A Methodology to Design and Fabricate a Smart Brace using Low-Cost Additive Manufacturing

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A Methodology to Design and Fabricate a Smart Ankle Brace using Low-Cost Additive Manufacturing†

Abstract

Ankle braces typically restrict the functional range of motion. Braces should preferably allow a free functional range of motion during sport, while protecting the foot at high-risk positions beyond that range. This could be achieved with 3D printed metamaterial structures that could have varying properties throughout an individual's ankle range of motion. This paper aims to illustrate an exploratory methodology of using an affordable Fused Deposition Modelling 3D printing technology to develop an ankle brace using metamaterial structures. It also showcases the design, manufacturing processes and testing of 3D printed customized ankle brace prototype designs that incorporated metamaterial structures. Initial tests showed that as designed, the prototype braces maintained the full range of motion for plantar flexion angles. Results also showed that the prototypes required one of the lowest moments during functional range of motion, while achieving almost twice to thrice the moment required beyond the functional range of motion.

Word Count: 150 words

Keywords: Ankle sprain, Metamaterial structures, Biomimetic, Anisotropic material properties, Tensile testing.

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1. Introduction

An ankle sprain is common during sport and can lead to persistent pain, ankle instability and possibly re-injury (Chen, McInnis, and Borg-Stein 2019). Ankle braces are being used to prevent ankle injuries (Bot and van Mechelen 1999; Cordova, Ingersoll, and LeBlanc 2000; Kaminski, Needle, and Delahunt 2019; Parsley et al. 2013). However, in doing so, ankle braces could also limit the range of motion, such as those of the ankle plantar flexion angles (Mann, Gruber, Murphy, and Docherty 2019). Limiting the functional range of motion could, in turn, reduce force absorption and increase vertical ground reaction force, leading to other injuries such as a bone fracture (Alentorn-Geli et al. 2009; Rowley and Richards 2015). Braces that could allow a free functional range of motion during sport, while protecting the foot at high-risk positions could bring about a revolutionary change to ankle brace designs. This could be achieved with materials with varying properties throughout an individual's ankle range of motion.

Metamaterials have become increasingly popular, especially with the progress of additive manufacturing or three-dimensional (3D) printing (Zadpoor 2016). Metamaterials, normally formed by repeated structures, have properties obtained from their structure rather than the material itself (Paulose, Meeussen, and Vitelli 2015). These 3D printed metamaterials thus present opportunities for personalised ankle braces to have varying properties through the joint range of motion, as opposed to fixed properties and structures in most commercial ankle braces. Materials are also often limited to proprietary materials that come with 3D printers, and metamaterials could be designed to achieve unique properties that are required for the design purpose and individual needs.

Personalised 3D printed orthoses are also relatively easy to manufacture compared to traditional methods (Cha et al. 2017; Santos et al. 2017). Conventional customized methods may require casts to be pre-manufactured or milled from a solid block resulting in design constraints (Telfer et al. 2012), tedious labour, long lead times (Santos et al. 2017) and costly orthoses.

Therefore, this paper presents a novel methodology of using an affordable Fused Deposition Modeling (FDM) 3D printing technology to develop an ankle brace designed with metamaterial structures that mimic the human ligament properties. An ankle inversion sprain injury is caused by an improper inverted or supinated landing position (Fong et al. 2009; Wright et al. 2000). The vertical ground reaction force will then act medially to the subtalar joint axis, and this consequently results in a large inversion or supination moment (Fong et al. 2009; Wright et al. 2000). Secondly, lateral peroneal muscles could not restrain the ankle inversion in time, leading to an ankle sprain injury (Fong et al. 2009). Yet, the use of ankle braces was also found to reduce muscle activity of the lower extremity during rehabilitation (Feger et al. 2014). Braces should therefore be designed to complement rather than replace muscle use, thereby weakening them. Hence, this novel ankle brace design aims to allow a functional range of motion during sports. Yet, the ankle brace is also designed to reduce ankle inversion velocity to allow the peroneal muscles to react in time to reduce ankle sprain injury risks. Benchtop testing was conducted to test the performance of the ankle brace prototype for proof-of-concept purposes.

2. Materials and Methods

Design considerations of orthoses include production time, cost, weight, practical use, durability, as well as attachment and removal (Santos et al. 2017). The ankle brace designed in this paper aimed to be simple, easy to manufacture, affordable, lightweight, and functional for sports play to reduce injury risks. It was not designed to replace the role of the muscles and ligaments in the ankle joint but to reduce ankle inversion velocity for the muscles to react in time to resist the ankle inversion loads. Thus, the brace was designed with little or no restriction to high inversion moments to overcome the inadequacies of existing semi-rigid braces in the market.

To allow the ankle brace to be fully customizable, a typical method would be to 3D scan the foot before designing the ankle brace around the foot (Santos et al. 2017). However, a fully customized ankle brace can be time consuming and expensive. Mass customisation could be an alternative method of manufacturing to allow for personalisation at a more affordable cost using standard mass-production methods (Hu 2013). This method is therefore adopted in the manufacturing processes of the ankle brace prototypes, with the incorporation of the FDM technology. Customization is only applied to the areas that require customized protection. The other portions of the ankle brace will adopt a standard design workflow. Figure 1 shows the workflow used in the development of the ankle brace in this paper.

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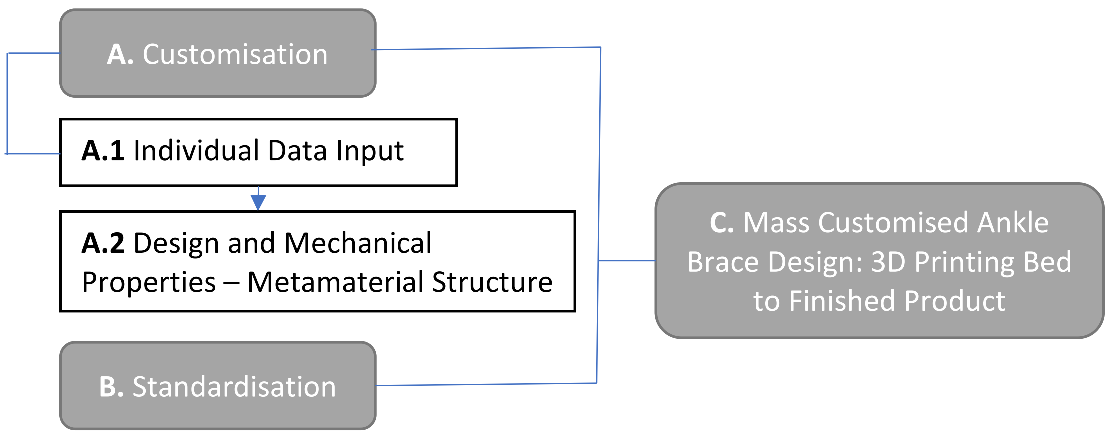

Figure 1: Design and Development Workflow for the Design of the Ankle Brace

2.1 ***Individual Data Input Guided by Biomechanics***

To develop an ankle prototype for proof-of-concept in this paper, the anthropometry data of the main author was collected as the subject for simplicity. The study was approved by the Nanyang Technological University Institutional Review Board (IRB-2021-02-017). According to Wei and others (2015), the ankle joint inversion moment during a Grade 1 ankle sprain was 23 Nm and the ankle external moment that caused pain and discomfort was 10 Nm. The moment experienced during pain and discomfort at 10 Nm was chosen as a key parameter in the design of this prototype. The distance A from the centre of the right ankle joint to the lateral malleolus was 4.1 cm.

