Finite Element Analysis of Trimmed Plastic Ankle-Foot Orthoses

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(Received 13 January 2016; received in revised form 31 May 2016; accepted 14 June 2016)

Abstract: The purpose of this study was to quantitatively analyze the stress and deformation that occur in plastic ankle-foot orthoses (PAFOs) during walking after it is trimmed. First, PAFOs with incorporated sensors were individually prepared for 2 patients with hemiplegia. Mechanical data were then obtained while individuals wore the PAFOs during walking. Here we report the results of mechanical data and finite element analysis of trimmed plastic ankle-foot orthoses worn by two patients with left-hemiplegia. The results could provide prosthetists with some suggestions for forming orthoses.

Keywords: Displacement, Finite Element Analysis, Gait Analysis, Plastic Ankle Foot Orthosis, Stress, Trimming

1. Introduction
Ankle-foot orthoses (AFOs) are important support tools for aiding walking by persons with sequelae of stroke. AFOs can be roughly divided into two types: plastic ankle-foot orthoses (PAFOs) and ankle-foot orthoses with metal struts. An investigation by Takashima et al. found that approximately 75% of AFOs are fabricated from plastic and 23% from metal [1]. Benefits related to appearance and light weights due to improvements in processing technology have resulted in increased PAFO prescriptions [2].

This study focuses on shoe-horn-type PAFO, which are in widespread use. Important points for consideration when manufacturing PAFOs include ease of bending at the ankle (flexibility), ankle joint angle, and sole length [3]. While these parameters can be varied during forming, the literature has suggested that it is sometimes difficult to determine which design is best suited to a particular user [4].

This is likely due, at least in part, to a lack of clear analysis of the effects of PAFO forming (trimming) on plastic flexibility and lower limb function [5]. Some ambiguity about the relation that PAFO form has with functionality and conformity evaluations for patients and devices is also reported [6-7].

Here, we first used a system for measuring device mechanics to gather data on walking with a PAFO. Based on the collected load data, we then used a 3D model of the measured device and finite element analysis (FEA) to investigate how the extent of trimming affects stress and deformation in the PAFO.

2. Method
2.1 Gait experiment
Table 1 shows the characteristics and Brunnstrom stage of the two hemiplegic patients who participated in this study. Brunnstrom stage which indicates paralysis level of patients' extremities is usually used for functional evaluations of patients in the medical community. Patient A had comparatively mild symptoms and patient B was able to walk independently without a cane but had comparatively severe symptoms. In this gait experiment, no instructions were given regarding stride length or walking speed, and the measurements were performed multiple times in an unforced manner at a walking pace according to the patient's own sensations. Additionally, three healthy volunteers simultaneously walked at a stride length and cadence matching that of the hemiplegic patients A and B. Table 2 shows the characteristics of the three healthy volunteers.

| Table 1 Characteristics of the hemiplegic patients |
|-----------------|-----------------|-----------------|
| Patient A | Patient B |
| Identification | | |
| Age | 62 | 68 |
| Sex | Woman | Man |
| Body weight | 65.1 kg | 68.1 kg |
| Walking times | 5 | 3 |
| U/E | V | III |
| L/E | V | IV |
| Finger | IV | III |
| L/E | V | IV |

※ Level of spasticity of upper extremity (U/E), finger, lower extremity (L/E)
1 (severely) < II < III < IV < V

| Table 2 Characteristics of the healthy volunteers |
|-----------------|-----------------|-----------------|
| Healthy person A | Healthy person B | Healthy person C |
| Age | 22 | 22 | 22 |
| Sex | Man | Man | Man |
| Body weight | 67.5 kg | 64.5 kg | 56.5 kg |
| Walking times | 5 | 5 | 5 |

Figure 1(a) shows the mechanical measurement system. As shown in Fig. 1(b), the device was divided into upper and lower portions in a way that did not disturb its structural function, and the separated device was connected via only a 6-axis force torque sensor.

Ethical approval was obtained from the ethics committee of Kindai University Graduate School of Biology-Oriented Science and Technology. Informed consent was obtained from all participants.
orthosis fabrication methods. And trimming of the inner surface is typically performed later as necessary, based on observation of the patient’s gait patterns.

