

DESIGN ANALYSIS AND STRUCTURAL
OPTIMISATION OF A RIGID ANKLE FOOT
ORTHOSIS

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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DESIGN ANALYSIS AND STRUCTURAL OPTIMISATION OF A RIGID
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ABSTRAK

Ortosis sendi-buku lali (AFO) yang ideal bagi merawat masalah anggota bawah badan adalah ortosis yang diperbuat mengikut acuan antropometri pemakai. Ortosis yang terdapat dipasaran sedia ada kebanyakannya tidak memenuhi ciri ideal tersebut. Namun begitu tidak dinafikan ortosis dipasaran kini mempunyai kos yang rendah. Penghasilan ortosis yang ideal pula, selain melibatkan kos yang tinggi, turut memerlukan masa pembuatan yang panjang kerana darjah kerumitan yang tinggi. Ia juga turut memerlukan kecekapan, ketelitian dan pengalaman yang tinggi seorang tukang ortosis. Bagi menyelesaikan masalah yang dinyatakan tadi, tesis ini mencadangkan satu metodologi rangkakerja menyeluruh bagi pembangunan suatu ortosis dari peringkat rekabentuk hinggalah peringkat pembuatan. Metodologi rangka kerja ini bertujuan untuk menyelesaikan permasalahan kos dan kerumitan proses pembuatan orthosis dengan mengintegrasikan solusi berkos rendah ke dalam fasa reka bentuk dan pembuatan. Dalam fasa reka bentuk, untuk mendapatkan ukuran antropometri yang jitu pemakai ortosis satu mesin pengimbas 3D berkos rendah telah digunakan. Data antropometri ini seterusnya digunakan untuk merekabentuk satu prototaip didalam perisian reka bentuk bantuan computer (CAD) komersial Autodesk Inventor. Sebelum prototaip ini direalisasikan melalui mesin pembentukan pengendapan terlakur (FDM), sifat mekanik bahan berdasarkan parameter cetakan perlu dikaji untuk memastikan hasil cetakan yang optimum. Hasil cetakan (Zortrax Acrylonitrile Butadiene Styrene (ABS)) menggunakan parameter cetakan yang berbeza seperti orientasi komponen, ketumpatan dan ketebalan lapisan diuji dengan ujian tegangan untuk mengenal pasti integriti struktur yang signifikan bagi pembuatan ortosis. Berdasarkan hasil ujian ini, parameter percetakan yang optimum dilaksanakan ke dalam Model Unsur Terhad (FEM) untuk mengkaji integriti struktur reka bentuk ortosis tersebut. Penilaian integriti struktur ortosis adalah penting untuk mengkaji ketersauran penggunaan mesin pembentukan pengendapan terlakur (FDM) dalam menghasilkan ortosis. Kajian Model Unsur Terhad (FEM) turut menjalankan pengoptimuman topologi bagi mengurangkan berat ortosis serta meminimumkan penggunaan bahan ketika penghasilan ortosis tanpa menjejaskan integriti struktur ortosis tersebut. Hasil daripada pengoptimuman topologi ini, pengurangan kos sebanyak 3% dan pengingkatan kekuatan struktur dari faktor keselamatan dari 0.289 ke 4.671 telah dicapai. Berdasarkan keputusan kajian ini, metodologi rangka kerja yang dicadangkan adalah terbukti lebih efisien dalam mengurangkan kos serta meningkatkan kekuatan bagi penghasilan ortosis yang spesifik kepada ukuran antropometri individu.