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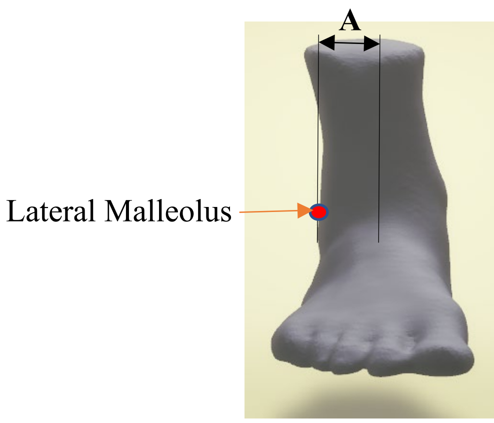

Figure 2: Distance A between the centre of the right ankle joint and the lateral malleolus.

Thus, the ankle brace was designed to resist the following force at 10 Nm external moment minimally:

$$Force = \frac{Moment}{Distance\ A} = \frac{10}{4.1/100} = 244\ N \quad (1)$$

Chu and others (2010) found that the maximum ankle inversion angles during common sporting motion (running, cutting, jump landing, stepping down) was less than 10°. Thus, the ankle brace should allow free movement within 10° of ankle inversion angle by having as low a Young's modulus and inversion moment as possible at this range of motion. There should then be an increase in Young's modulus and inversion moment beyond this point to reduce inversion velocity for the brace to function. Based on the subject's measurements, the ankle brace was designed to allow 10% of skin surface strain at 10° of ankle inversion angle and 33% strain at maximum inversion range of motion at the lateral aspect of the brace. The amount of skin surface strain was estimated using a measuring tape, with the foot at neutral, at the ankle inversion angle of 10° and at maximum inversion range of motion using the isokinetic dynamometer (Biodex System 4 Pro, Biodex Medical Systems, Inc., Shirley, NY, USA). Young's modulus of the metamaterial structure specimens in the next section was tested using the tensile test machine (Instron 5569, Instron Corporation, Norwood, MA, USA) to ensure that the design was within the specifications.

2.2 *Metamaterial Structure*

2.2.1 Prototype A – Diamond Mesh Design

The mesh diamond metamaterial structures were first adopted, drawing inspiration from the human ligament and mesh packaging. They were simple to implement yet provided different Young's moduli at different stages of loading, simulating the viscoelastic properties of the human ligament (Figure 3). The diamond mesh would stretch easily, flexing the diamond structures (see Figure 3, Zone I) until the diamond structures became fully elongated and straightened. After which, a higher force was required to stretch the diamond structures, as illustrated in Figure 3 (Zone II). Threshold strain was set at 10% of strain at 10° of ankle inversion angle based on the measurements made in the previous section.

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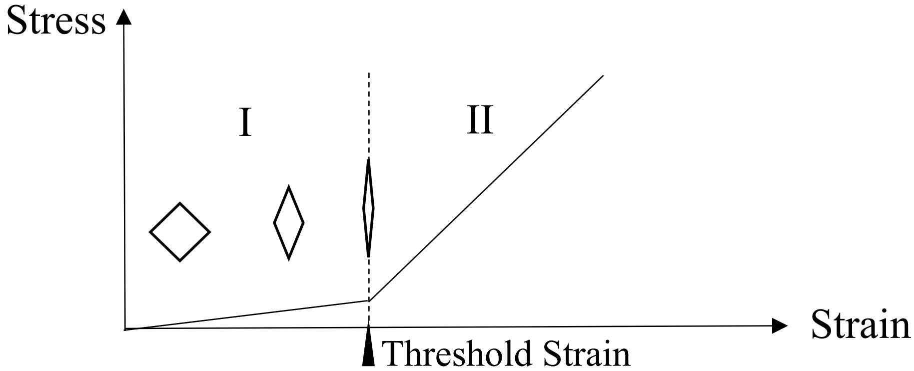

Figure 3: Stress-strain curve of the diamond metamaterial structures.

Traditionally, such mesh diamond metamaterial structures are manufactured using double extrusion. However, customization is difficult using the conventional double extrusion method compared to additive manufacturing or 3D printing. In addition, the diamond structures are asymmetrical, thus introducing anisotropic material properties. In one direction (direction A), applying the axial force allows the material to stretch easily (see Figure 4a). Conversely, applying the axial force in the transverse direction (direction B) allows the material to stretch less easily (see Figure 4b). Structures can thus be printed to create customized tensile properties in different regions and directions. These properties are influenced by parameters such as type of geometric shape, size of geometric shape (diameter of the printed polymer), and shape thickness.

<Figure 4 is inserted here>

(a) **(b)**

Figure 4: Material a) stretches easily in one direction b) but less easily in the transverse direction.

Figure 5 shows the tensile properties of the material in directions A and B. Young's modulus could be adjusted by just varying the design parameters, such as the thickness and diamond gap length (Figure 5). Direction A had a Young's modulus that was too low to be practical. Direction B instead had a Young's modulus that was too high to allow a free functional range of motion before threshold strain. To meet the design specifications such that a practical cross-sectional area was provided to meet the targeted 244 N of loads, a hybrid design combining the previous two designs in both directions (prototype A) was adopted. This will form the first customized structure to restrain the ankle at positions beyond the functional range of motion. This structure's dimensions are modified based on the individual data input for customization. For this study, length of H was 20% of length of V (Figure 5). In the cross-sectional view of the triangular sections, dimension T was 3 mm for direction B and 2.5 mm for direction A. Dimension A was two thirds of dimension W (Figure 5).

