Skin Strain Field Analysis of the Human Ankle Joint

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Abstract

The Lines of Non-Extension (LoNE) represent the skin’s directions where, during human motion, the skin doesn’t deform. The use of the LoNE in the design of an orthosis that will act like a second skin is a new approach for the drop-foot pathology correction.

The main purpose of this work is to obtain the strain field maps of the ankle and foot’s skin, for the ankle’s large movements, and find the directions of the LoNE in the same region. The acquisition of the skin’s deformations data were performed with a system of four infrared cameras that calculate the spatial position of reflective markers placed on the skin. The skin’s strain tensor calculus from the analyzed movements, planar flexion and dorsiflexion, were performed by a finite element software. A computational program was developed that uses the calculus performed by this software and calculates the magnitude and direction of the principal skin strains. The developed program uses the previous results to calculate the directions of minimum skin strain. All the directions were obtained for the larger movements and they were considered valid for the movements with intermediate amplitudes. Finally, the LoNE found based in the obtained results were drawn and seven sets of lines on non-extension were obtained in the analyzed skin’s region.

Keywords: Lines of Non-Extension, Second Skin, Drop Foot, Skin’s Strain Field, Ankle Motion, Ankle-Foot Orthoses.

1. Introduction

Drop-foot is a condition where the dorsiflexion is compromised due to a weakness in the dorsiflexors muscles. This condition has as principal causes: dorsiflexors injuries, peripheral nerve injuries, stroke, cerebral palsy, multiple sclerosis and diabetes [1]. People with drop-foot have a pathological gait characterized by the lack of dorsiflexion during swing period and a foot slap in heel strike [2].

There are three main approaches for the drop-foot correction: the use of ankle-foot orthoses (AFOs), functional electrical stimulation (FES) and tendon transfer from the posterior tibial muscle [3]. The AFOs are the main focus of this work.

The use of a soft orthosis that acts like a second active skin is a new approach to correct drop-foot and, at the same time, increase the patient’s comfort and walking quality by overcoming the limitations of a conventional orthosis.

In the design of a new medical device that contacts with the skin it is important to have in consideration the skin-device interface [4]. The shear stress at the skin-device interface leads to repeated micro-traumas that can result in chronic wounding [5, 6]. Many studies about the skin’s biomechanical properties have been made. In 1861, Karl Lenger was the first to report that skin’s collagen fibrils have a natural orientation [7]. The oldest in vivo studies to measure skin’s deformation were performed by measuring the uni- and bi-axial tension [8, 9]. More recent studies, using 3D motion capture, directly measure skin’s deformation [10, 11]. In the late sixties, Arthur Iberall was the first to suggest the existence of a network of non-extension lines covering all human skin’s surface. He noticed that in some skin’s directions, during human motion, distortion and no deformation are suffered. Iberall proved that we can pass inextensible wires over these skin’s lines without restrict the free human motion [12]. Following Iberall, a master student Kristen Bethke at MIT, using more sophisticate methods for acquisition and analysis of the human skin strain, mapped the lines of non-extension in the leg [11]. Both Iberall and Bethke studies were conducted with a view to improve mobility in astronauts’ spacesuits. The work developed in this study is the first to map the network of lines of non-extension about the human ankle and the only one that used this approach for the development of a new orthosis that acts like a second skin.

The purpose of this study is to obtain the skin strain field map at the ankle joint by calculating the directions and magnitudes of the principal strains and finding the directions of the lines of non-extension (LoNE). The results shall provide useful information for the development of a new active orthosis that will act as a second skin in the drop-foot correction.

2. Strain Field Analysis

In the reference configuration, or initial configuration, a body occupies a region \( S_0 \) defined relative to a fixed orthonormal axis system, referred in this thesis as global axis system, in the 3D Euclidian space \((O, e_1^g, e_2^g, e_3^g)\). The vector position of each point will be defined relative to the origin \( O \) and all vectors will be defined by their components relative to the global axis system. In the initial position \((t = 0)\), each material point has a given position in the Euclidian space defined by \( X \). When the body deforms, each point occupies a new position in space that is given by \( x \) for a time \( t \),

\[
x = \chi(X, t)
\]

(2.1)
According to the material (or Lagrangean) description, displacement is expressed as a function of a material point, in the reference position, and of time \( t \). The vector that defines a particle’s motion from the initial position to the current position at time \( t \), is called the displacement vector \( d \) of the particle \([13]\). 

\[
d = x - X = \chi(X, t) - X \quad (2.2)
\]