The trimming was performed according to Sumiya et al. [8] and Hayakawa et al. [9] with trimming lines determined by the authors at 20%, 40%, and 60% relative to 100% being the height from the sole of the foot to the center of the lateral malleolus, as in Fig.3. The maximum radius of curvature was 25 mm. This technique allows trimming to be quantitatively assessed. Additionally, the outer shape of the orthoses was acquired by using an optical measurement device (Go!SCAN 3D, CREAFORM). The company indicates that the accuracy of the system is +0.022 mm and –0.026 mm which supposedly doesn’t suffer under the influence of our analysis.

To allow real-time load data measurements during device use, we installed 6-axis force sensors in three locations, two on the sole of the foot and one on the posterior calf, and a single-axis load cell in one location, on the device ankle belt. Finally, a flexible goniometer for measuring the ankle joint angle was installed along the lateral portion of the fifth metatarsal and the lateral portion of the fibula before the experiment was conducted.

2.2 Coordinate systems
Elements of the load vector follow the right-handed orthogonal coordinate system shown in Fig.2, with Fx in the direction of body load, Fy in the medial direction, and Fz in the posterior direction.

Fz: Posterior direction load
Fy: Medial direction load
Fx: Weight direction load
My: Moment around medial direction
Mx: Moment around weight direction
Mz: Moment around posterior direction

2.3 Finite element analysis and trimming
2.3.1 Trimming and form measurement
In consideration of safety, relatively thick, hard-to-bend devices are commonly prescribed first in conventional orthosis fabrication methods. And trimming of the inner

Fig. 1 Device mechanics measurement system and the separated device

(a) Mechanical measurement system
(b) The separated PAFO

Fig.2 Device coordinate system (left foot shown)

Fig. 2.3 Trimming line determination method

2.3.2 Finite element analysis
Finite element analysis was performed on the gait analysis results for each patient, focusing on the plantar flexion action at the initial stance phase. Information regarding the PAFO shapes used for FEA is indicated in Table 3. All elemental type is shell. The thickness of the orthoses used by patients A and B was measured by ultrasonic thickness meter (DC-C2000, SATO commercial Co., Ltd.). Ten points at the lateral and medial malleolus of the orthoses were averaged to obtain the PAFO thickness. The thickness of the PAFO used by patient A in the gait test was 4.3 mm, and that of patient B was 3.7 mm. If the PAFO, however, is trimmed, we can’t use it for later experiments. Therefore we only use the dedicated PAFO for trimming in order to research about verification of consistency between experiment results and calculated results. The PAFO thickness used in the simulation consistency test for patient B was 3.4 mm. The polypropylene from which the PAFOs were made had a Young’s modulus of 2030 MPa and a Poisson’s ratio of 0.4103 which are used for FEA. The former value was obtained experimentally, and the latter value was taken from reported [9] data. As a constraint condition, the heel was completely constrained. For the load condition, the force vector imparted as an external force to the orthoses during walking was used, as obtained from the calf sensor. In these simulations, we adopt ANSYS (version 12.0) algorithm (static and implicit method) all of
which converged conditionally under our proposed conditions. About 3 minutes is needed for usual FEA calculation. The amount force is dispersedly loaded at 20 nodes around the specific point which is decided from kinematic data from a 6-axis sensor. Every heel position nodes of a foot is restricted about translation and rotation.

Table 3 Numbers of elements and nodes in the device forms

<table>
<thead>
<tr>
<th>Patient</th>
<th>0% trimming</th>
<th>20% trimming right</th>
<th>20% trimming left</th>
<th>20% trimming double</th>
<th>40% trimming right</th>
<th>40% trimming left</th>
<th>40% trimming double</th>
<th>60% trimming right</th>
<th>60% trimming left</th>
<th>60% trimming double</th>
</tr>
</thead>
<tbody>
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<td>Elements</td>
<td>14042</td>
<td>14448</td>
<td>14420</td>
<td>13073</td>
<td>13721</td>
<td>13456</td>
<td>12532</td>
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<td>12438</td>
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<td>Nodes</td>
<td>7989</td>
<td>8186</td>
<td>7967</td>
<td>7238</td>
<td>7596</td>
<td>7461</td>
<td>6950</td>
<td>7453</td>
<td>7415</td>
<td>6912</td>
</tr>
</tbody>
</table>