ABSTRACT

The ideal type of Ankle Foot Orthosis (AFO) for treating patients with lower limb impairments are those that closely follow the wearer's anthropometry. Most mass-produced AFO that are available in the market does not cater the aforementioned requirements nonetheless it is cost-effective. Conversely, the existing AFO that does conform to individual anthropometry is expensive due to complex geometry, requiring skilled and experienced orthotist. Adding to this cost is the long lead time required to produce a unit of orthosis. In order to mitigate the aforementioned problems of mass produced and individual-specific AFO, this thesis proposes a methodological framework that addresses these issues from the design phase to the fabrication phase. This methodological framework aims to rectify the cost and complexity issue by integrating inexpensive solutions into the design and fabrication stage. In the design phase, a low-cost 3D scanning is adopted to obtain an accurate 3D capture of an individual's anthropometry. An initial AFO prototype is modelled based on this 3D capture data through the use of a commercially available Computer Aided Design (CAD) software package, Autodesk Inventor. Subsequently a tensile test was performed to investigate different mechanical properties arising from varying printing parameters namely; material orientation, build density and print layer thickness of Zortrax Acrylonitrile Butadiene Styrene (ABS) material which is the material used in the fabrication stage employing the use of a low cost Zortrax M200 3D printer. This experimental investigation is not trivial as it provides significant insight on the mechanical characteristics of the varying parameters mentioned above. Based upon the experimental investigation, the best printing parameters were fed into the Finite Element Model to further investigate the structural integrity of the design as well as to carry out the proposed Topology Optimisation method. The evaluation of the structural integrity is important in order to weigh the feasibility of using the Fused Deposition Modelling (FDM) process in the manufacture of tailor made AFO. A structural optimisation is carried out to reduce the weigh and subsequently the cost of production without comprising the structural integrity of the AFO. From the study, by the implementing structural optimisation, specifically the topology method, the end design exhibits a cost reduction 3% and an actual improvement in structural integrity particularly the factor of safety from 0.289 before optimization to 4.671 after optimization suggesting a marked improvement. Therefore, this study has contributed to the body of knowledge by demonstrating that the proposed methodological framework is sound in the manufacture of individually customised AFO.

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LIST OF SYMBOLS

C_e	Execution Cost
C_{fp}	Prototype Cost
C_m	Material Cost
C_p	Processing Cost
C_{pc}	Personal Computer
C_{pp}	Post-Processing Cost
C_{sl}	Software License Cost
F_{BW}	Body Weight Force
F_{CTC}	Leg to Shank Contact Force
F_R	Ground Reaction Force
F_a	Ankle Stabilising Force
L_{hind}	End of Heel Moment Length
M_a	Ankle Stabilising Moment
M_b	Push Off Moment
M_m	Maintenance Cost Per Month
PC_e	PC Energy Consumption Hour Rate
P_{bp}	Bowl Price
P_e	Machine Energy Consumption Rate Per Hour
P_{kh}	Local Average Energy Specific Cost
P_{kh}	Local Average Energy Specific Cost
P_m	Specific Cost Per Model Material Volume
P_{mat}	Specific Material Cost Per Spool
P_{mp}	Machine Price
P_s	Specific Cost Per Support Material Volume
P_{ub}	Energy Consumption Rate Per Hour for the Ultrasonic Bowl
R_x	Rotation in X-Axis
R_y	Rotation in Y-Axis
R_z	Rotation in Z-Axis
S_c	Soap Cost Per Washing Time at Post-Processing
S_r	Soap Rate Per Package

T_p	Designer Processing Time
T_{pm}	Model Permanence Time Inside the Ultrasonic Bowl
T_x	Translation in X-Axis
T_y	Translation in Y-Axis
T_z	Translation in Z-Axis
V_c	Model/Support Material Volume Per Cartridge
V_m	Model Volume Utilised
V_s	Support Volume Utilised
V_{total}	Total Weight Per Spool
V_{util}	Total Material Utilised
W_{at}	Bowl Availability Time Per Year
W_{at}	Machine Availability Time Per Year
W_{at}	PC Availability
m_{leg}	Leg Shank Mass
r'_f	Machine Running Cost Per Hour
θ_1	Shank Contact Angel
θ_2	Dorsiflexion Angle
σ_{MAX}	Maximum Stress
σ_{YIELD}	Yield Stress
ω_0	Operator Cost Per Hour
ω_d	Designer Cost Per Hour
L	Moment Arm Length