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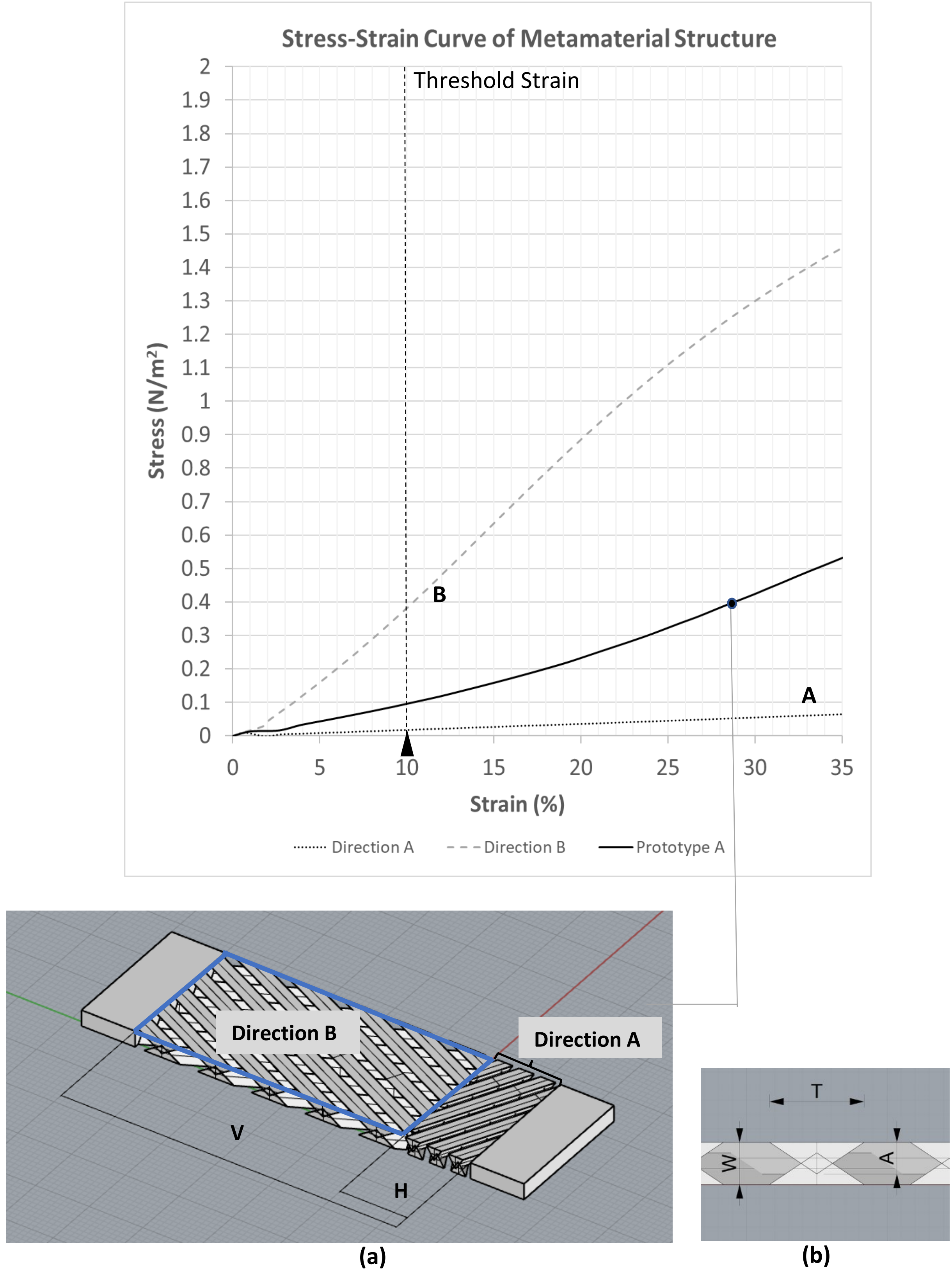

Figure 5: Stress-strain diagram of the diamond mesh structure in directions A and B and the hybrid design (prototype A). Young's modulus will increase after 'threshold strain' beyond the functional range of motion to restrain the ankle. Details of dimensions were that (a) length

of H was 20% of length of V and (b) in the cross-sectional view, dimension T was 3 mm for direction B and 2.5 mm for direction A. Dimension A was two thirds of dimension W.

To achieve the properties as stated above, 3D printing had to be carried out. The top and bottom layers of the structures were printed separately, such that pivoting was allowed during axial load (Figure 6). Traditional 2D manufacturing techniques such as laser cutting will not allow such pivoting structures to be obtained with a single cut. Besides, such 2D manufacturing techniques will result in undercut issues in the 3D structures in this prototype A design.

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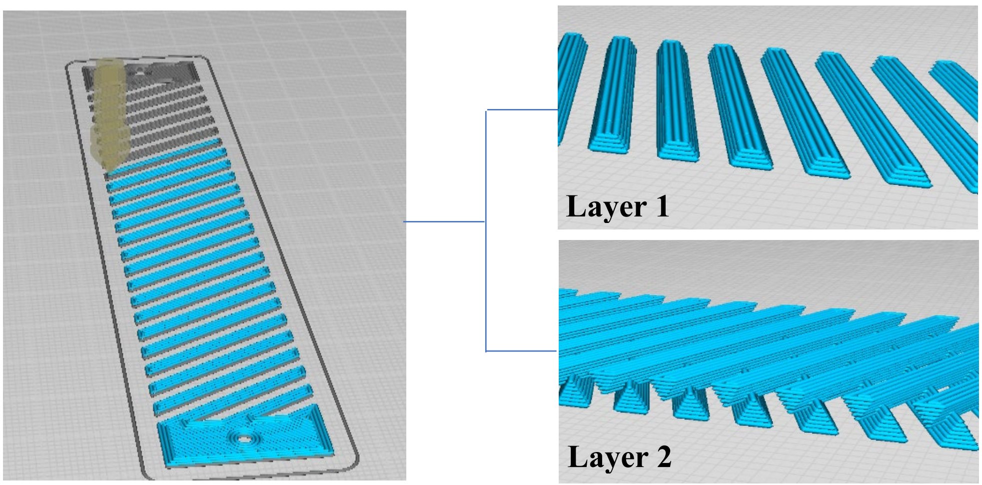

Figure 6: Printing of the metamaterial structure by two layers to allow for pivoting

2.2.2 Prototype B – Oriental Design

The "square grid" structure (Kolken and Zadpoor 2017) was found to provide a low Young's modulus in the functional range of motion. However, beyond the functional range of motion, its Young's modulus was too low to restrain the forces required in an ankle brace. The "square grid" structure was thus modified to improve the Young's modulus required for the ankle brace specifications (Figure 7). During the design process, a series of iterations were made with the support of simulation using SOLIDWORKS (Student Edition v2020, Dassault

Systèmes SolidWorks Corporation, Waltham, MA, USA) to identify areas of load-bearing. In the design, arches were included to allow for better flexing of the material within the functional range of motion as the arches straighten up. Beyond the functional range of motion, the applied load would stretch the arches and act as additional load-bearing structures of the design. Arches were modified in terms of dimensions and positions of application to limit Young's modulus within the functional range of motion and increase Young's modulus beyond that. The 'I' structures were also modified to include larger sizes to allow space for arches to be modified more effectively. The final design is shown in Figure 7.

The Young's modulus increased after the 'threshold strain', beyond the functional range of motion. Unfortunately, Young's modulus also increased within the functional range of motion before the threshold strain point with the additional arch support (Figure 8). This would result in higher moments required for ankle inversion in the functional range of motion during sport. However, Young's modulus in the functional range of motion is comparable to Prototype A.

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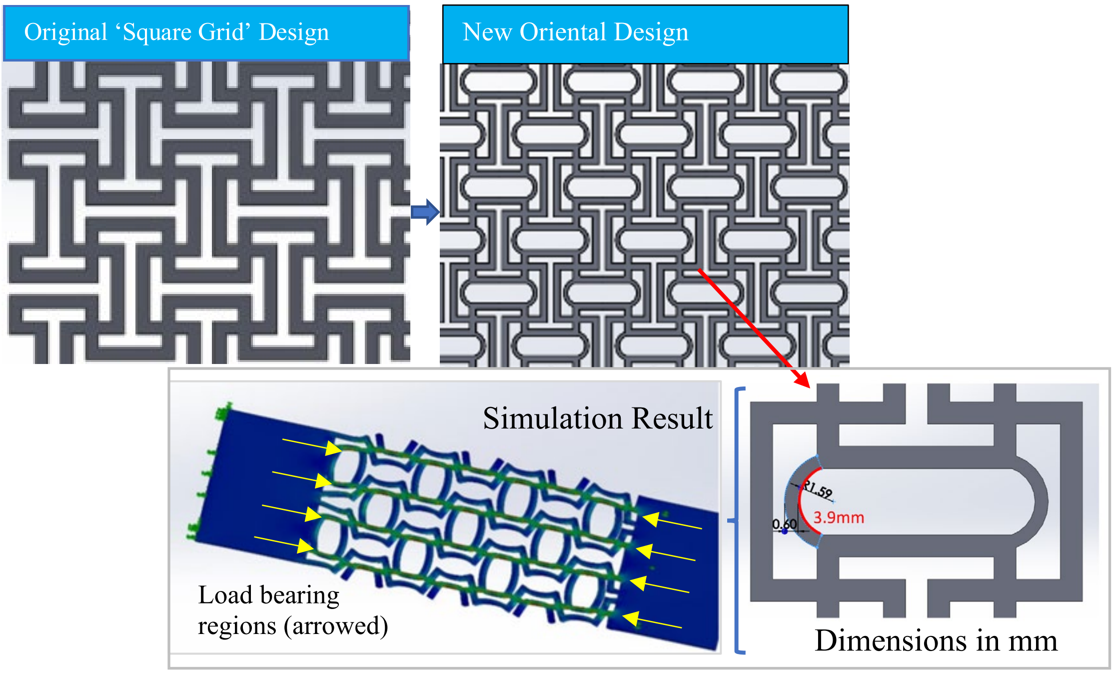

Figure 7: Oriental design modified from the “square grid” design (Kolken and Zadpoor, 2017) with dimensions in mm. As load applied, simulation results showed that the arch could provide additional support to the structure (along arrowed regions).