3. Results
3.1 Gait analysis results
Stride length and cadence were determined from video. Patient A had a stride length of 30 cm and a cadence of 50 steps/min; patient B had a stride length of 20 cm and a cadence of 60 steps/min. The healthy volunteers walked at conditions (stride length and cadence) matching those of the patients. For the test results, Fig.4 shows Fz, the load in the posterior direction for hemiplegic patient A; Fig.5 shows the ankle joint angle for patient A; Fig.6 shows Fz for patient B; and Fig.7 shows the ankle joint angle for patient B. Figures 8 and 9 show Fz and the ankle joint angle, respectively, for the three healthy volunteers matched to patient A. Figures 10 and 11 do the same for the three healthy volunteers matched to patient B.
above the center of the sensor installed at the calf section of the orthosis. A force was generated at that location of (Fx, Fy, Fz) = (32.1, -1.7, 73.3) N, and the ankle joint angle at that moment was observed from the flexible goniometer to be 3.7°. The maximum load vector, the test device shown in Fig. 13 was used to investigate the amount of displacement of the 3.4 mm thick PAFO when subjected to the maximum plantar flexion load obtained from the gait analysis was measured in each actual PAFO trimming state. Seven trimming methods were used, which are listed in Table 4. Figure 14 shows the actual test values and calculated results for equivalent stress and strain. Here is defined as the highest value of the sum of squares of the respective vector components.

3.2 Verification of consistency between experiment results and calculated results
To verify the validity of FEA, we compared linear and nonlinear FEA (large deformation) analysis values with strain values for loads applied using up to 6 kg weights in 1 kg increments. Figure 12 shows the results. From the figure, we can see that the experimental and calculated results generally agree, but that values from the nonlinear analysis are slightly closer to the experimental results than those from the linear analysis. Accordingly, we decided to use nonlinear FEA in our analysis.

Furthermore, to investigate the state of deformation when the PAFO was stressed by the maximum plantar flexion load vector, the test device shown in Fig. 13 was used to investigate the amount of displacement of the 3.4 mm thick PAFO used by hemiplegic patient B. The amount of PAFO deformation was taken as the amount of displacement in the Z direction of the position of a measurement point at the center of the 6-axis force sensor installed at the calf. Also, to determine the actual increase in displacement resulting from PAFO trimming, the amount of displacement when subjected to the maximum plantar flexion load obtained from the gait analysis was measured in each actual PAFO trimming state. Seven trimming methods were used, which are listed in Table 4. Figure 14 shows the actual test values obtained from each trimming method, as well as the simulation values obtained using the FEA. As a result, the actual test values and the theoretical values were found to nearly coincide with each other without the result of trimming No.7. We considered that a large deformation was observed when orthosis was trimmed a large amount such as No.7. FEA was, however, found to yield realistic values in general without a large deformation. [10]
3.3 Results of finite element analysis

Below we present simulation results for equivalent stress and displacement from nonlinear FEA when maximum plantar flexion load is applied to the device after medial, lateral, and both-sides trimming. Although we obtained stress distribution diagrams and displacement diagrams for both patients A and B, here we present the results for patient B only. Figures 15–17, respectively, show stress distributions after right-side, left-side, and both-sides trimming. Figures 18–20 similarly show displacement diagrams for each trimming.

![Device for reproducing maximum plantar flexion load](image)

![Trimming method number allocation](image)

![Comparison of experimental values, linear FEA values, and nonlinear FEA values](image)

![Stress distribution diagrams for patient B](image)
and maximum stress (SMX) according to trimming line are
how the amount of deformation at the center of the 6-axis
spread to the top as well.
PAFO when greater bilateral trimming was performed.
relatively more concentrated at the medial malleolus of the
the uniform stress distribution was observed to become
uniformly at the inner and outer malleolus sections at each
trimming level from 0% to 60% in increments of 20%. Also,
uniform stress distribution was observed to become
relatively more concentrated at the medial malleolus of the
patient A, which was taken to be representative, was checked.
Comparing the plantar/dorsal flexion load with the ankle joint
angles of the healthy volunteers, as indicated in Figs. 8–11, a
tendency was noted in bilateral trimming for a
patient A and B resulting from trimming as indicated in
Figures 21, 22, and 23 show the results of investigating

Maximum deformation (DMX), minimum stress (SMN) and maximum stress (SMX) according to trimming line are shown in Table 5.