LIST OF ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
AFO	Ankle Foot Orthosis
AM	Additive Manufacturing
CAD	Computer Aided Design
CMM	Coordinate Measurement Machine
EMG	Electromyography
FDM	Fused Deposition Modelling
FEA	Finite Element Analysis
PA	Polyamide
PC	Personal Computer
SLA	Stereo lithography
SLS	Selective Laser Sintering
SO	Structural Optimisation
STL	Stereo lithography File Format
UTS	Universal Testing System
UV	Ultraviolet

REFERENCES

- Ahn, S., Montero, M., Odell, D., Roundy, S., & Wright, P. K. (2002). Anisotropic material properties of fused deposition modeling ABS. *Rapid Prototyping Journal*, 8(4), 248–257. <https://doi.org/10.1108/13552540210441166>
- Ashtankar, K. M., Kuthe, A. M., & Rathour, B. S. (2013). Effect of Build Orientation on Mechanical Properties of Rapid Prototyping (Fused Deposition Modelling) Made Acrylonitrile Butadiene Styrene (ABS) Parts. In *Volume 11: Emerging Technologies* (Vol. 11, p. V011T06A017), 1-7. <https://doi.org/10.1115/IMECE2013-63146>
- Becker Orthopedic Appliance. (2003). *Thermoforming Guide*. Troy, Michigan: Becker Orthopedic
- Belegundu, A., & Chandrupatla, T. (2011). *Optimization Concepts and Applications in Engineering*. Upper Saddle River, NJ: Prentice Hall.
- Bellini, A., & Güçeri, S. (2003). Mechanical characterization of parts fabricated using fused deposition modeling. *Rapid Prototyping Journal*, 9(4), 252–264. <https://doi.org/10.1108/13552540310489631>
- Bendsoe, M. P., & Bendsoe, M. P. (1995). *Optimization of Structural Topology, Shape and Material*. Retrieved 12 March, 2017, from <http://www.ltu.se/omltu/ledigajobb/d21826/d21828/1.48687>
- Castiblanco, O., & Shareef, I. (2017). Optimization of StepLock ® Orthotic Knee Joint Design. *Procedia Manufacturing*, 10, 622-633. doi:10.1016/j.promfg.2017.07.065
- Cai, L., Byrd, P., Zhang, H., Schlarman, K., Zhang, Y., Golub, M., & Zhang, J. (2016). Effect of Printing Orientation on Strength of 3D Printed ABS Plastics. *TMS 2016: 145th Annual Meeting & Exhibition: Supplemental Proceedings*, 199-204. doi:10.1002/9781119274896.ch25
- Center for Economics and Business Research Ltd. (2011). *The Economic Impact of Improved Orthotic Services Provision*. London: British Healthcare Trades Association.
- Das, S. C., Ranganathan, R., & N., M. (2018). Effect of build orientation on the strength and cost of PolyJet 3D printed parts. *Rapid Prototyping Journal*. doi:10.1108/rpj-08-2016-0137

- European Powder Metallurgy Association. (2015). *Introduction To Additive Manufacturing Technology* (1st ed.). Retrieved 21 December, 2016 from <https://www.epma.com/640-introduction-to-additive-manufacturing-technology-brochure>
- Faustini, M. C., Neptune, R. R., Crawford, R. H., & Stanhope, S. J. (2008). Manufacture of Passive Dynamic Ankle–Foot Orthoses Using Selective Laser Sintering. *IEEE Transactions on Biomedical Engineering*, 55(2), 784-790. <https://doi.org/10.1109/tbme.2007.912638>
- Gibson, I., & Bártolo, P. J. (2011). *History of Stereolithographic Process*. Boston, MA: Springer. <https://doi.org/10.1007/978-0-387-92904-0>
- Gibson, K. S., Woodburn, J., Porter, D., & Telfer, S. (2014). Functionally optimized orthoses for early rheumatoid arthritis foot disease: A study of mechanisms and patient experience. *Arthritis Care and Research*, 66(10), 1456–1464. <https://doi.org/10.1002/acr.22060>
- Hawke, F., Burns, J., Radford, J., & du Toit, V. (2008). Custom foot orthoses for the treatment of foot pain: a systematic review. *Journal of Foot and Ankle Research*, 11(1), 43-46. <https://doi.org/10.1186/1757-1146-1-S1-O46>
- Mello, Martins, Parra, B., Pamplona, Salgado, E., & Seguso, R. (2010). Systematic proposal to calculate price of prototypes manufactured through rapid prototyping an FDM 3D printer in a university lab. *Rapid Prototyping Journal*, 16(6), 411–416. <https://doi.org/10.1108/13552541011083326>
- Hopkinson, N., & Dickens, P. (2003). Analysis of rapid manufacturing - Using layer manufacturing processes for production. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 217(1), 31–39. <https://doi.org/10.1243/095440603762554596>
- Hull, C. (1986). United States Patent No. 4,575,330.
- ICRC. (2010). *Manufacturing Guidelines Ankle-Foot Orthosis*. International Committee of the Red Cross, ICRC. Retrieved 3 July, 2016 from <https://www.icrc.org/eng/assets/files/other/eng-afo-2010.pdf>
- Jang, G. W., Kim, K. J., & Kim, Y. Y. (2008). Integrated topology and shape optimization software for compliant MEMS mechanism design. *Advances in Engineering Software*, 39(1), 1–14. <https://doi.org/10.1016/j.advengsoft.2006.12.003>