If displacement is known for all body’s particles, it is possible to construct the deformed body from the original, and deformation can be described by the displacement field. The particle’s motion is given by function \( \chi(X, t) \) which is single-valued, continuous, and has a unique inverse \( \chi^{-1} \) \([13]\).

\[
X = \chi^{-1}(x, t) \quad (2.3)
\]

It is possible to calculate stretching and distortion of a body if change in distance between any pair of points is known. Considering an infinitesimal line connecting the point \( P(x_1, x_2, x_3)_p \) with an initial coordinates \( X_p \), to a neighbor point \( P'(x_1', x_2', x_3')_p \), with initial coordinates \( X_p \), the vector that defines the relative position between the points is given by \( dX \) \([13]\).

\[
x_{p'} = X_p + dX \quad (2.4)
\]

As space is assumed to be Euclidean, the square of the lengths \( dS \) of \( PP' \) is given by the Pythagoras rule,

\[
dS^2 = dX_1^2 + dX_2^2 + dX_3^2 \quad (2.5)
\]

When \( P \) and \( P' \) deform into the points \( R(x_1R, x_2R, x_3R) \) and \( R'(x_1R', x_2R', x_3R') \), respectively, at a fixed time \( t \), the correspondent vector that defines the positions between the two points is defined by \( dX \) and the square of the length \( dS \) of \( RR' \) is given by \([13]\).

\[
x_{p'} = x_R + dX \quad (2.6)
\]

\[
dS^2 = dx_1^2 + dx_2^2 + dx_3^2 \quad (2.7)
\]

The relation between \( dX \) and \( dx \) is given by \( F(X, t) \), which is the deformation gradient \([13]\).

\[
dX = F(X, t) \cdot dx \quad (2.8)
\]

\[
F = \frac{\partial \chi}{\partial X} = \begin{bmatrix}
\frac{\partial \chi_1}{\partial X_1} & \frac{\partial \chi_1}{\partial X_2} & \frac{\partial \chi_1}{\partial X_3} \\
\frac{\partial \chi_2}{\partial X_1} & \frac{\partial \chi_2}{\partial X_2} & \frac{\partial \chi_2}{\partial X_3} \\
\frac{\partial \chi_3}{\partial X_1} & \frac{\partial \chi_3}{\partial X_2} & \frac{\partial \chi_3}{\partial X_3}
\end{bmatrix} \quad (2.9)
\]

The deformation gradient \( F(X, t) \) is the material gradient of the motion, i.e., it represents changes in spatial position due to changes in material point, at a fixed time \( t \).

The rigid body motion is given by

\[
x = \chi(X, t) = c(t) + Q(t)X \quad (2.10)
\]

where \( c(t) \) describes displacement of a point of the body and \( Q(t) \) is the rotation tensor \([13]\).

The deformation gradient \( F \), according to the polar decomposition theorem, can be decomposed into a product of two tensors an orthogonal tensor \( Q \) and a positive definite symmetric tensor \( U \) or \( V \) in the form

\[
F = QU = VQ \quad (2.11)
\]

The tensor \( U \) is the right stretch tensor and \( V \) is the left stretch tensor, the terms right and lefts correspond to their position on the equation relative to the tensor \( Q \). Right and left stretch tensors are both positive definite and symmetric tensors.

\[
x \cdot U \cdot x \geq 0 \quad (2.12)
\]

\[
x \cdot V \cdot x \geq 0 \quad (2.13)
\]

\[
U = U^T \quad (2.14)
\]

\[
V = V^T \quad (2.15)
\]

The tensors \( U \) and \( V \) can be defined as

\[
U = \sqrt{FF^T} \quad (2.16)
\]

\[
V = \sqrt{FF^T} \quad (2.17)
\]

They have the same three real positive eigenvalues, or principal stretches, \( \lambda_k \) (with \( k = 1, 2, 3 \)), and different eigenvectors, or principal directions, \( n^u_k \) and \( n^v_k \) (with \( k = 1, 2, 3 \)). The eigenvectors of \( V \) can be obtained by rotating the eigenvector of \( U \) with \( Q \).

\[
n^u_k = Q \cdot n^v_k \quad k = 1, 2, 3 \quad (2.18)
\]

In this work, for each element \( j \), the nominal strain tensor \( \varepsilon^j \) for the current (deformed) configuration is calculated as

\[
\varepsilon^j = V - I = \sum_{k=1}^{3} (\lambda_k - 1)n^u_k(n^v_k)^T \quad (2.19)
\]

where \( I \) is the identity tensor \([14]\). The principal values of nominal strain are ratios of change in length to length in the reference (initial) configuration in principal directions. Nominal strain gives a direct measure of deformation \([14]\).

