2014 3rd International Conference on Environment Energy and Biotechnology
IPCBEE vol.70 (2014) © (2014) IACSIT Press, Singapore
DOI: 10.7763/IPCBEE. 2014. V70. 16

Development of Patient Specific Ankle Foot Orthosis through 3D Reconstruction

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Abstract. Designing and manufacturing methods of assistive devices involve manual techniques such as casting molding of the limbs to be treated. Such methods require skillful labor and often based on trial and error rather than systematic engineering and evidence based principles. 3D scanning allows computer aided design tools to be incorporated, however, this approach also relies on the external model. It is difficult to infer axes of rotation of joints from external models. In this article we have demonstrated an approach of designing ankle foot orthosis (AFO) with commercially available ankle joint that facilitate simultaneous viewing of external and skeletal geometry of the limbs. The output model of AFO is compatible with computer aided manufacturing.

Keywords: AFO, design, 3D model

1. Introduction

Patients suffering from stroke and other neurological disorder have muscle weakness and reduced walking capability. Assistive devices such as ankle foot orthoses (AFO) are prescribed to compensate such impairments. Patient specific orthotic device designing and fabrication requires manual techniques such as casting, making moulds of the limbs to be treated and vacuum forming [1], [2]. Such design and fabrication processes are time consuming, requires skilled labour and often cumbersome for the patients. Moreover, such techniques are based on trial and error rather than systematic engineering and evidence-based principles. Manufacturing of orthotics in these techniques relies on experience of orthotists as the axes of rotation of joints are not inferable from external observations. The axes of rotation are partially specified by the skeletal structure.

Development of digital models of freeform surfaces of the anatomy of human body parts by 3D scanning allows incorporating computer aided design. Several articles [1]-[3] are found exploring the feasibility of computer aided design and manufacturing of AFOs based on external modelling. Darling and Sun [4] first designed a simple AFO, not intended to clinical application, through 3D reconstruction of both external and skeletal structure. In our research we have collected CT-scan data of two healthy subjects and developed solid model of external and skeletal geometry through 3D reconstruction. Based on those model computer aided design of AFO for both subjects with commercially available ankle joint (Dream Brace) were developed. Such design of AFO is compatible to computer aided manufacturing and also discards moulding etc. Dream Brace ankle joint of Ortho Inc. uses one way frictional clutch to prevent drop foot, which makes the design feasible for clinical application.

2. Materials and Methods

2.1. Data acquisition

CT-scanning of two adult healthy subjects was accomplished keeping the ankle in neutral position. The imaging data of two subjects' left leg were converted to 3D model through reconstruction. 3D reconstruction

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of CT-scan data in DICOM format was performed using MIMICS software (Materialise NV). For each data set, two separate models were developed for soft tissues and bony dense tissues (Fig. 1). To get a noise free model segmentation, region growing, edit mask operations were performed. 3D models were then exported to Abaqus (ABAQUS Inc.) mesh (.inp) format for landmarking and parameterization, while both the software shared the common coordinate system.

2.2. Parameterization and orthotic design

The orthotic was designed based on the fitting parameters established on the skeletal and soft tissue models. It was accomplished by establishing orthogonal sets of plane along the models based on the coordinated system recommended by the Standardization and Terminology Committee (STC) of the International Society of Biomechanics (ISB) [5].

The lower leg of the two subjects were treated as two rigid components (foot and shank) attached by one-degree-of-freedom hinge. There were three components in the orthotic design; foot plate, side bar and calf support.