<table>
<thead>
<tr>
<th>Trim (%)</th>
<th>DMX (mm)</th>
<th>SMN [Pa]</th>
<th>SMX [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right</td>
<td>0</td>
<td>0.026259</td>
<td>9.93E-07</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.029139</td>
<td>9.93E-07</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>0.030256</td>
<td>9.93E-07</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.040323</td>
<td>9.93E-07</td>
</tr>
<tr>
<td>Left</td>
<td>0</td>
<td>0.026259</td>
<td>9.93E-07</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.024769</td>
<td>9.93E-07</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>0.02514</td>
<td>9.93E-07</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.026128</td>
<td>9.93E-07</td>
</tr>
<tr>
<td>Both</td>
<td>0</td>
<td>0.026259</td>
<td>9.93E-07</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.029139</td>
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<tr>
<td></td>
<td>60</td>
<td>0.040323</td>
<td>9.93E-07</td>
</tr>
</tbody>
</table>

DMX: Max Deformation, SMN: Min Stress, SMX: Max Stress

From the results above, we can see the following. In the PAFO of hemiplegic patient A, stress was distributed nearly uniformly at the inner and outer malleolus sections at each trimming level from 0% to 60% in increments of 20%. Also, the uniform stress distribution was observed to become relatively more concentrated at the medial malleolus of the PAFO when greater bilateral trimming was performed. Furthermore, it could be confirmed that the stress that was distributed in the direction of the bottom inside of the PAFO spread to the top as well.

Figures 21, 22, and 23 show the results of investigating how the amount of deformation at the center of the 6-axis force sensor changed as a result of trimming, focusing on the Z direction, the plantar flexion direction.

4. Discussion
Comparing the plantar/dorsal flexion load with the ankle joint angles of the healthy volunteers, as indicated in Figs. 8–11, a tendency can be noted by examining Fig.4, which shows the data for patient A, who had relatively mild symptoms. This tendency was toward a lower plantar flexion load and a greater dorsal flexion load. Meanwhile, a tendency can be noted in Fig.6, which shows the data for patient B, toward a lower plantar and dorsal flexion load. The angle data (Figs.5 and 7) exhibited a similar tendency to the load data.

Next, the amount of stress and deformation in the PAFOs when subjected to the maximum plantar flexion load of patient A, which was taken to be representative, was checked. First, it was found that greater right-side trimming caused spreading in the area exhibiting a distribution of stress downwards from the medial malleolus. Meanwhile, greater
left-side trimming was found to cause the spreading of the stress distribution area, not only in the downward direction but also in the upward direction of the orthosis. Furthermore, a tendency was noted in bilateral trimming for a comparatively high stress distribution to spread to the bottom and top of the medial side of the orthosis relative to the medial and lateral malleoli and the tendo calcaneus.

Next, the PAFO displacement amounts for hemiplegic patients A and B resulting from trimming as indicated in Figs. 21, 22, and 23 exhibited an increase resulting from greater trimming. A dramatic increase in displacement was noted for both the patients at a bilateral trimming amount of 40–60%, as shown in Fig. 21.

From these results, we recognize that it is possible to control concentration of stresses and deformation amounts in operation of trimming to the orthosis. Fig. 24 shows the flowchart of orthotic modification using simulation software in summarization of our discussion.

![Flowchart of orthosis modification using simulation](image)

### 5. Conclusion

The results of this study are summarized as follows:

Gait analysis showed that for both patients there was a load vector in a somewhat lateral-facing direction originating from a position slightly medial from where the sensor was installed, though the value for this vector was fairly small. It was suggested that relatively severe symptoms tended to result in greater plantar flexion load and a smaller dorsal flexion load than in healthy volunteers.