The calculation of the lines of non-extension (LoNE) about the ankle joint is based on the analysis of the skin deformation during ankle. It was assumed that the surface of the foot can be modeled as a set of planar elements, and for each element \( j \), the strain tensor was calculated, at the element’s centroid using ABAQUS software.

The two-dimensional (2D) strain tensor for a point, \( Q \), in an element can be defined by three components: two normal strains, \( \varepsilon_{11} \) and \( \varepsilon_{22} \), and a shear strain, \( \varepsilon_{12} = \varepsilon_{21} \). The components are defined with respect to a cartesian coordinate system, the element’s local axis system \( e_1e_2e_3 \) \([15]\).

\[
\varepsilon = \begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{12} \\
\varepsilon_{22}
\end{bmatrix} \quad (2.20)
\]

The calculus of the principals’ skin strains is based in the Mohr’s circle equations. The center of the circle is given by \( (2.21) \) and the circle’s radius by \( (2.22) \) \([15]\).

\[
\varepsilon_m = \frac{\varepsilon_{11} + \varepsilon_{22}}{2} \quad (2.21)
\]

\[
R = \sqrt{(\frac{\varepsilon_{11} - \varepsilon_{22}}{2})^2 + (\frac{\varepsilon_{12}}{2})^2} \quad (2.22)
\]

Through strain tensor, or Mohr’s circle, it is possible to calculate the magnitudes and directions of principal
strains. The magnitudes of maximum principal strain, \(\varepsilon_1\), and minimum principal strain, \(\varepsilon_{II}\), are given by
\[
\varepsilon_1 = \varepsilon_m + R \\
\varepsilon_{II} = \varepsilon_m - R
\]
(2.23) (2.24)

The directions of the principal axes of strain are given by \(\theta_p\) rotation of the element’s local axis system, \(\mathbf{e}_1\) and \(\mathbf{e}_2\). In these directions there are only deformations of the element and no distortion. The angle \(\theta_p\) is given by
\[
tg(2\theta_p) = \frac{\varepsilon_{12}}{\varepsilon_{11} - \varepsilon_{22}}
\]
(2.25)

By using Mohr’s circle it is easy to determine in which direction of the element, for the initial configuration, the element suffered a certain deformation and distortion. In this study the directions of the principal strains and the directions in which the element doesn’t suffer deformation, that means, where \(\varepsilon = 0\), it will be calculated.

3. Laboratory Procedure and Developed Program

In this study, data was collected from the right foot of two female subjects, in their 20’s, using the Qualisys Motion Capture System, with four ProReflex™ MCU500 cameras, that uses the 2D image captured by each camera to calculate the 3D spatial positions of the reflective markers placed on the skin. It was not possible to collect the data from all foot at the same time and the cameras were disposed in an arc and calibrated for a small acquisition volume [16]. Data were collected with an 80Hz frequency.

3.1 Markers Placement

The study area was the skin area usually covered by a normal sock except the toes and the foot sole. The geometric element used to analyze the skin strains was the triangle. The right foot of two subjects was covered with reflectors so that they stay at an initial distance of approximately 2cm in the anatomical reference position of the foot (Figure 3.1).

![Figure 3.1 Markers grid on the right’s foot skin of the subject 1. From left to right: lateral, medial, posterior and anterior foot’s view.](image)

In subject 1 and subject 2 were placed 132 and 141 markers, respectively.

3.2 Analyzed Movements

The skin strain was analyzed for plantar flexion and dorsiflexion movements and, each of them was performed in two ways. One of the plantar flexion movements was performed keeping the toes in the ground and lifting the heel, typical plantar flexion (TPF), and the other keeping the entire sole on the ground and moving the leg, ground plantar flexion (GPF). Similarly to the plantar flexion, one of the dorsiflexion movements was performed keeping the heel on the ground and lifting the toes, typical dorsiflexion (TDF), and almost the entire foot’s sole of the ground and the other was performed keeping the entire foot sole on the ground and moving the leg, ground dorsiflexion (GDF).

3.3 Data Treatment and Analysis

A program in MATLAB was developed to perform the analysis of the skin strains on the foot. This program receives the 3D spatial coordinates of each reflective marker, from the acquisitions, and performs the strains field analyses.

In this study has used a refined mesh to perform the calculus of the skin strains in order to obtain a better visualization of the line’s directions and to obtain more precise calculus. As in the Iberall’s study, it was assumed that the deformation results for the extreme distortions are valid for the intermediate states of distortion [12]. The strains on the skin, during dorsiflexion and plantar flexion, were calculated for movements from the initial position to intermediates and final positions. Each of the two study movements was divided into five intervals of motion. It was considered that total rotation of the ankle during dorsiflexion (100DF), or plantar flexion (100PF), corresponds to 100% of the total angles of motion. Note that, during the anatomical reference position, it is considered that the foot is in a 0° angle.