The parameterization of foot plate was based on the coordinate system B0-S0-H0, while B0 represents the vertical plane tangent to the lateral side of the heel, S0 stands for horizontal plane tangent to the sole of the foot and H0 is a vertical plane tangent to the anterior part of the heel (Fig. 2). All the features of the foot plate are dependent on the offset distance of the planes from those base planes. The length of the foot plate is two third of the foot length. The heel component is designed on the basis of the Dream Brace joint kit. The standardization of the proximal calf support is based on the coordinate system LF0-LS0-LT0, where LF0 plane is the parallel to frontal plane of tibia-fibula and tangent to the posterior side of the calf. LS0 is parallel to sagittal plane and tangent to lateral edge of the lower leg and LT0 is parallel to transverse plane at inter-melleolar point located midway between medial malleolus and lateral malleolus. The width of this component is 35 millimeter and the circumference is 40 millimeter plus half of the circumference of the calf.

Fig. 1: 3D model of lower limb.

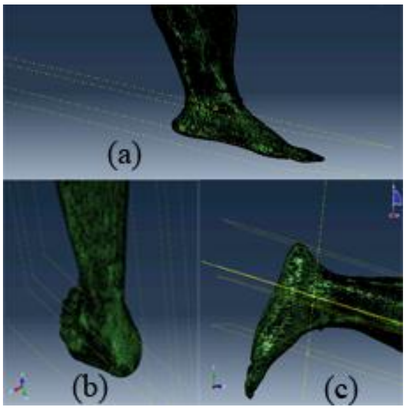

Fig. 2: (a) S offsets (b) B offsets (c) H offsets

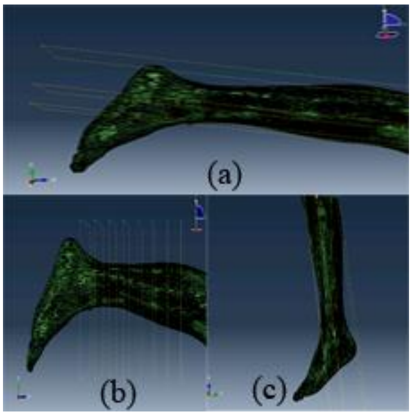

Fig. 3: (a) LF offsets (b) LT offsets (c) LS offsets

Side bar of the orthotic was designed based on the mid line of leg in anterior posterior position. The parameterization of the mid line is also based on the LF0-LS0-LT0 (Fig. 3). Five evenly spaced offset planes of LT0 were drawn in between the mid-point of calf support and ankle rotation axis to detect the mid line of the lower leg.

The orthotic was designed in Solidworks 2010 (Dassault Systèmes SolidWorks Corp.) based on the fitting parameters (Fig. 4). The design table tool of Solidworks software facilitate to insert the parameters for each subjects and change the design of the orthotic device accordingly.


Fig. 4: CAD model of AFO

3. Result and Discussion

3.1. Foot plate

Table 1: Designation and distances of offset planes for foot plate

Plane	Description	Offsets (mm) Subject 1	Offsets (mm) Subject 2
B0	Vertical plane tangent to the lateral edge of the foot	0	0
B1	The lateral edge of the heel	14.4	15.6
B2	The axis of rotation of ankle from skeletal model	34.44	36.1
B3	The medial edge of the hill	72.7	75.2
B4	Vertical plane tangent to medial edge	85.1	87.5
S0	Horizontal plane tangent to sole of the foot	0	0
S1	The axis of rotation of ankle for dorsiflexion	85.65	82.1
S2	Derived parameter, height of fitting position of dream brace ankle joint (S1-32.5)	53.15	49.6
H0	Vertical plane tangent to the posterior edge of heel	0	0
H1	The axis of rotation for dorsiflexion	66.63	69.20
H2	The edge first meta tarsal head	235	217.50
H3	Derive parameter, foot plate length (3/4 H2)	176.30	163.13

3.2. Sidebar

An offset plane (LT5) from LT0 was drawn 20 millimetre below the proximal deepest point of the lower leg. The distance in between these two planes is 317 millimetre for subject 1 and 305 millimetre for subject 2. Four other planes (LT1, LT2, LT3, and LT4) parallel to LT0 were drawn in equal interval in between LT0 and LT5.