- Jin, Y. A., Plott, J., Chen, R., Wensman, J., & Shih, A. (2015). Additive manufacturing of custom orthoses and prostheses - A review. *Procedia CIRP*, 36, 199–204. <https://doi.org/10.1016/j.procir.2015.02.125>
- Jumani, M. S., Shaikh, S., & Khaliqdina, J. H. (2013). Stereolithography Technique for Fabrication of Custom Foot Orthoses: A Cost Benefit Analysis. *Sindh University Research Journal - SURJ (Science Series)*, 45(4), 749–754.
- Kalyani, V. L., & Bansal, D. (2016). Future Communication Technology : A Comparison Between Claytronics And 3-D Printing, 564(2015), 8–28. Retrieved from <http://oaji.net/articles/2016/2725-1472722726.pdf>
- Kilian, S., Zander, U., & Talke, F. E. (2003). Suspension modeling and optimization using finite element analysis. *Tribology International*, 36(4–6), 317–324. [https://doi.org/10.1016/S0301-679X\(02\)00204-9](https://doi.org/10.1016/S0301-679X(02)00204-9)
- Krone, R., & Schuster, P. (2006). An Investigation on the Importance of Material Anisotropy in Finite-Element Modeling of the Human Femur. *SAE Technical Paper Series*, 3(1), 18-24. <https://doi.org/10.4271/2006-01-0064>
- Lin, Y., Lin, K., & Chen, C. (2017). Evaluation of the walking performance between 3D-printed and traditional fabricated ankle-foot orthoses— A prospective study. *Gait & Posture*, 3(1), 1–2. <https://doi.org/10.1016/j.gaitpost.2017.06.471>
- Marro, A., Bandukwala, T., & Mak, W. (2016). Three-Dimensional Printing and Medical Imaging: A Review of the Methods and Applications. *Current Problems in Diagnostic Radiology*, 45(1). <https://doi.org/10.1067/j.cpradiol.2015.07.009>
- Martins, E. (2003). *Contabilidade de Custos*. São Paulo (SP): Atlas.
- Matthew, C., Mary-Ellen, A., & Keith, R. (2011). Reliability of capturing foot parameters using digital scanning and the neutral suspension casting technique. *Journal of Foot and Ankle Research*, 4(1), 9. <https://doi.org/10.1186/1757-1146-4-9>
- Mavroidis, C., Ranky, R. G., Sivak, M. L., Patrilli, B. L., DiPisa, J., Caddle, A., Bonato, P. (2011). Patient specific ankle-foot orthoses using rapid prototyping. *Journal of Neuro Engineering and Rehabilitation*, 8(1), 1. <https://doi.org/10.1186/1743-0003-8-1>
- Olason, A., & Tidman, D. (2010). *Methodology for Topology and Shape Optimization in the Design Process*, 74 - 106. Göteborg: Chalmers University of Technology.