<Figure 8 is inserted here>

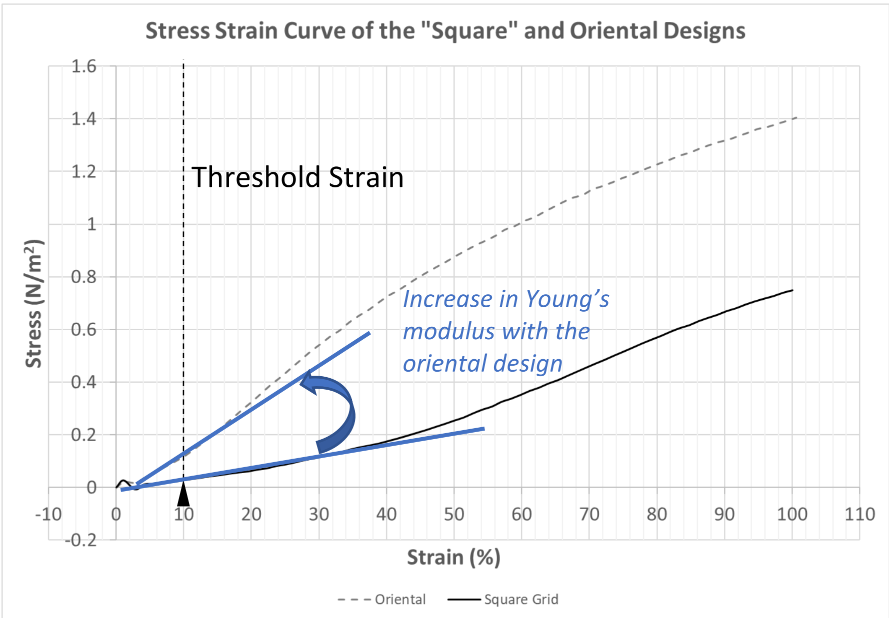

Figure 8: Stress-strain diagram of the “square grid” and oriental designs.

2.2.3 Prototype C – "Horseshoe" Design

The "horseshoe" structure was designed to imitate the stress-strain behavior of the human skin (Jang et al. 2015). The base shape of the triangular lattice is an equilateral triangle. Although the horseshoe structure can be adapted to other lattice configurations such as the honeycomb, Ma and others (2016) determined that the triangular configuration allowed for the sharpest transition at the critical strain required. The generalized stress-strain curve of the "horseshoe" structure could be obtained by the normalized width ($\bar{w} = w/R$) and the arc angle (θ), where w denotes the width of the curved beam used to make up the horseshoe structure and R denotes the radius of the horseshoe structure curvature (Figure 9) (Ma et al. 2016). Additionally, according to Zhang and others (2013), the width of individual beams of the structure should be much thinner than the thickness of the structure to avoid out-of-plane deformation. The equilateral triangle was designed using the dimensions R = 10 mm, w = 0.5 mm, arc angle = 90° for this proof-of-concept.

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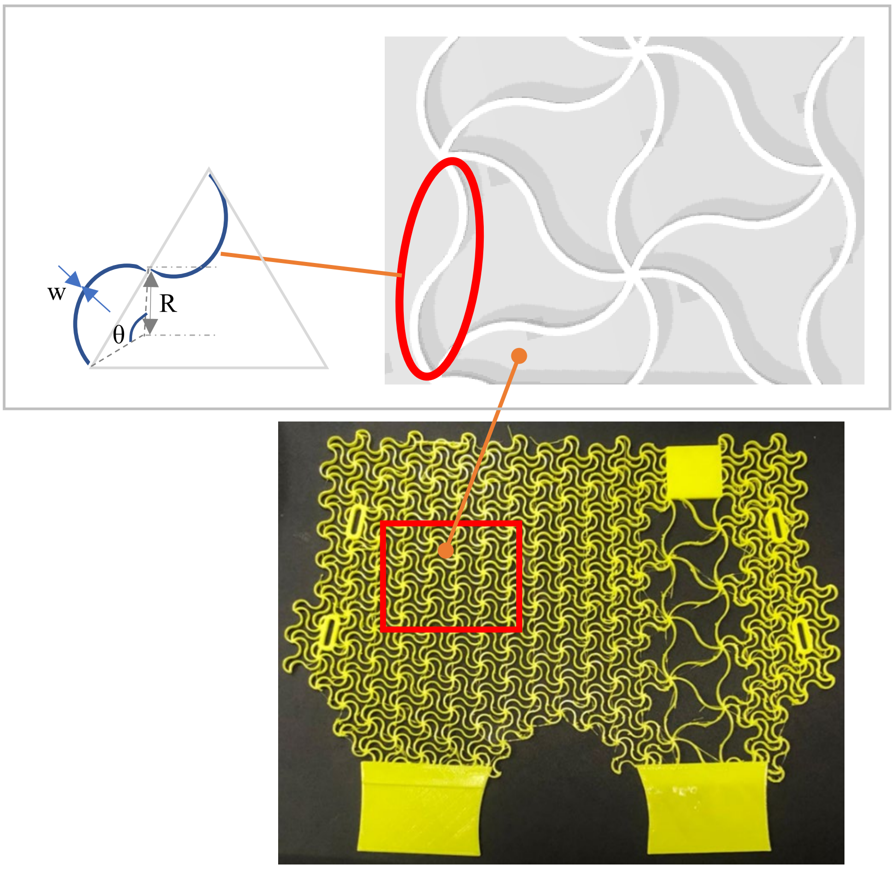


Figure 9: Parameters of the "horseshoe" structure: normalized width ($\bar{w} = w/R$) and the arc angle (θ), where w denotes the width of the curved beam used to make up the horseshoe structure and R denotes the radius of the horseshoe structure curvature (Ma et al. 2016).

2.3 Non-functional Area of Brace

For the rest of the ankle brace structure, the "square grid" structure (Kolken and Zadpoor, 2017) was used for metamaterial Prototypes A (diamond mesh design) and B (oriental design), modifying the dimensions to fit the metamaterial structure used (Figure 10). This structure was used in the prototype as preliminary results showed that it wrapped seamlessly onto body joints, resulting in increased comfort. The last design, Prototype C ("horseshoe" design), was designed entirely with the "horseshoe" structures (Figure 10). Flexible thermoplastic polyurethane material (NinjaFlex, NinjaTek, Fenner Inc., Manheim, PA, USA) with a shore hardness of 85A and tensile modulus of 12 MPa was eventually selected to allow minimal resistance during the functional range of motion.

