Skin strain field analysis at the ankle-foot complex through digital image correlation

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Abstract

The human skin strain analysis finds use in the prospect for new medical devices that have permanent contact with the skin and are kinematically compatible with the joints. This thesis follows and is supported by previous work conducted at IST, and on the research performed at MIT in the development of compliant devices for the ankle-foot complex [Domingues, 2014, Bethke, 2005].

Digital image correlation was used to compute spatial and temporal strain distributions at the ankle-foot complex of 18 healthy volunteers of both genders, aged 20 to 36 years old. A high resolution 3D point cloud was provided by VIC-3D from Correlated Solutions, and using MATLAB the deformation gradient tensor and the Lagrangian strain tensor for each element of the point cloud was computed. Thus, subject specific analysis on the strain magnitude pattern, principal directions of deformation and LONEs (Lines of Non-Extension) were performed in order to provide a qualitative and quantitative characterization of the human skin strain field with this novel method.

The combined use of high resolution and high frame-rate cameras with digital image correlation, provides outstanding spatial resolution and allows accurate high speed motion analysis. Strain can be measured with an expressively higher resolution, since one can inspect an approximately 2 mm distance between each tracked material point in the surface of the skin. This allows an improvement over previous methods and the introduction of a more reliable, reproducible and flexible method of assessing skin strain field for the development of biomedical devices.

1. INTRODUCTION

1.1. Motivation and objectives

The knowledge of the detailed behaviour of the ankle-foot complex is critical for many biomechanical applications. Complementing the gait analises that target the mechanical loading of the joints of the ankle-foot complex, it is also important to be aware of the skin deformation events that occur in that region of the human body, in order to improve the compatibility of the newest trend of biomedical devices that have permanent contact with the human skin, without harming the individual carrying them.

The improvement of spatial resolution and of reproducibility of the skin strain measurement using digital image correlation over several subjects are the main goals of this work, building on previous efforts conducted in IST (Instituto Superior Técnico) and MIT (Massachusetts Institute of Technology) that showed these characteristics as main drawbacks. Taking advantage of a commercial software such as VIC-3D, which allows high spatial resolution, and of MATLAB, which allows quick prototyping and development, one aims to build a set of tools that result on a fast and efficient experimental and numerical procedure to analyse the skin deformation at the ankle-foot complex.

1.2. State-of-the-art

The very first study about skin deformation and LONEs was performed by Arthur Iberall in 1951 [Iberall, April 3, 1951], and since then, there have been a few studies on the skin deformation of *in vivo* subjects. Such studies are the under pillar of our work aiming at the design of better ankle-foot orthoses, as the knowledge of the skin's strain map and its relationship to the joint movements on it is critical to increase the performance of a compliant biomedical device that is in contact with the human skin.

His work led to the development of a manual technique to find LONEs over the skin's surface and to constrain the highly mobile pressure-retaining layer using the previously obtained net of LONEs. Those same lines presented reproducibility for the human form, and were a source of reliable data to design devices with mechanical coupling with the human body.

Thirty five years later, Kristen Bethke studied the effects of the knee joint in the shape changes in the human skin, and mostly, the strain maps present at the knee. With the purpose of introducing the theory of advanced locomotion mechanical counter pressure space-suits, she studied the changes in the human body shape during joint motion [Bethke, 2005, Bethke et al., 2005]. In particular, she performed an experiment to analyse the strain over the lower limb surface during the knee flexion.

In 2010, Sara Marreiros in her Master thesis also studied the LONEs [Marreiros, Novembro de 2010, Domingues et al., 2011]. The main objective of her work was to obtain the skin deformation around the ankle-foot complex when dorsiflexion/plantarflexion are performed in its maximum amplitude, with the aim of developing a soft second-skin orthosis to correct a common gait deviation amongst stroke patients: drop-foot.

Andrew T. Marecki, in the middle of 2012, presented yet another method to analyse in a quantitative way the human skin deformation [Marecki, 2012]. He then implemented an automated method to track markers and digital correspondences between 3D volumes. Using this method, Marecki presents in his thesis the skin deformation analysis of a complete 360°view of the human knee and of a transtibial amputee's residual limb.