- Organisation Internationale de Normalisation (ISO). (1989). *Prosthetics and orthotics : vocabulary. Part 1, General terms for external limb prostheses and external orthoses = Prothèses et orthèses : vocabulaire. Partie 1, Termes généraux pour prothèses de membre et orthèses externes. TT - (1st ed.). International standard ISO= Norme internationale ISO; 8549-1; Normes ISO (Organisation internationale de normalisation); 8549-1. TA -*. Genève, Switzerland : International Organization for Standardization,.
- Palermo, E. (2013). Fused Deposition Modeling: Most Common 3D Printing Method, 2016(11th March). Retrieved March 11, 2017, from <http://www.livescience.com/39810-fused-deposition-modeling.html>
- Pallari, J. H. P., Dalgarno, K. W., & Woodburn, J. (2010). Mass customization of foot orthoses for rheumatoid arthritis using selective laser sintering. *IEEE Transactions on Biomedical Engineering*, 57(7), 1750–1756. <https://doi.org/10.1109/TBME.2010.2044178>
- Park, J. H., Noh, S. C., Jang, H. S., Yu, W. J., Park, M. K., & Choi, H. H. (2009). The Study of Correlation between Foot-pressure Distribution and Scoliosis. *IFMBE Proceedings 13th International Conference on Biomedical Engineering*, 974-978. https://doi.org/10.1007/978-3-540-92841-6_241
- Peter W. Christensen, A. K. (2009). *An Introduction to Structural Optimization*. Berlin: Springer Netherland.
- Plagenhoef, S., Evans, F. G., & Abdelnour, T. (1983). Anatomical Data for Analyzing Human Motion. *Research Quarterly for Exercise and Sport*, 54(2), 169–178. <https://doi.org/10.1080/02701367.1983.10605290>
- Pucci, J. U., Christophe, B. R., Sisti, J. A., & Connolly, E. S. (2017). Three-dimensional printing: technologies, applications, and limitations in neurosurgery. *Biotechnology Advances*, 35(5), 521–529. <https://doi.org/10.1016/j.biotechadv.2017.05.007>
- Rao, N., Wening, J., Hasso, D., Gnanapragasam, G., Perera, P., Srigiriraju, P., & Aruin, A. S. (2014). The Effects of Two Different Ankle-Foot Orthoses on Gait of Patients with Acute Hemiparetic Cerebrovascular Accident. *Rehabilitation Research and Practice*, 2014, 1–7. <https://doi.org/10.1155/2014/301469>
- Saleh, J. M. (2013). *Cost Modelling of Rapid Manufacturing Based Mass Customisation System For Fabrication of Custom Foot Orthoses* (Doctoral Dissertation). Retrieved 7 February, 2016, from <https://theses.ncl.ac.uk/dspace/handle/10443/2193>