Nonlinear FEA was found to be valid during walking. The actual test values and FEA values for the maximum plantar flexion load during gait were found to be consistent with each other. As a result, FEA may be a suitable method for confirming stress and deformation of orthoses during walking. It can be inferred from the results of orthosis deformation for both patients when trimming was performed that nearly the same amount of deformation arose in the plantar flexion direction (Z direction) as a result of left-side trimming and as a result of right-side trimming. For bilateral trimming amounts of 40% and greater, a dramatic increase in displacement in the plantar flexion direction was noted.

### Acknowledgement

This work was supported partially by a JSPS Grant-in-Aid for Scientific Research (C) (No. 16K01579) and a grant of Strategic Research Foundation Grant-aided Project for Private Universities from the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT), 2013-2017 (S1311045).

### References


An Alternative Treatment for Microalgae Harvesting Procedure with Waste Oil and its Application in Shock Wave Emulsion

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(Received 10 January 2016; received in revised form 10 May 2016; accepted 30 June 2016)

Abstract: Biomass is a composition of various types of waste materials that can be utilized as useful form of energy. However this new kind of energy hasn't met its full potential in production of energy especially in electricity generation due to its lower performance in terms of thermal efficiency. In this decade, within the raising from biomass energy, the co-combustion and carbon emission reducing are the trend for the energy industry. For this study, we used vegetable oil as the main material and under emulsion with water and surfactants to simulate using aquatic biomass material for next stage application. Samples are evaluated by visual effects, and selected three types of surfactant for heat value testing. The emulsion samples are able to tested and the heat values are close to simulated results. This method is able to apply in the aquatic biomass materials, such as algae.

Keywords: Biomass Energy, Waste Vegetable Oil, Emulsion, Renewable Energy

1. Introduction

Since 19th Century and after industry revolution, the usage of fossil fuel increased rapidly with the CO₂ emission into the atmosphere. Global warming and climate become the most concern environmental issue recently, and the research aims to find a replacement for the energy resource [1]. Renewable energy seems might become the solution. Renewable energy includes wind energy, hydropower energy, solar energy, OTEC (Ocean Thermal Energy Conversion), wave energy and biomass energy.

Biomass energy is using the material from living or recently living organism, and with the most mature technology which wildly using in developing countries. Compare to other renewable energy sources, biomass energy has the stability as its advantage. Biofuel is a kind of biomass energy; mostly use the oil crops, such as soybean, corn, palm and sunflower seed, to produce fuel for the energy use. However after the early 21st century the food crisis in Latin America, the material which uses for biofuel production needs other alternative source and without food competition (1st, and 2nd generation biofuel)[2].

Microalgae, the aquatic microorganism, has no competition with food crop and great potential for energy uses. Microalgae is widely used in fish feed application, and also used in food/medical application after 1990 (Fig. 1). The first using microalgae as an environmental research started in 1980, US DOE (Department Of Energy) first experimented in Hawaii for microalgae biofuel production and CO₂ fixation, and the project is called Aquatic Species Program, ASP. Japanese Government also participated into related researches in 1979. However, the cost for biofuel production and CO₂ fixation had no significant breakthrough in that time. Those projects processed for decades and stopped in the late 20th century. After the food crisis, the researches use microalgae to produce biofuel raised and also have been called 3rd generation biofuel [3].

Fig. 1 The development for microalgae application

The production of microalgae biodiesel includes microalgae species selection, aquaculture, harvesting, and lipid transesterification. According to the ASP report [4], the cost of harvesting procedure is up to 38% in total expand. Also, in the Gudin and Therpenier also reported [5] that the cost to collect microalgae cell or concentrated might cost 20~30%. Microalgae in solution, the concentration is low and the size of microalgae cell also is small (3~30 μm). However, the general procedure is using centrifuge and dehydration, which increases cost and energy wastes. How to construct a method or technology to enhance harvesting efficiency and lower the cost, becomes a critical issue for the 3rd general biofuel.

2. Emulsion Technology in Energy Application

The gas emission of diesel engine especially motor vehicle and other heat engines includes nitrogen oxides (NOₓ) and particle matters (PM) which is an environmental pollution...