<Figure 10 is inserted here>

Figure 10: Ankle brace prototype A (diamond mesh design), prototype B (oriental design) and prototype C ("horseshoe" design)

2.4 Design Features and Processes

Design Considerations

There have been many ankle braces in the market. The purpose of the ankle brace used in this paper was not to out-perform these braces. Rather, the brace was to slow down the ankle inversion velocity, allowing the peroneal muscles to restrain the ankle inversion in time.

2.4.1 3D printing of a customised ankle brace

For the ankle brace to be 3D printed, the brace needed to be laid out and printed on the flat print bed. Drawing inspirations from socks and commercial braces, a “butterfly”- like design was used as a standard design template for all individuals (Figure 11). The designs were carried out using the design software (Rhino 6 Education Lab Version, Robert McNeel & Associates, Seattle, WA, USA). The red regions are where customization was carried out using the metamaterial structure described earlier.

<Figure 11 is inserted here>

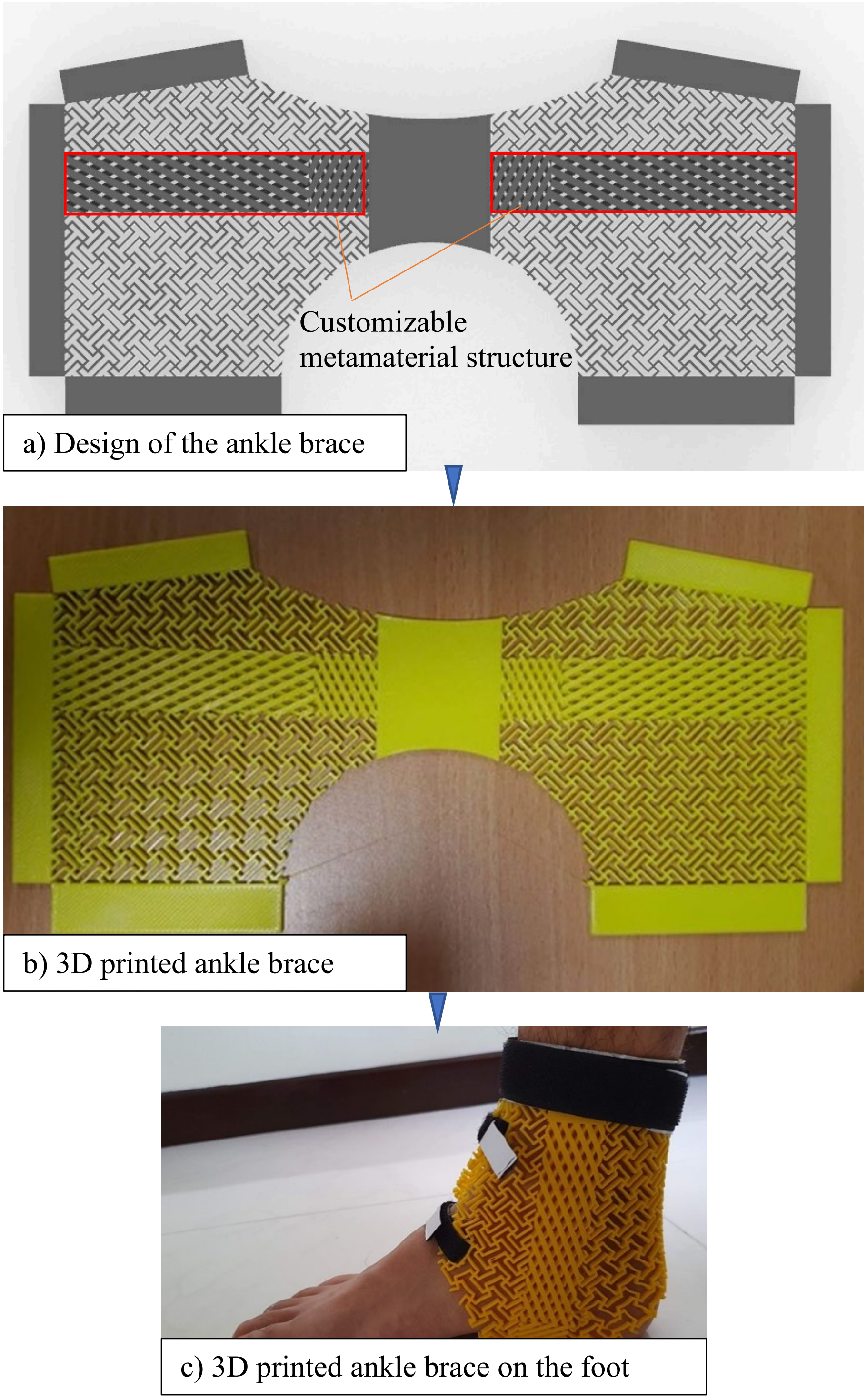


Figure 11: a) Design of the ‘butterfly’ ankle brace with red zones for customized protection; b) 3D printed brace laid out flat on the print bed; and c) 3D printed ankle brace on the foot.

The ankle brace was then printed using a LulzBot FDM 3D Printer (TAZ 5, Fargo Additive Manufacturing Equipment 3D, Fargo, ND, USA) fitted with a FlexyStruder extruder head.

Benchtop Testing for Proof-of-Concept

Competitive analysis was conducted on the prototype ankle brace, with respect to other commercially available braces:

- Prototype ankle brace
- Semi-Rigid: Donjoy PRO Ankle Brace
- Semi-Rigid, Hinge Design: Ultra Zoom Ankle Brace
- Lace-up Design: Med Spec ASO Ankle Stabilizer
- Sleeve Design: Saibike Ankle Support

Range of motion benchtop testing was conducted on the main author using the isokinetic dynamometer (Biodex System 4 Pro, Biodex Medical Systems, Inc., Shirley, NY, USA) and using a goniometer (Lafayette Gollehon Extendable Goniometer, Lafayette Instrument, Lafayette, IN, USA) to measure the maximum plantar flexion angles. For each ankle brace, zero position was set at the ankle's neutral position when the foot was relaxed. The range of motion test was also conducted in the barefoot condition.

A test jig version 1 was first built, followed by a test jig version 2, to measure the moment required to invert the ankle to 10° and 30°. The jigs are seen in Figure 12. A 3D printed foot with a ball and socket joint at the ankle was also manufactured for the test jig version 2. A foot plate was designed and oriented such that the axis of rotation was vertical and parallel to direction of the weight of all the parts, thus avoiding the need to incorporate weight into the force calculations for version 2 (Appendices 1 - 3). Prototypes B and C were unavailable when the test jig version 1 was used. Test jig version 2 also could not fit the lace-up design, and test results from both jigs were thus included. A portable electronic scale (Weiheng portable electronic scale, Guangzhou Weiheng Electronics, Guangdong, China) was used to measure the force required to rotate the ankle brace. A ratio was calculated to indicate the amount of moment required to invert the ankle to 30° over 10°. A bigger ratio shows that increased moment is required to invert the ankle beyond the functional range of motion compared to within.