The spatial position of each marker at the initial configuration, anatomic reference position, is defined by \(\mathbf{X}^i\), where \(i\) corresponds to the marker number. The spatial position of each marker in the deformed configuration is defined by \(\mathbf{x}^i\). For each point, \(i\), is calculated the displacement vector, \(\mathbf{d}^i\), given by \( (3.1)\) between the initial position and the deformed position (Erro! A origem da referência não foi encontrada). All these positions are in reference to the global axis system \((\mathbf{e}_1^g, \mathbf{e}_2^g, \mathbf{e}_3^g)\) and the program attributes an identification number, \(j\), to each element.

\[
\mathbf{d}^i = \mathbf{x}^i - \mathbf{X}^i
\]

The strain analyses were performed in ABAQUS software. This software receives the coordinates of the initial vector, \(\mathbf{X}^i\), and the respective point’s identification number, \(i\), for all points of the refined
mesh, the elements parameters and the displacement vector from the initial position to the deformed position for each point, $d^I$ [14].

As the markers were placed with a small distance between them, it was considered that, for each element, skin is locally flat and skin deformations occur in the element plane. It was performed a non-linear analysis due to the large rigid body motion and the strain calculus was performed for the centroid of each element. From the ABAQUS analyses it is obtained, for each element, the strain tensor, the centroid’s coordinates and the directions of the local axis system. All data, by default, are expressed for the deformed configuration [14].

3.4 Principal Strain Directions and Lines of Non-Extension (LoNE)

The directions and values of principal strains, for each element, are directly calculated, relatively to the local axis system, using the Mohr’s circle equations (2.21) to (2.25). Considering $\epsilon^I_j$ the maximum principal strain and $\epsilon^I_H$ the minimum principal strain of the element $j$ and $\epsilon^I_{min}$ the maximum and $\epsilon^I_{min}$ the minimum principal directions of strain with respect to the local axis system, three different situations can occur. The maximum and minimum principal strain, $\epsilon^I_j$ and $\epsilon^I_H$, can have both either positive or negative values or they can have different signals.

In the case, where $\epsilon^I_j$ is positive and $\epsilon^I_H$ is negative, there are two directions of minimum strain in $j$ element, $\epsilon^I_{minj}$ and $\epsilon^I_{minj}$, which correspond to the directions of non-extension (zero strain). In the cases which there are only extensions, or contractions, there is only one direction of minimum strain. In the cases where all strains are positive the direction of minimum strain corresponds to the direction of the minimum contraction in modulus, the direction of maximum principal strain $\epsilon^I_J$, and the minimum strain have the value $\epsilon^I_H$ (3.2). In the cases where all strains are negative the direction of minimum strain corresponds to the direction of the minimum contraction in modulus, the direction of maximum principal strain $\epsilon^I_J$, and the minimum strain have the value $\epsilon^I_H$ (3.3).

$$
\epsilon^I_{minj} = \epsilon^I_H, \text{if } \epsilon^I_j > 0 \text{ and } \epsilon^I_H \geq 0 \quad (3.2) \\
\epsilon^I_{minj} = \epsilon^I_J, \text{if } \epsilon^I_j \leq 0 \text{ and } \epsilon^I_H < 0 \quad (3.3)
$$

4. Results and Discussion

A color code was created for the representation of the strain field analyses (Table 4.1). The length of the lines corresponds to the relative strains magnitudes.

<table>
<thead>
<tr>
<th>Color</th>
<th>Principal Strains Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>Minimum</td>
</tr>
<tr>
<td>Principal</td>
<td>Principal</td>
</tr>
<tr>
<td>Strain ($\epsilon^I_j$)</td>
<td>Strain ($\epsilon^I_H$)</td>
</tr>
<tr>
<td>Red ($\bullet$)</td>
<td>Pink ($\bullet$)</td>
</tr>
<tr>
<td>Ciano ($\circ$)</td>
<td>Blue ($\circ$)</td>
</tr>
</tbody>
</table>

Table 4.1 Color code used in the representation of the skin’s strain field for each strain case.

In the minimum strains analysis, when directions of non-extension ($\epsilon = 0$) were found, they were represented with a cross where each line corresponds to one of the non-extension’s direction. In the cases where zero extension does not exist, i.e. in cases of pure extension or compression, the minimum stretch direction was represented with a single line.