Table 2: Designation and distances of offset planes for sidebar

Plane	Description	Offset (mm) Subject 1	Offset (mm) Subject 2
LF0	The parallel plane to the frontal plane of tibia-fibula and tangent to the posterior side of the calf	0	0
LF1	Mid-point in between the anterior and posterior edge intersection point of LF0, ideally coplanar with frontal plane	68.25	71.43
LF2	Mid-point in between the anterior and posterior edge intersection point of LT1	65.25	68.90
LF3	Mid-point in between the anterior and posterior edge intersection point of LT2	61.25	62.90
LF4	Mid-point in between the anterior and posterior edge intersection point of LT3	55.65	57.26
LF5	Mid-point in between the anterior and posterior edge intersection point of LT4	50.25	52.98
LF6	Mid-point in between the anterior and posterior edge intersection point of LT5	52.85	55.02
LS0	Parallel to sagittal plane and tangent to lateral edge of the lower leg	0	0
LS1	At the intersection point of the LT0 and lateral edge of the lower leg	40	37
LS2	At the intersection point of the LT0 and medial edge of the lower leg	78.1	82.1
LS3	At the intersection point of the LT1 and lateral edge of the lower leg	37.7	34.3
LS4	At the intersection point of the LT1 and medial edge of the lower leg	67.2	61.3
LS5	At the intersection point of the LT2 and lateral edge of the lower leg	17.5	14.23
LS6	At the intersection point of the LT2 and medial edge of the lower leg	75.5	79.3
LS7	At the intersection point of the LT3 and lateral edge of the lower leg	9	8.9
LS8	At the intersection point of the LT3 and medial edge of the lower leg	66	64.2
LS9	At the intersection point of the LT4 and lateral edge of the lower leg	0	0
LS10	At the intersection point of the LT4 and medial edge of the lower leg	61	59.4
LS11	At the intersection point of the LT5 and lateral edge of the lower leg	5	6.4
LS12	At the intersection point of the LT5 and medial edge of the lower leg	66	64

3.3. Shank support

LT5 is intended to be the top of the orthotic as well as the shank support. Another plane LT6, 35 millimetre offset from LT5 in distal direction, was drawn as to define the bottom of the shank support.

Table 3: Designation and distances of offset planes for shank support

Plane	Description	Offset (mm) Subject 1	Offset (mm) Subject 1
LF0	The parallel plane to the frontal plane of tibia-fibula and tangent to the posterior side of the calf	0	0
LF7	At the intersection point of posterior edge of calf and LT5	2.25	2
LF8	At the mid-point in between posterior and anterior edges intersection points of LT5 with calf	52.85	56
LF9	Derived parameter, (LF8-LF70)/2	25.125	27
LF10	Derived parameter, (LF8 + 20)	72.85	76
LS13	At the intersection point of LT6 and lateral most edge of the calf	4	2.5
LS14	At the intersection point of LT6 and medial most edge of the calf	139	148
LS15	At the intersection point of LT6, LF9 and lateral edge of the calf	18	21
LS15	At the intersection point of LT6, LF9 and medial edge of the calf	128	135

Above table and description present the planes description, and offset distances of each parameter planes of the lower leg of two subjects. Fig. 4 shows the designed components of the ankle foot orthotic device.

The design technique demonstrated in this article has advantages over the traditional design techniques. Unlike external modelling methods, this method allows the clinicians to observe external and skeletal patient specific geometry simultaneously. Parameterization is a quicker process than casting and it facilitate incorporation of computer aided design tools. Although, this method is less cumbersome for patients, there is an issue of concern, as CT-scan involves exposure of the limbs to ionizing radiation.

4. Conclusion

The method shows computer aided design approach for patient specific orthotic with commercially available AFO joint. The parameterization of 3D model of the limb to be treated allows rapid and intricate designing. The output of format of Solidworks might facilitate several freeform fabrication techniques.

5. Acknowledgement

This research is supported by UM High Impact Research Grant (UM.C/HIR/MOHE/ENG/28) from University of Malaya, Malaysia.

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