<Figure 12 is inserted here>

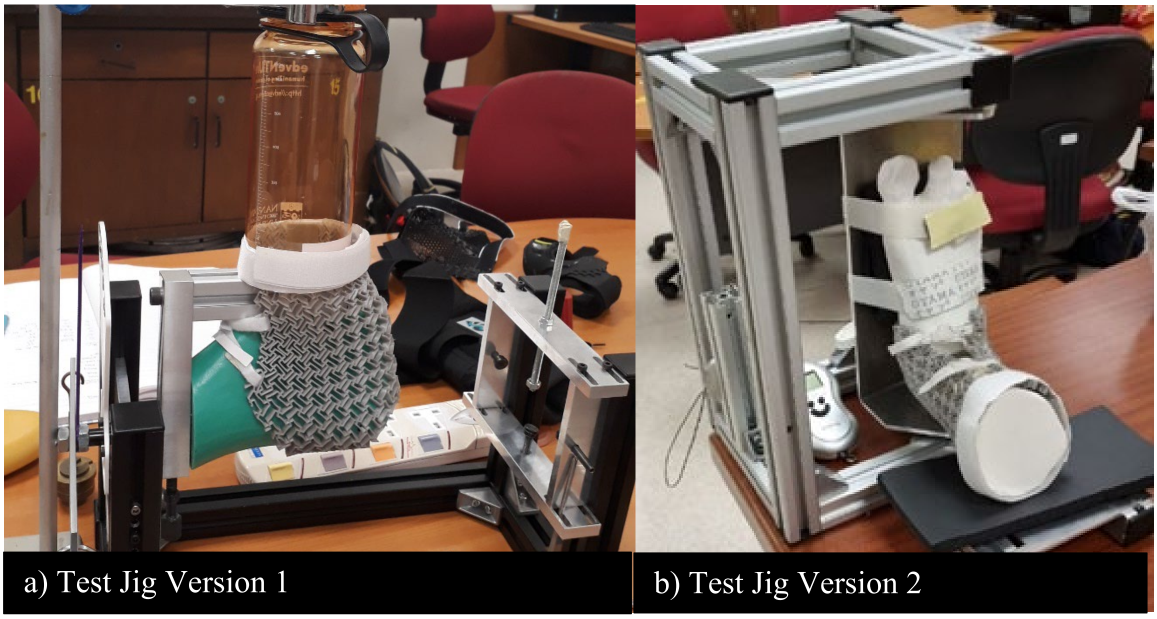


Figure 12: Two test jig versions 1 and 2 were built to measure the moment required to invert the ankle brace to 10° and 30°. A 3D printed foot with a ball and socket joint at the ankle was also manufactured for test jig version 2.

Results

Table 1 shows the results of the range of motion of the prototype ankle braces compared to four commercially available ankle brace products. The prototype ankle braces allowed full plantar range of motion, similar to barefoot testing. The other commercial braces, especially the semi-rigid hinge design, resulted in a reduced plantar range of motion (Range: 1° to 12° reduction in plantar flexion angles).

< Table 1 is inserted here>

Table 1: Maximum ankle plantar flexion angles of the prototype ankle brace compared to other commercially available ankle braces.

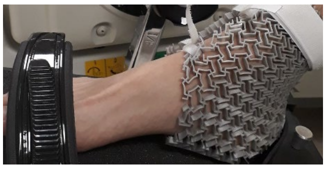
Type of Ankle Brace	Images	Category of Ankle Brace	Maximum Ankle Plantarflexion Angle (°)
Barefoot	-	-	50
Prototypes A, B and C		3D Printed	50
Donjoy POD		Semi-Rigid	41
Ultra Zoom		Semi-Rigid, Hinge	38
Med Spec ASO Stabilizer		Lace-Up	43
Saibike Ankle Support		Sleeve	49

Table 2 shows the amount of moment required to invert the ankle to 10° and 30°. The prototype braces B and C had ratios comparable to the commercial Donjoy POD product, which was the best performing commercial product in this aspect. Prototype A was comparable to the sleeve product in terms of the ratio. Moments required to rotate the ankle at the functional range of motion (less than 10°) among the prototype braces were lower than all other commercial products except the sleeve design (Saibike Ankle Support).

< Table 2 goes here >

Table 2: Moment to invert prototype and commercially available ankle braces to 10° and 30°. Prototypes B and C were unavailable when the test jig version 1 was used. Test jig version 2 also could not fit the lace-up design, and these results were excluded.

Type of Ankle Brace	Category of Ankle Brace	(A) Test Jig Version 1			(B) Test Jig Version 2		
		(A.1) Moment for 10° Inversion (Nm)	(A.2) Moment for 30° Inversion (Nm)	Ratio (A.2/A.1)	(B.1) Moment for 10° Inversion (Nm)	(B.2) Moment for 30° Inversion (Nm)	Ratio (B.2/B.1)
Prototype A - Diamond Mesh	3D Printed	0.50	0.84	1.7	0.37	0.55	1.5
Prototype B - Oriental	3D Printed				0.31	0.92	2.9
Prototype C - Horseshoe	3D Printed				0.16	0.45	2.9
Donjoy POD	Semi-Rigid	0.71	1.91	2.7	1.15	3.27	2.9
Ultra Zoom	Semi-Rigid, Hinge	1.76	3.37	1.9	0.98	1.85	1.9
Med Spec ASO Ankle Stabilizer	Lace-Up	1.90	3.57	1.9			
Saibike Ankle Support	Sleeve	0.44	0.59	1.3	0.15	0.22	1.5

Discussion

This paper aims to illustrate a new methodology of using an affordable FDM 3D printing technology to develop an ankle brace designed with metamaterial structures that mimic human ligament properties. Three prototypes were developed as a proof of concept, incorporating the metamaterial structure, customized to each individual.

The prototypes required one of the lowest moments during the functional range of motion and yet achieved almost twice or thrice the moment required beyond that range. All the commercial braces allowed a free functional range of motion of 10°. However, more effort or moment was required to rotate the ankle for most of these tested braces than for our prototype ankle braces. This suggests that the 3D printed prototype braces achieved their purpose of allowing low moments for easy ankle inversion in the functional range of motion.

Beyond the functional range of motion, the moments of the prototype braces increased by almost two to three times, with similar performances with the commercial ankle braces, especially for prototypes B and C. This could help slow motion down in this range. However, the actual moments of the prototypes (Range: 0.45 Nm – 0.92 Nm) were much less than commercial products (Range: 0.22 Nm – 3.27 Nm) using the self-designed jig Version 2 as the prototype ankle braces were not designed to be stiff enough to replace the player's muscles. Overall, the Donjoy POD seemed to perform the best among the commercial braces with the highest ratio in terms of the moment required at 30°, compared to at 10° of ankle inversion. Prototype B and C had a comparable ratio (2.9) as the Donjoy Pod. Prototype B had a higher moment required than prototype C for better protection at 30° of inversion. However, prototype B also had a correspondingly higher moment required to invert the test jig ankle to 10° than prototype C and this could affect the performance in the functional range of motion. Nevertheless, prototype C could not resist the moments required to invert the test ankle to 30° and went into plastic deformation soon after that. Collectively, prototype B would be a better choice for the 3D printed ankle brace.

Initial tests also showed that as designed, the prototype ankle braces allowed full plantar range of motion, similar to barefoot testing. This was unlike the other commercial braces, especially the semi-rigid and lace-up designs, resulting in a reduced plantar range of motion. Ankle plantar flexion is required to help in force absorption (Alentorn-Geli et al., 2009). On average, ankle plantar flexion angles were less than 30° (Mean 29° SD(8°)) during natural single-leg landings (Teng, Leong and Kong 2020). Therefore, while restrictions of plantar flexion angles were observed, all the braces could still allow functional plantar flexion range of motion in single-leg landings (Table 1). However, a more effective way of assessment was to measure the moment required to reach the plantar range of motion. This was not measured during the test as this was not the focus of the study, and the test jigs were not designed to measure this. The semi-rigid hinge and lace-up braces probably required more effort to produce similar ankle plantar flexion angles as the prototypes.