![Image of strain field](image)

Figure 4.1 At left, principal strains’ field for 100TPF. At right, the directions of minimum strain for 100TPF. Both analyses were performed with the original mesh and represented in the lateral foot’s view. The yellow diamond indicates the lateral malleolus location.

To simplify the description of the foot’s lines and strains directions we will call longitudinal direction to a proximal to distal direction on the skin and circumferential direction the direction normal to the longitudinal.

The original mesh (no refined) difficult strain field analysis due to the low amount of information (Figure 4.1) so a refined mesh was used (each triangle was divided into 16 triangles), for each of the different analyses.

4.1 Skin’s Strain Field

At first, it was analyzed the skin strain field from the complete typical plantar flexion (100TPF). It is presented the graphical analysis for the subject 1, Figure 4.2, and the values of maximum skin’s deformation obtained in this movement for both subjects, Table 4.2.

In both subjects the largest values of the skin’s deformation, during 100TPF, were obtained in the anterior region to ankle joint and posterior region of the the distal part of Achilles’ tendon. In both areas these strains have longitudinal directions.
Figure 4.2 Right foot’s strains’ field represented in 100TPF configuration (refined mesh, subject 1). At upper left, medial view. At upper right, posterior view. At bottom left, lateral view. At bottom right, anterior view.

Table 4.2 Values of maximum and minimum deformation obtained in 100TPF for both subjects.

<table>
<thead>
<tr>
<th></th>
<th>Minimum Value of Deformation</th>
<th>Maximum Value of Deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>-0.4626</td>
<td>0.3781</td>
</tr>
<tr>
<td>Subject 2</td>
<td>-0.5524</td>
<td>0.3784</td>
</tr>
</tbody>
</table>

The largest skin compressions were obtained in the posterior region of the Achilles’ tendon, with longitudinal directions. Small extensions were obtained in the same area, with circumferential directions. The largest compressions (-0.4626 in subject 1 and -0.5524 in subject 2), in modulus, were obtained in the point at the posterior direction to the ankle joint and the compressions’ magnitudes decrease as we move away from this point both in the longitudinal as circumferential directions.

The largest extension values were obtained in the anterior region to the middle of the ankle joint (0.3781 in subject 1 and 0.3784 in subject 2). Similarity to the compression, they decrease as we move away from this point in both longitudinal and circumferential directions.

Both lateral and medial malleolus correspond to skin areas where there is an inversion of the deformations’ signals. The principal directions in both malleolus’ region are very irregular, this probably happens due to the ankle joint motion and low refinement of the original marker’s grid. In a closer look it is possible to observe that, in both lateral and medial foot’s views, in the malleolus’ region, the grid has a bulge and the surface’s relief isn’t soft. In these areas the markers grid should have been denser but the existing acquisition’s equipment didn’t allow that.

The lowest skin’s strain values were obtained around distal leg, about 6 cm above malleolus, and in calcaneus’ region. In the lateral, medial and anterior views we can note a slightly compression, with an approximately longitudinal direction, in the distal metatarsus’ region. This compression it’s only noted at the distal line of grid’s squares.

In order to analyze the foot’s skin deformation during plantar flexion, without the interference of the metatarsophalangeal joint, it was performed the strain analysis maintaining the foot’s sole on the ground during the movement, Figure 4.3.

Figure 4.3 Right foot’s strains’ field for the 100GPF deformed shape (refined mesh, subject 2). On the top, medial foot’s view. At bottom, lateral foot’s view.

Observing the strain’s field from the 100GPF is possible to note that the relative magnitudes and directions of the skin’s principal strains are approximately equal to the obtained in 100TPF except in the distal metatarsus’ region. In the 100GPF, the slightly compression verified in the distal metatarsus’ region at 100TPF is not present. In the ground movement, there is no interference of the metatarsopodalalangeal joint in the skin’s deformation. The skin strain field from the complete typical dorsiflexion (100TDF) is presented in Figure 4.4 and the values of maximum skin’s deformation for both subjects in Table 4.3.

As in the previous analyses, the largest values of skin’s deformations were obtained in the anterior region to ankle joint and in the posterior region to the Achilles’ tendon. In the 100TDF the largest strains have a longitudinal direction like in 100TPF but with opposite signals. In dorsiflexion, the largest skin’s compression (-0.2068 in subject 1 and -0.3421 in subject 2) take place in the anterior region to ankle joint and the largest
skin’s extension (0.2593 in subject 1 and 0.2679 subject 2) occur in the posterior region to the distal portion of Achilles’ tendon. When comparing the maximum strain’s values that were obtained in the 100TDF with the correspondent values in 100TPF, the magnitudes were smaller in this analysis. Dorsiflexion is a less broad movement than plantar flexion so the total skin’s deformation is smaller.

