerged into water for two hours. In the case of 3PB, the condition of wide Woodcast® samples that included a pattern of circular holes is also shown.

Figure 9: Typical appearance of failure due to the separation of layers in a fibreglass sample (top) and due to excesive tension in a Woodcast® sample (bottom).

Figure 1:

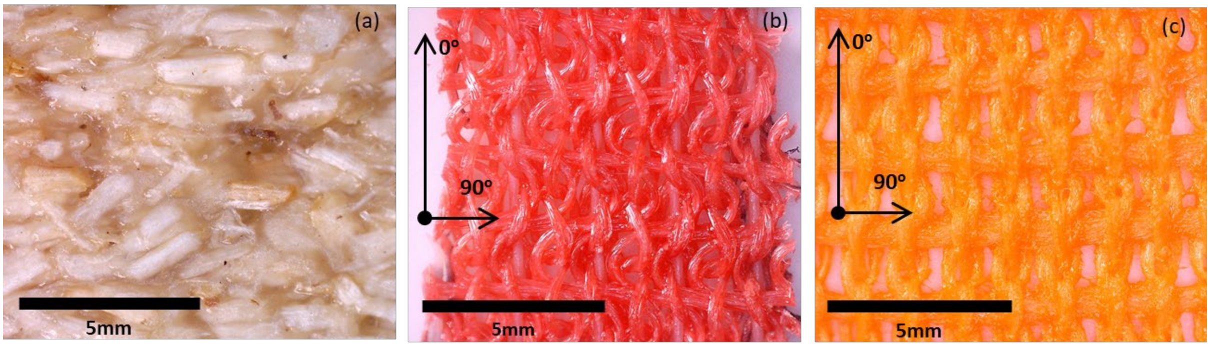


Figure 2:

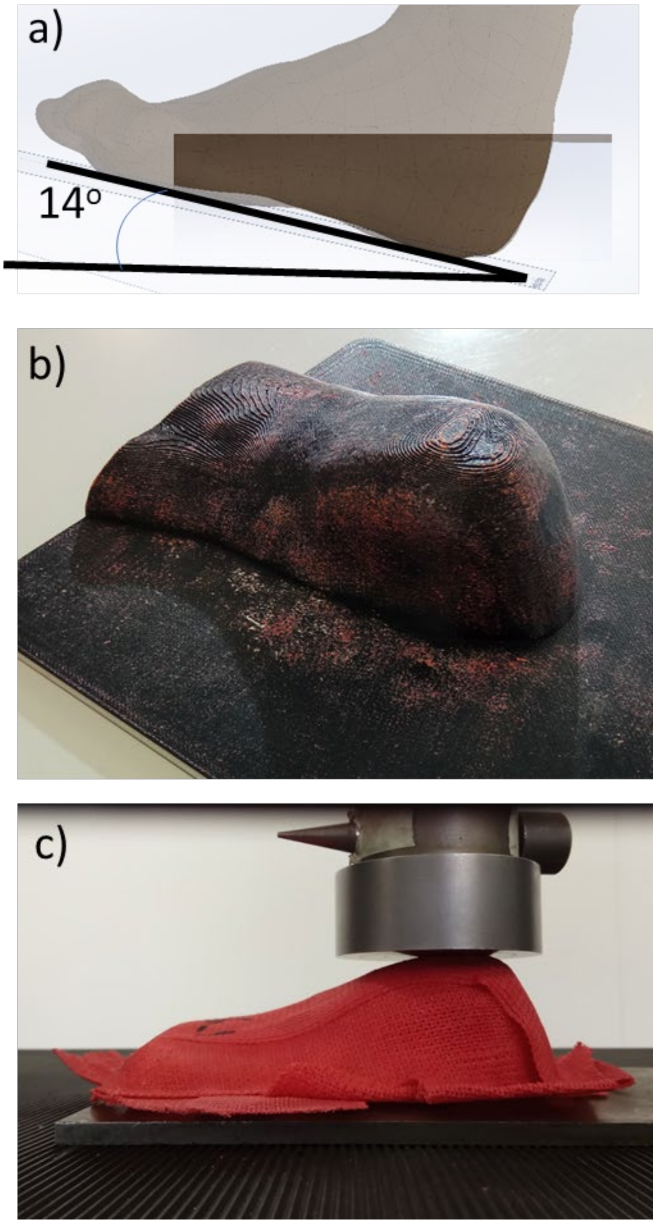


Figure 3:

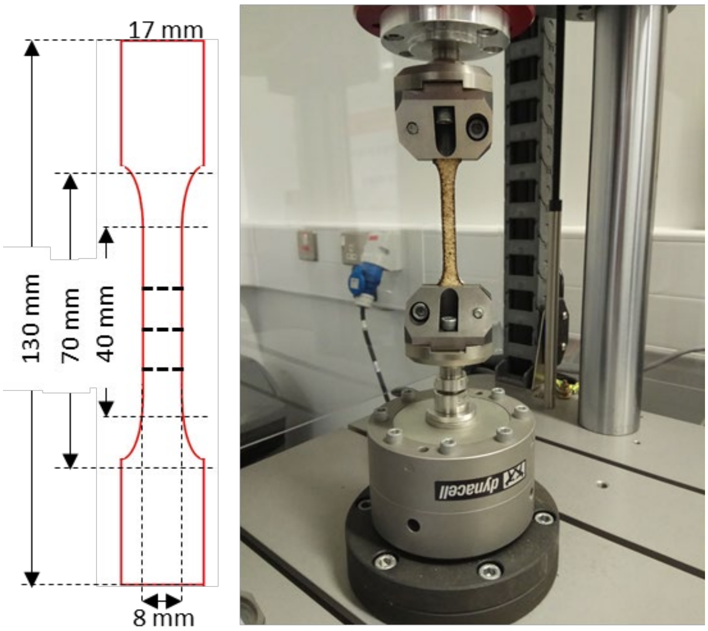


Figure 4:

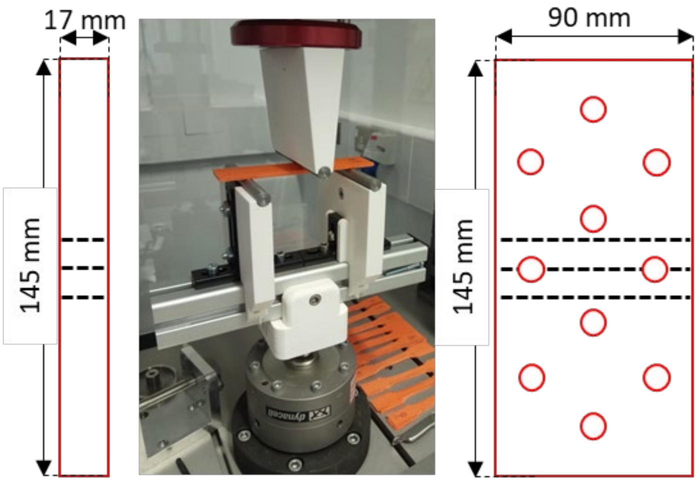


Figure 5:

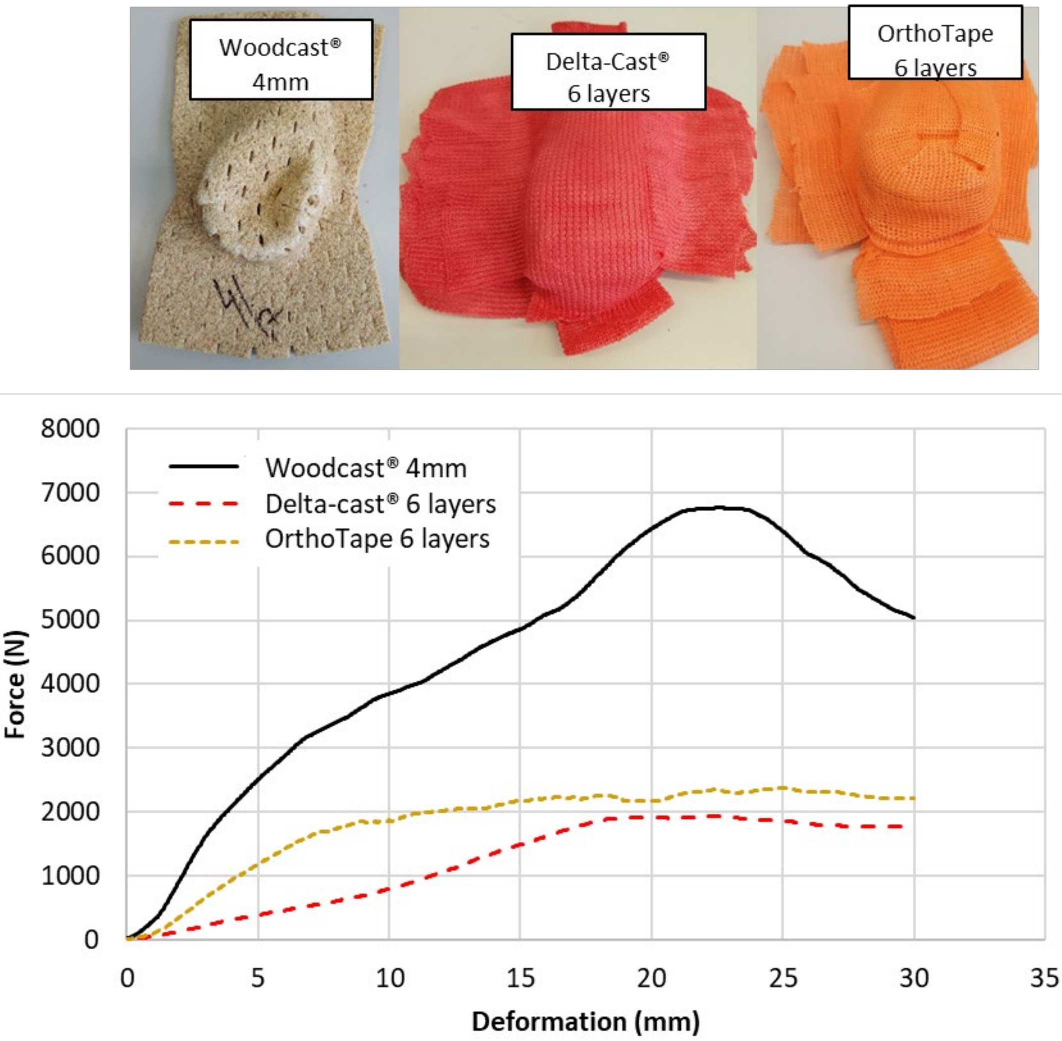
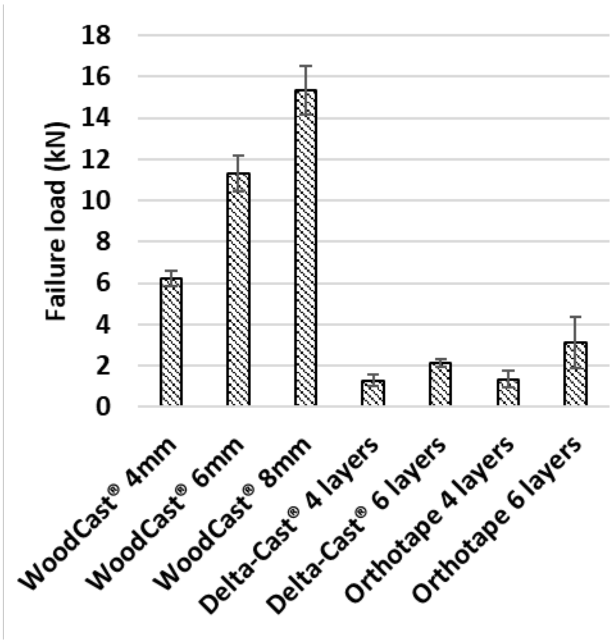

Woodcast®
4mm
Delta-Cast®
6 layers
OrthoTape
6 layers
Woodcast® 4mm
Delta-cast® 6 layers
OrthoTape 6 layers
Force (N)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
5
10
15
20
25
30
35
Deformation (mm)

Figure 6:



Failure load (kN)
0
2
4
6
8
10
12
14
16
18
WoodCast® 4mm
WoodCast® 6mm
WoodCast® 8mm
Delta-Cast® 4 layers
Delta-Cast® 6 layers
Orthotape 4 layers
Orthotape 6 layers

Figure 7:

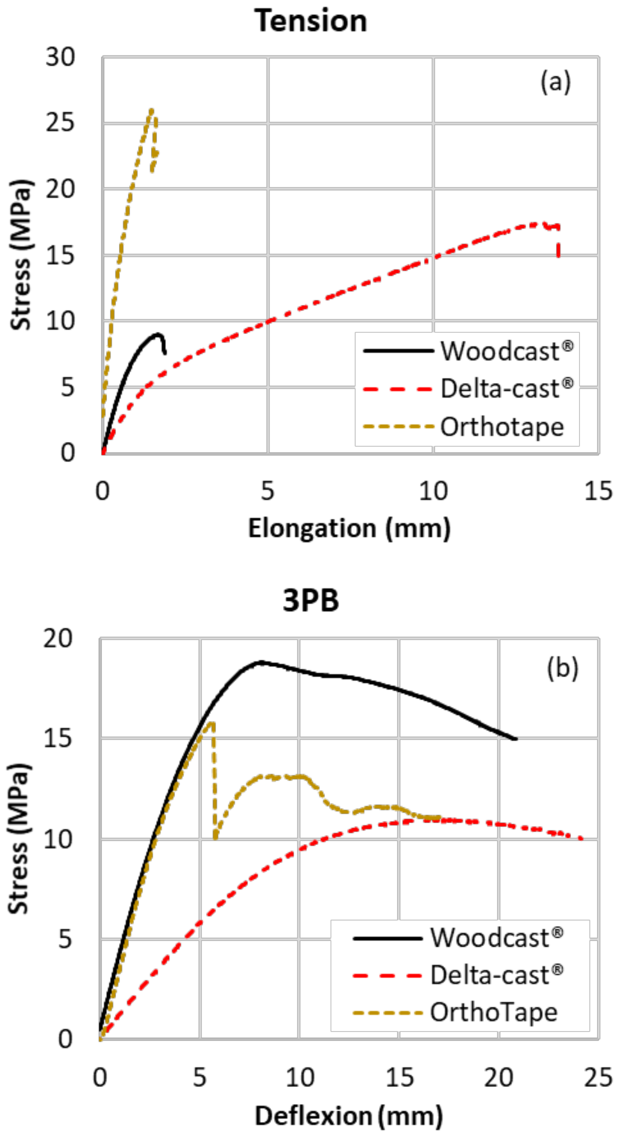
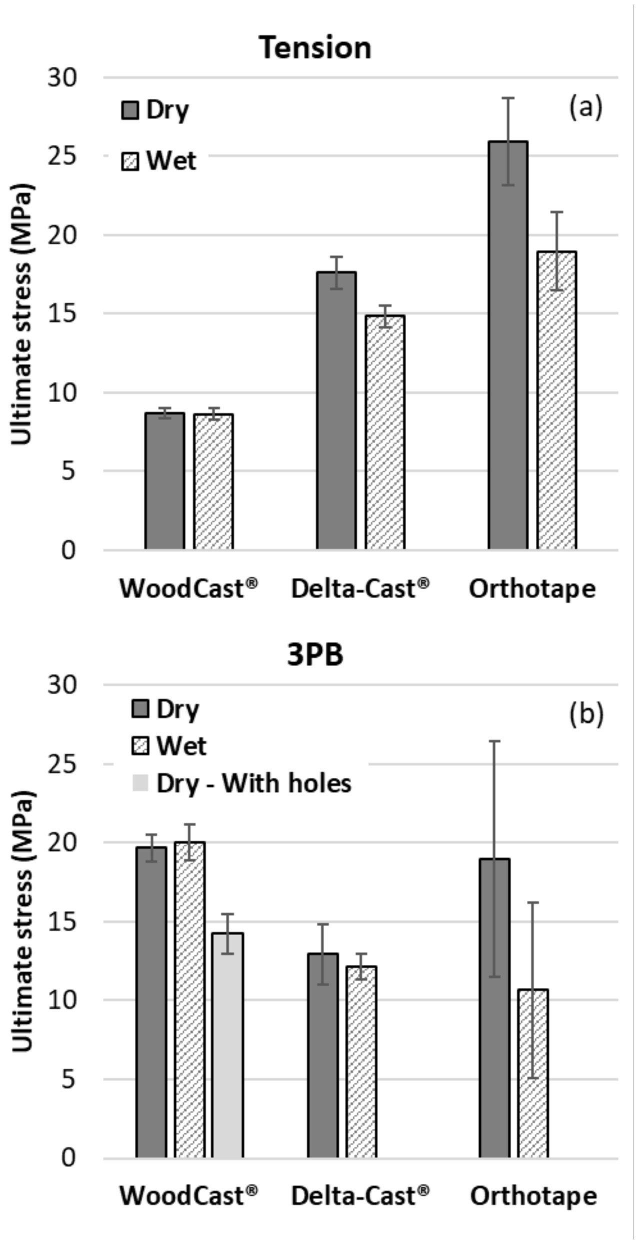

Tension
(a)
Stress (MPa)
30
25
20
15
10
5
0
0
5
10
15
Elongation (mm)
Woodcast®
Delta-cast®
Orthotape
3PB
(b)
Stress (MPa)
20
15
10
5
0
0
5
10
15
20
25
Deflexion (mm)
Woodcast®
Delta-cast®
OrthoTape

Figure 8:


Tension
(a)
Dry
Wet
Ultimate stress (MPa)
30
25
20
15
10
5
0
WoodCast®
Delta-Cast®
Orthotape
3PB
(b)
Dry
Wet
Dry - With holes
Ultimate stress (MPa)
30
25
20
15
10
5
0
WoodCast®
Delta-Cast®
Orthotape