Together, the prototypes have achieved their design purposes for proof-of-concept. FDM has allowed for mass customization with unique properties at selected regions based on individual needs and at relatively affordable costs. Using 3D printers with higher resolution to print more refined structures or sourcing for other flexible 3D printed materials could further reduce the inversion moment in the functional range of motion. Comparatively, more traditional 2D manufacturing methods such as laser cut could be simpler to use and faster to manufacture. Yet, these 2D methods do not allow for more complex 3D structures to be manufactured. Besides, such 2D methods may have 'undercut' issues for 3D structures such as that found in prototype A. Also, for prototype A, the upper and lower layers must be printed separately for the 'pivoting' effect to work to allow greater flexibility in the functional range of motion. This could not be achieved using laser cutting when the structures are cut out in one sequence. Furthermore, although this paper used 2D structures as a proof-of-concept in prototypes B and C, 3D complex layers of different structures could be developed in future to create more unique metamaterial properties in braces. Therefore, this paper aims to introduce the methodology to design mass customized braces using 3D printing as the core technique.

Conclusion

This paper illustrates a new methodology of using an affordable FDM 3D printing technology to develop an ankle brace designed with metamaterial structures that mimic human ligament properties. A prototype was developed as a proof of concept, incorporating the metamaterial structure, customized to each individual. Initial tests show that as designed, the prototype braces maintained the full range of motion for plantar flexion angles. Initial tests also show that the prototype requires one of the lowest moments during a functional range of motion, yet achieving almost twice to thrice the moment required beyond the functional range of motion. Unlike commercial ankle brace designs, the prototype designs could better allow players to play without restrictions in the functional range of motion during sport. Yet, at high-risk positions, the prototype designs could aid in reducing ankle inversion velocity to allow the peroneal muscles to react in time to help in reducing ankle sprain injury risks.

Text Word Count = 4319

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Declaration of Interest Statement:

The authors declare that there is no conflict of interest.

Biographical note.

Dr Phillis Teng is a senior research fellow at the Nanyang Technological University, Singapore (NTU), with the passion in biomechanics research, especially in injury risk reduction. She has a diverse background in biomechanics research and mechanical engineering, with 6.5 years of industry experience as an Engineer at Hewlett-Packard Singapore. She obtained her PhD in NTU in 2015 and her PhD research on 'Investigation of Foot Landing Techniques and Muscle Activation during Single-Leg Drop Landings: Implications for Non-Contact Anterior Cruciate Ligament Injuries' has produced 4 journal and 4 conference papers. Her past 10 years in research included areas in sport injury risk reduction; human perception in comfort and fit; mechanical shoe testing; 3D printed brace development using metamaterial structures; and biomechanics study of customized 3D printed insoles. She is now with the Rehabilitation Research Institute of Singapore, studying knee osteoarthritis risks and exploring the possibility for an early biomechanics intervention.

A/P Kah Fai Leong is an associate professor in the School of Mechanical and Aerospace Engineering, Nanyang Technological University. He obtained his B.Eng. (Mech.) with Honours from the National University of Singapore in 1981 and M.Sc. degrees in Engineering Product Design and Mechanical Engineering, from Stanford University in 1987. Prior to joining NTU, he has worked several years as a product development engineer and designer in the Singapore electronics industries. He was awarded the Merit Award in 1994 and Distinguished Award in 1997 for his contributions to the national standardisation program. His research interests are in Additive Manufacturing for biomedical applications, particularly in tissue engineering; sports technology; sports science; polymer matrix composites; design science; and design education. He has co-authored five books, published more than ten book chapters and more than 200 papers in international journals, conferences, and seminars in these areas. He has been invited as a keynote speaker for a number of premier conferences and has acted as reviewers for several journals, including Materials and Design, Virtual and Physical Prototyping; Additive Manufacturing; Materials Today, Trends in Biotechnology, Biomaterials, Acta Biomaterials, Journal of the Mechanical Behavior of Biomedical Materials, amongst others.

A/P Pui Wah (Veni) Kong is the Associate Dean for Research Grants Management and an Associate Professor at the National Institute of Education, Nanyang Technological University, Singapore. Her research interests are sports and clinical biomechanics, with applications in human performance, injury prevention and rehabilitation. Dr Kong has led research projects on high-performance sports, gait, footwear, foot health, low back pain, massage, and sports injuries. She conducted laboratory experiments and field tests on athletes, school children, older adults, firefighters, paramedics, military personnel, and patients with various musculoskeletal health conditions. She worked closely with hospitals, clinics, government agencies and industrial partners to conduct interdisciplinary research that can impact the society. She was the recipient of the Fellow of International Society of Biomechanics in Sports (FISBS) in 2020, among other presentation awards from the International Sports Engineering Association, British Association of Sport and Exercise Sciences, Asian Society of Sport Biomechanics and Sports Medicine Association Singapore.

Mr Er Bin Hao created the template for ankle brace development as part of his final year engineering project and is currently a UX designer, working on designing digital products that help to solve the sustainability challenge. Having graduated from Nanyang Technological University, Singapore with a Bachelor in Mechanical Engineering, he has since pivoted to a career in user experience and design, working with companies to deliver visual solutions and data driven metrics in order to help in energy management and carbon net zero.

Mr Chew Zhi Yuan graduated from Nanyang Technological University in 2021 and obtained a degree in Mechanical Engineering. For his final year engineering project, he re-designed the existing metamaterial structure to improve its tensile properties and used simulation in his design iterations. He also explored the use of printing on cloth to enhance the ankle brace comfort levels.

Ms Tan Phei Shien graduated from Nanyang Technological University in 2021 and obtained a degree in Mechanical Engineering with a specialisation in Design. She has worked on various design projects throughout her undergraduate course and her work on utilizing metamaterials in an ankle brace was her first research related project. She also designed and developed the newer test jig to allow for ankle brace testing and competitive analysis.

Mr Chor Hiong Tee (Frankie) is a Project Officer at the Rehabilitation Research Institute of Singapore, Nanyang Technology University, Singapore. His research interests include product aesthetics, human-centered design and design strategies. Frankie has more than a decade of design and research experience in the multimedia, advertising and industrial design industries.

Since graduating with a Bachelor of Fine Art in Product Design from Nanyang Technological University (NTU), he has managed numerous research projects in academia and industrial collaborations with commercial partners. As an industrial designer/design researcher, Frankie is instrumental in developing various consumer products, ranging from home service robots for the elderly, intelligent wearables for lifestyle needs, gears and equipment for sports and medical rehabilitation applications. His collaboration with the Badminton World Federation (BWF) to develop an outdoor shuttlecock solution has led to a successful commercial launch of a new outdoor game called Air Badminton. In addition, Frankie has written a book chapter and helped edit manuscripts for a collaborative book project on Digital Manufacturing for the HP-NTU Corporate Laboratory in NTU.