Figure 4.4 Right foot’s strains’ field represented in 100TDF (complete typical dorsiflexion, subject 1). At left, medial foot’s view. At right, lateral foot’s view.

Table 4.3 Values of maximum and minimum deformation obtained in 100TDF for both subjects.

<table>
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</tr>
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<td>Subject 2</td>
<td>-0.3421</td>
</tr>
</tbody>
</table>

In the dorsiflexion movement, as in plantar flexion, the lowest skin’s strains values, in modulus, were obtained in the calcaneus region and around the distal leg, about 6cm above malleolus.

Finally, in this movement, unlike what happens in 100TPF, the metatarsophalangeal joint doesn’t seem to influence the skin’s deformation during dorsiflexion.

4.2 Directions of Minimum Skin Stretch

The minimum skin’s strains directions were graphically represented in the foot’s anatomical reference position.

At first, it is presented the directions of minimum strain for the complete typical plantar flexion (100TPF), Figure 4.5.

In these analyses, directions of non-extension were obtained in most of the mesh’s elements, i.e. in most of the elements the principal strain have different signals. Considering small skin regions, these results shows that, during this movement, the skin adapts to the foot’s movement compressing in one direction and extending in the other.

In these results three skin regions were obtained where the directions of minimum strain, in all surface’s elements, are perfectly consistent between them (Table 4.4).

Figure 4.5 Directions of minimum stretch during 100TPF (right foot, subject 1). A) Medial foot’s view. B) Posterior foot’s view. C) Lateral foot’s view. D) Anterior foot’s view.

In these three regions all the directions of minimum strain are directions of non-extension. The transition between these directions is soft from an element to the adjacent element, i.e. following the directions of minimum extension is easy to note the skin’s orientation of the lines of non-extension (LoNE) in these regions.

On the remaining skin surface of the foot and leg, some inconsistencies were obtained in the directions of minimum stretch between the elements of the initial mesh. In some cases, in the transition between two adjacent elements, the line’s directions are not perfectly aligned and these inconsistencies were verified more often in three distinct regions (Table 4.5).

In these three regions some differences exist in the cause and type of the obtained inconsistencies. In region R4, the skin suffers direct influence of the metatarsophalangeal joint, during the analyzed movement (typical plantar flexion). The calcaneus region R5 is formed by two lines of squares from the original mesh. In some triangles of the proximal line is verified consistence with the results of the adjacent triangles in region R1, but in the distal line of squares it was obtained results that make no sense when compared with the adjacent surface results.
Table 4.4 Foot’s and leg’s regions where the directions of minimum strain are perfectly consistent between the elements. Analyses from typical plantar flexion, subject 1.

<table>
<thead>
<tr>
<th>Region’s Identification</th>
<th>Illustration of the Anatomical Location</th>
<th>Description of the Anatomical Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td><img src="image1" alt="Image" /></td>
<td>Distal leg’s and foot’s skin with a posterior location to both lateral and medial malleolus and a superior location to 2 cm bellow the ankle joint.</td>
</tr>
<tr>
<td>R2</td>
<td><img src="image2" alt="Image" /></td>
<td>Between the proximal extremity of metatarsals and 2 cm proximally to the distal end of them.</td>
</tr>
<tr>
<td>R3</td>
<td><img src="image3" alt="Image" /></td>
<td>Distal leg’s skin with an anterior position to both lateral and medial malleolus and a superior location to 2 cm above the ankle joint.</td>
</tr>
</tbody>
</table>

Table 4.5 Foot’s and leg’s regions where the directions of minimum strain have some inconsistencies between the elements of the original mesh. Analyses from typical plantar flexion, subject 1.

<table>
<thead>
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<th>Description of the Anatomical Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>R4</td>
<td><img src="image4" alt="Image" /></td>
<td>Between the distal extremity of metatarsals and 2 cm proximally to this extremity.</td>
</tr>
<tr>
<td>R5</td>
<td><img src="image5" alt="Image" /></td>
<td>Calcaneus region. Foot’s skin with a posterior location to both lateral and medial malleolus and 2 cm bellow the ankle joint.</td>
</tr>
<tr>
<td>R6</td>
<td><img src="image6" alt="Image" /></td>
<td>Between the proximal extremity of metatarsals, the anterior region to both lateral and medial malleolus and bellow 2 cm above the ankle joint.</td>
</tr>
</tbody>
</table>

There are two possible causes for these results in R5, the markers trajectories’ noise and the influence of body weight when the heel is on the ground. In this region the skin’s deformation is low, so the markers trajectories’ noise has a larger influence in the results. This movement begins with the foot in the anatomical reference position so heel’s skin suffers a slightly compression due to the foot standing on the ground.