- Schmid, M., Kleijnen, R., Vetterli, M., & Wegener, K. (2017). Influence of the Origin of Polyamide 12 Powder on the Laser Sintering Process and Laser Sintered Parts. *Journal of Applied Sciences*, 7(5), 462. <https://doi.org/10.3390/app7050462>
- Schrank, E. S., & Stanhope, S. J. (2011). Dimensional accuracy of ankle-foot orthoses constructed by rapid customization and manufacturing framework. *Journal of Rehabilitation Research and Development*, 48(1), 31–42. <https://doi.org/10.1682/JRRD.2009.12.0195>
- Singh, S., Sachdeva, A., & Sharma, V. S. V. (2012). Investigation of Dimensional Accuracy / Mechanical Properties of Part Produced by Selective Laser Sintering. *International Journal of Applied Science and Engineering*, 1, 59–68. <https://doi.org/10.1081/j.asce.39941>
- Singiresu S. Rao. (2009). *Engineering Optimization: Theory and Practice*. New Jersey: John Wiley & Sons
- Sutradhar, A., Paulino, G. H., Miller, M. J., & Nguyen, T. H. (2010). Topological optimization for designing patient-specific large craniofacial segmental bone replacements. *Proceedings of the National Academy of Sciences*, 107(30), 13222–13227. <https://doi.org/10.1073/pnas.1001208107>
- Taha, Z., Aris, M. A., Ahmad, Z., Hassan, M. H. A., & Sahim, N. N. (2013). A Low Cost 3D Foot Scanner for Custom-Made Sports Shoes. *Applied Mechanics and Materials*, 440, 369–372. <https://doi.org/10.4028/www.scientific.net/AMM.440.369>
- Telfer, S., Abbott, M., Steultjens, M., Rafferty, D., & Woodburn, J. (2013). Dose-response effects of customised foot orthoses on lower limb muscle activity and plantar pressures in pronated foot type. *Gait and Posture*, 38(3), 443–449. <https://doi.org/10.1016/j.gaitpost.2013.01.012>
- Telfer, S., Pallari, J., Munguia, J., Dalgarno, K., McGeough, M., & Woodburn, J. (2012). Embracing additive manufacture: implications for foot and ankle orthosis design. *BMC Musculoskeletal Disorders*, 13(1), 84-91. <https://doi.org/10.1186/1471-2474-13-84>
- Telfer, S., & Woodburn, J. (2010). The use of 3D surface scanning for the measurement and assessment of the human foot. *Journal of Foot and Ankle Research*, 3(1), 19. <https://doi.org/10.1186/1757-1146-3-19>
- Tenaga Nasional Berhad. (2014). TNB Electricity Tariff Rates. Retrieved March 3, 2017, from

https://www.tnb.com.my/assets/files/Tariff_Rate_Final_01.Jan.2014.pdf

- Trotter, L. C., & Pierrynowski, M. R. (2008). The short-term effectiveness of full-contact custom-made foot orthoses and prefabricated shoe inserts on lower-extremity musculoskeletal pain: a randomized clinical trial. *Journal of the American Podiatric Medical Association*, 98(5), 357–363. <https://doi.org/98/5/357> [pii]
- Tymrak, B. M., Kreiger, M., & Pearce, J. M. (2014). Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions. *Materials and Design*, 58, 242–246. <https://doi.org/10.1016/j.matdes.2014.02.038>
- Upadhyay, K., Dwivedi, R., & Singh, A. K. (2017). Determination and Comparison of the Anisotropic Strengths of Fused Deposition Modelling P400 ABS. *Advances in 3D Printing & Additive Manufacturing Technologies*, 9-28. <https://doi.org/10.1007/978-981-10-0812-2>
- Vidakis, N., Vairis, A., Petousis, M., Savvakis, K., & Kechagias, J. (2016). Fused Deposition Modelling Parts Tensile Strength Characterisation. *Academic Journal of Manufacturing Engineering*, 14(2), 87–94.
- Walbran, M., Turner, K., & McDaid, A. J. (2016). Customized 3D printed ankle-foot orthosis with adaptable carbon fibre composite spring joint. *Cogent Engineering*, 3(1), 1–11. <https://doi.org/10.1080/23311916.2016.1227022>
- Wong, M., Wong, D., & Wong, A. (2010). A Review of Ankle Foot Orthotic Interventions for Patients with Stroke. *The Internet Journal of Rehabilitation*, 1(1), 2-4. <https://doi.org/10.5580/26b3>
- Wong, K. V., & Hernandez, A. (2012). A Review of Additive Manufacturing. *ISRN Mechanical Engineering*, 2012, 1–10. <https://doi.org/10.5402/2012/208760>
- Xu, F., Wong, Y. S., & Loh, H. T. (2000). Toward generic models for comparative evaluation and process selection in rapid prototyping and manufacturing. (2002). *Journal of Manufacturing Systems*, 21(6), 471. [https://doi.org/10.1016/s0278-6125\(02\)80076-0](https://doi.org/10.1016/s0278-6125(02)80076-0).
- Yasuhiro Mine, Takamichi Takashima, H. F. (2006). *Study of the Design Method of an Ankle-Foot-Orthosis. Mechatronics for Safety, Security and Dependability in a New Era*. Elsevier Ltd. <https://doi.org/10.1016/B978-008044963-0/50007-2>