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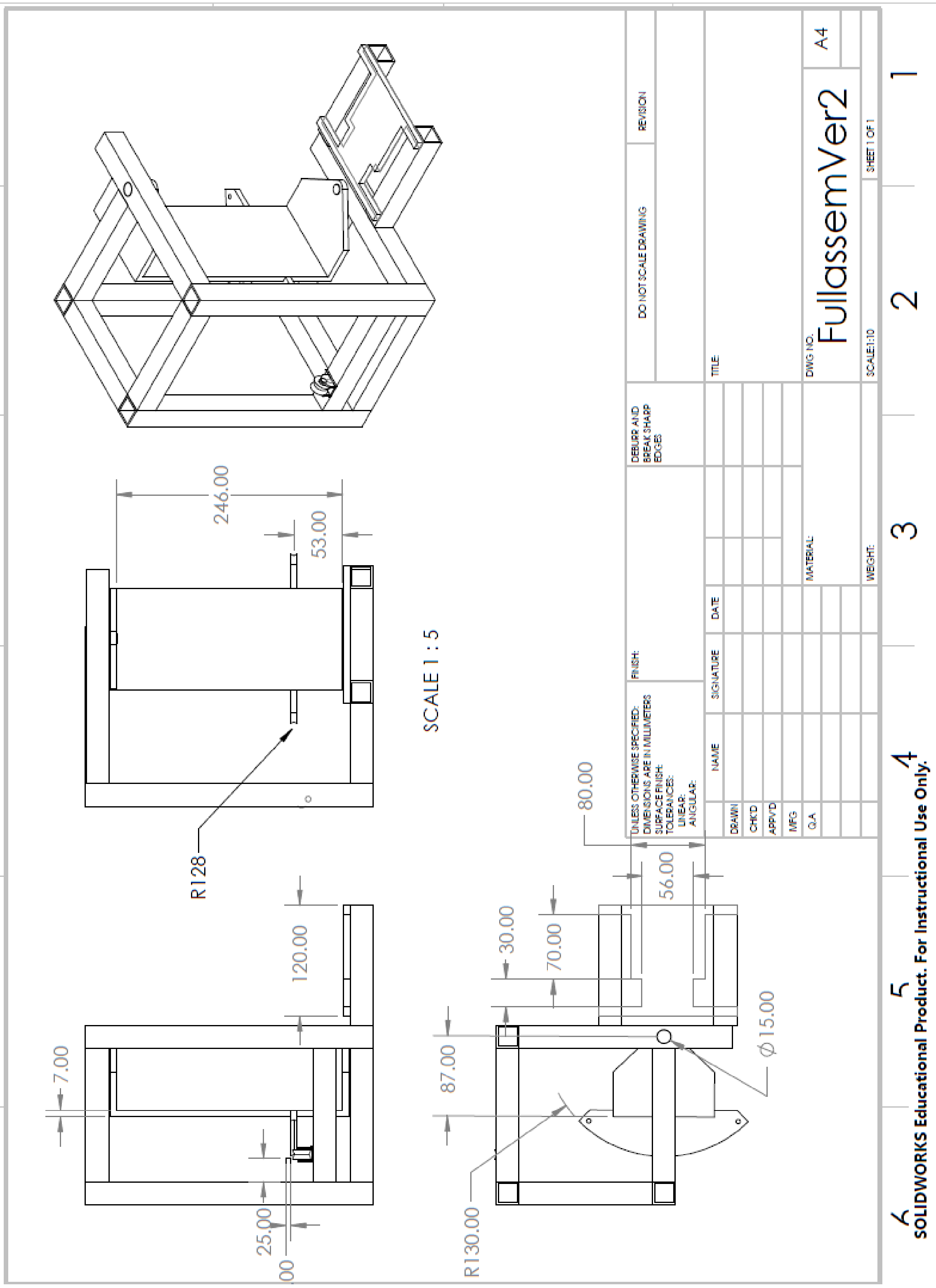
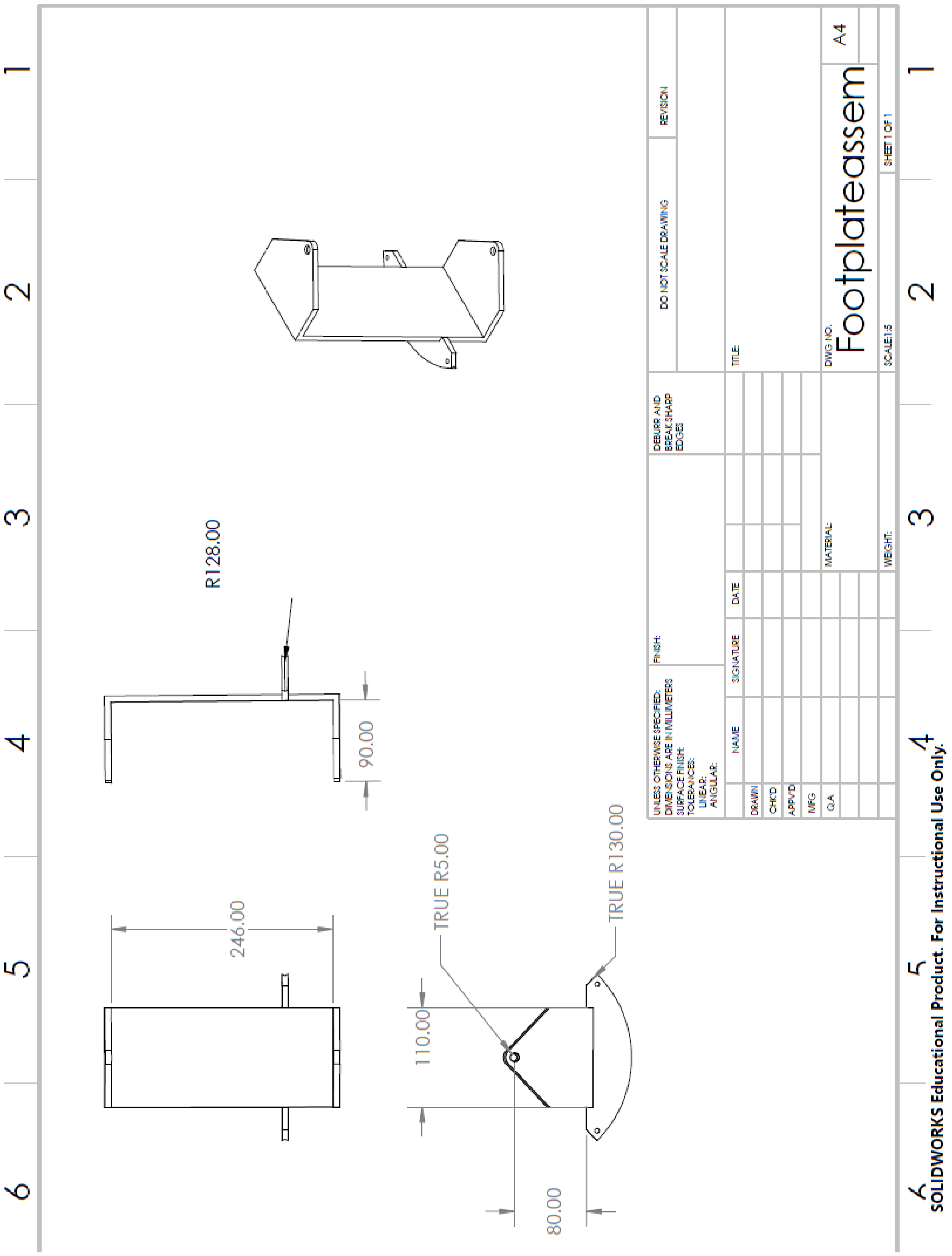
Appendix 1 – Engineering Drawing of full jig



Apeendix 2 – Engineering Drawing of Foot Plate



Appendix 3 – CAD model of Foot with joint