The region R6 is a region where interesting results were obtained. In the anterior ankle region, high extension values where obtained with aligned direction between the mesh elements in all foot’s views. However, for the minimum stretch results there are some differences between these views.

In the lateral foot view the elements of the original mesh form some triangles, obtaining for those elements just one direction of minimum strain, whereas in the others were obtained two directions but with a small
angle between them. This results are a little different from the obtained in the anterior and medial view where were obtained, in all elements, two directions of minimum strain (non-extension) for the same region. Analyzing the sequence of results from the same movement (20TPF, 40TPF, 60TPF, 80TPF and 100TPF) for the lateral view, it is possible to notice that, in the lateral view, for less broader movements two directions of non-extension were obtained. As the amplitude of the movement increases the angle between the lines decreases until they became just one line.

In both medial and lateral foot views, in the regions of the transverses arches and the regions with an anterior position to both malleolus corresponds to the foot’s regions where the low refinement of the original mesh is more visible. Like in the anterior region to the ankle joint, elements were obtained with just one direction of minimum strain. The transition between the obtained directions isn’t soft and the triangles that form the original mesh (not refined) are perfectly identifiable, contrasting to the results obtained in the regions R1, R2 and R3. Some of the obtained directions in one element, from the original mesh, don’t have a soft continuity with the directions of the adjacent elements but have continuity with one a little further. These regions are the most irregular in the foot and the ones where more problems to calculate the markers trajectories were found because they weren’t always caught by the cameras.

The directions of minimum strain were also calculated for the typical dorsiflexion movement, Figure 4.6.

![Figure 4.6 Directions of minimum strain during 100TDF (right foot, subject 1). At left, medial foot’s view. At right, lateral foot’s view.](image)

In the regions R1 and R3, the obtained results are consistent between them and the directions are similar to the obtained in the plantar flexion movement. In the remaining skin surface the results are similar to the obtained in plantar flexion except in the metatarsus region. During this movement the reflective surfaces of the skin’s markers acquired orientations approximately perpendicular to the cameras and in the maximum amplitude some markers leave from the cameras’ field of view.

4.3 Lines of Non-Extension

The obtained directions of minimum strain for punctual locations on the foot and leg give the information to predict the location and orientation of the lines of non-extension (LoNE) in the analyzed anatomical region. The lines were drawn by hand and it was taken into account a series of information and presuppositions during the drawing.

As the inconsistencies between the obtained directions from 100TPF and 100TDF corresponds to the regions where there were more difficulties to acquire the markers’ trajectories and the plantar flexion movement is a larger movement, it were considered, for drawing the lines of non-extension, the obtained directions from typical plantar flexion (100TPF). According to Arthur Iberall [12] the obtained directions of non-extension from an extreme skin’s deformation are valid for the intermediates deformations so it was assumed that the obtained LoNE from plantar flexion are valid for the dorsiflexion.

Despite the directions of non-extension in the malleolus regions that were found, the lines drawn pass around these regions, giving to this area more freedom in the movement. For the drawing of the LoNE, not just the directions of minimum strain were taken into account but also the information of the principal’s strain field. The orientation of the lines was drawn following parallel directions to the punctual minimum strain directions. In the cases where it was found inconsistencies between the directions, the obtained directions in more distant elements was taken in consideration from the critical points and the information from the principal strains’ field (the direction of minimum strain can’t be parallel to the direction of maximum strain, in modulus).

Seven sets of lines of non-extension (LoNE) with parallel orientations were obtained (Table 4.6).

Comparing the information from the principal’s strain field analyses and the locations of the LoNE is possible to note that different sets of lines pass through the two regions of maximum deformations.

The sets L2, L3, L6 and L7 pass through the anterior region to the ankle joint. The set L1, do not pass through a region of large deformations, but these lines are important to support the foot’s weight mainly during swing period. The sets L4 and L5 pass through the posterior region to the Achilles’ tendon, one of the foot’s regions that suffer the largest foot’s skin deformation during the gait cycle.

4.4 Comparison of results with previous works

The LoNE found by Iberall [12, 17] and the LoNE used in the Bio-Suit [11, 18] have, in the distal portion of the lower limb, a configuration that forms a spiral.
around the leg and is clearly the existence of two types of lines, one with a high inclination that spirals around the leg one time until it reaches the knee, and another with a low inclination that spirals around the leg several times until it reaches the knee.

