DESIGN ANALYSIS AND STRUCTURAL OPTIMISATION OF A RIGID ANKLE FOOT ORTHOSIS

MOHD YASHIM WONG PAUL TZE

Master of Science

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

(Supervisor's Signature)

Full Name : PROF DR ZAHARI BIN TAHA

Position : PROFESSOR

Date :

(Co-supervisor's Signature)

Full Name :

Position :

Date :

STUDENT’S DECLARATION

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.

____

(Student’s Signature)

Full Name : MOHD YASHIM WONG PAUL TZE
ID Number : MFM14001
Date :

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MOHD YASHIM WONG PAUL TZE

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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 mengintegrasi 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, pengurangkan kos sebanyak 3% dan peningkatan 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 Zotrax 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.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

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 Permenance 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

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