Table 4.6 Sets of LoNE obtained for the leg and foot. Lines’ sets identification and medial, posterior and lateral view of each set, represented in the anatomical reference position. Right foot of the subject 1, directions of minimum strain from 100TPF.

<table>
<thead>
<tr>
<th>Lines’ identification</th>
<th>View</th>
<th>Lines’ identification</th>
<th>View</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Medial / Posterior / Lateral</td>
<td>L5</td>
<td>Medial / Posterior / Lateral</td>
</tr>
<tr>
<td>L2</td>
<td>L6</td>
<td>L3</td>
<td>L7</td>
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</tbody>
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| L4                    | Figure 4.7 The seven sets of lines of non-extension (LoNE) drawn in the field of minimum strains of the right foot and distal leg of subject 1. At left, medial foot’s and leg’s view. At center, posterior foot’s and leg’s view. At right, lateral foot’s and leg’s view. The L1 is represented by the blue lines, L2 by the orange, L3 by the dark green, L4 by the purple, L5 by the pink, L6 by the brown and the L7 by the light green lines.

In this study, it were obtained three sets of LoNE (L4, L5, and L6) that have a spiral orientation in the distal leg that continues upwards through this anatomical segment. All the directions of minimum strain obtained above the ankle joint are directions of non-extension, with one of the directions having a greater inclination through the leg than the other. These lines and directions of non-extension are consistent and have continuity with the lines found by Iberall and the lines from the Bio-Suit.

5. Conclusions

This study was developed with the main purpose of drawing the LoNE, lines of non-extension, in the region of the ankle joint, to help in the development of an orthosis that will act like a second skin in the drop-foot pathology correction.

In the analyses of the skin strain field, the expected results were obtained. Greater values of the skin’s deformation were obtained in the anterior and posterior regions to the ankle joint, both in plantar flexion and dorsiflexion movement. The anterior region to the ankle joint suffers the largest extensions during plantar flexion and the largest compressions during dorsiflexion. The posterior region to the ankle joint, in opposition to the anterior region, suffers the largest extensions during dorsiflexion and the largest compressions during plantar flexion. Comparing the two analyzed movements, the
magnitudes of the skin’s deformation in these regions are greater in plantar flexion than in dorsiflexion and, in both cases, the principal’s directions of deformation have longitudinal directions. The lowest strains were obtained in the calcaneus region at approximately 6cm above the ankle joint.

From the analyses of the principal strain field, an analyses of the minimum strains’ direction, in modulus, was performed. In both analyses, dorsiflexion and plantar flexion, it was obtained a larger density of directions of non-extension in the analyzed skin’s surface. The regions where just one direction of minimum strain was obtained corresponds to regions where there were more difficulties during the acquisition or in regions were one of the principal’s direction has a value near zero. In the directions where one, or both, of the principal strains are approximately zero more inconsistencies between the directions of minimum strain were obtained. This fact was maybe due to the greater influence of the noise of the marker’s trajectories in the directions’ calculus. The low original mesh’s refinement was highly noted in the obtained directions in the anterior region to the ankle joint and in the malleolus’ region. These regions have an irregular shape, obtaining some inconsistencies in the directions of minimum strain between the elements from the original mesh.

Despite having achieved some inconsistencies in the directions of minimum strain in some regions, it was possible to draw the LoNE, lines of non-extension, in the studied skin’s surface. Seven sets of LoNE were found with the same anatomical orientation and that different sets pass through the two regions of larger deformations. In the metatarsals region was found the only set of lines that do not go through any of the two regions of maximum deformations, with a circumferential orientation.

Three of the others six sets of LoNE start and end in the sole, and one of them passes through the leg. Finally, the other three sets of LoNE start in the foot’s sole and have an ascendant spiral orientation through the leg. Two of the sets of LoNE that just start in the foot pass through the posterior region to the ankle joint and all the other sets, except the one that is located in the metatarsals region, go through the anterior region to the ankle joint. Any of these LoNE sets pass through the malleolus regions because this region should not be restricted and is a region of low skin’s deformation. The orientations of the three LoNE sets that have a spiral orientation through the leg are consistent with the lines found by Iberall [17] and the lines used in the Bio-Suit spacesuit [19].

The sets of LoNE that go through the two regions of larger skin’s deformations are very important, although these regions suffer large deformation during the foot’s motion, there are directions where the skin does not deform and, in these directions, it is possible to pass inextensible wires without restriction of the foot’s free motion. In these wires we can fix the orthosis actuators that will perform the orthosis’ deformation and other orthosis components, such as movement sensors and electric cables, without restricting the foot’s motion.

6. References