The most recent study on human skin deformation was conducted in the PhD thesis of Rita Domingues [Domingues, 2014]. The thesis aimed at the development of an active ankle-foot orthosis, using data from the observation of the skin deformation around the ankle and the dynamic behaviour of the foot during gait. She proposed the use of the LONEs as sites for structural support of actuators, and the directions of maximum extension to guide the distribution and alignment of actuators for a maximum compliance of the biomedical device with the human skin.

2. Biomedical concepts

2.1. Gait cycle description

Walking is a repetitive event, and the gait cycle can be defined as the time interval between two occurrences of the same phase of the gait [Whittle, 2014]. The "initial contact", where one foot initially touches the ground, is usually accepted as the beginning of a gait cycle. Usually the initial contact of the right foot is established as the starting point for the gait cycle and it lasts until the next initial contact of the right foot. The left foot goes through the same sequence of events, but delayed by half a cycle.

In this experiment, the gait cycle description will be delivered according to the description made by Rita Domingues in [Domingues, 2014]. The gait cycle is therefore divided in two phases (Stance and Swing phases) and in six states (Figure 1):

- State 1 is inherited to the time gap between heel-strike and toe-strike. During this time, the foot is landed under control due to a controlled plantarflexion, since that torque is applied in the opposite direction;

- State 2 and 3 are related with a controlled dorsiflexion. During State 2 the foot dorsiflexes in order to take the foot into a reference position. In State 3 the ankle continues to perform dorsiflexion and reaches a local maximum in the ankle angular position;

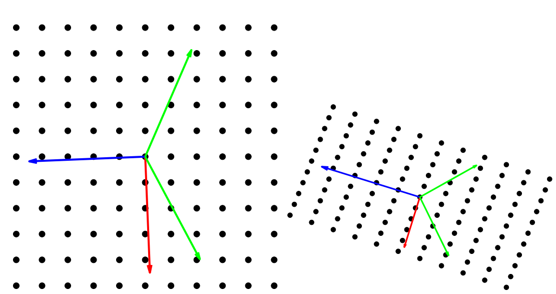
- State 4 is related to powered plantarflexion, and includes the time between controlled dorsiflexion and the toe-off, i.e. when the foot leaves the ground. This time period is correlated with a propulsion phase which acts as a preparation for swing;

- State 5 is the first phase of the gait cycle where the ankle-foot complex has no ground support and a dorsiflexion occurs in order to take the foot into a reference position;

- State 6 both dorsiflexion and plantarflexion events are null and the ankle-foot complex is kept in a reference configuration.

3. Directional effects of skin

Human skin presents a diversity of patterns of deformation, with its anisotropic and elastic properties and its collagen fibers forcing the skin deformation behaviour to become responsive to those properties. A tension state in the skin may be represented by major and minor strains (larger and smaller extension/compression) together with the specific case where a LONE occurs.It is not practical to quantify the amount of deformation that occurs in the skin in a very precise point, but assuming a constant deformation of a very small surface, Major strain directions, Minor strain directions and LONEs can be identified in the following manner with the aid of Figure 2:



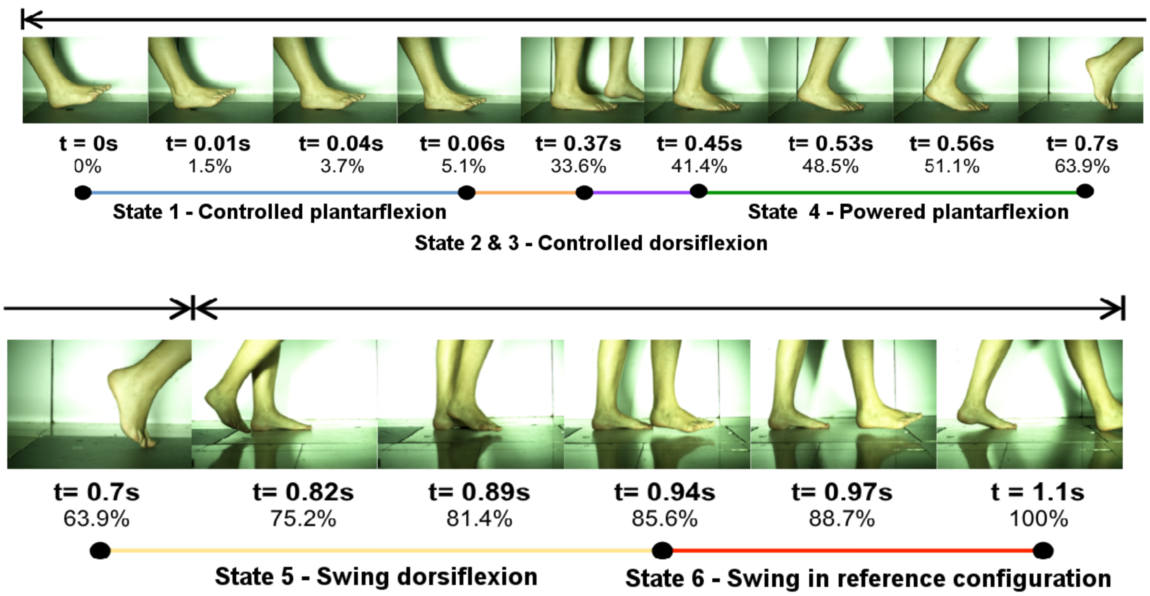


Figure 1: *Gait cycle description [Domingues, 2014]*

Figure 2: *Reference (up) and deformed (down) configuration of a body, where blue direction represents a Major strain direction, red direction represents a Minor strain direction and green directions represent LONE, i.e. directions of non-extension*

- The blue line represents a Major strain direction, where the strain's magnitude is the most positive along all directions in that surface;

- The red line represents a Minor strain direction, where the strain's magnitude is the most negative along all directions in that surface;

- The green line represents a LONE, a direction where no deformation, and possibly only rigid body motion occurred.

There have been many studies on the skin's behaviour when subjected to tension states and its consequent effects. In the very beginning, Langer [Langer, 1978, Ridge and Wright, 1966] studied the directional effects on skin, who pricked numerous small circular holes in a cadaver, noticing that those circular wounds achieved an elliptical shape. Those holes were in such a great number, that matching the path through the ellipses major axes he could determine the Langer Lines, lines which formed a network of tension directions.

Other studies on direction effects of skin came with Iberall [Whittle, 2014, Hall, 2007, Iberall, 1970], where the notion of LONE was first introduced, as described in the previous chapter. Assuming skin's elastic behaviour, Iberall used round shaped stamps to cover subjects' skin with printed circles, asked them to deform a specific region of the skin and realized that when a circle deformed into an ellipse there is the possibility of occurring two diameters with its length unchanged. He noticed that when the circles deformed into the ellipses, those two diameters (LONE's) had only rotated and not stretched. Those two directions could then be mapped to a grid of directions where no extension occurred, by performing an analysis of LONEs in each point in the body.

The knowledge of the skin's deformation when it is subjected to a tension, whether internal (from collagen fibers) or external (e.g. an orthosis), has been useful through the years in many industrial and engineering fields, ranging from areas like cosmetic applications or biomedical devices, to deploy a mobile pressure suit or to improve spacesuit design.

4. Image registration

Although the geometric details have been introduced in the previous section, one should first be able to make a precise matching of different regions in both images of the camera in order to deploy an accurate measurement of the 3D real surface. This topic falls under the *Image registration*, a very important issue, specially in the topic of 3D digital image correlation.

The image matching from a stereo system is a key method for recovering information about the 3D environment that is observed. Humans do it naturally, the eyes acting like a pair of stereo vision cameras, processing the depth of the surrounding environment.

Nowadays there are several stereo matching methods which rely on different computational approaches. Here we will focus on a specific kind of stereo method, which is a *direct, local and dense method* [Cyganek and Siebert, 2011]. Therefore, in a digital image correlation program such as VIC-3D, the correspondence between two different images (i.e. from two different cameras) is achieved by a specific type of image registration method named *area-based matching* [Cyganek and Siebert, 2011].

Area-based matching is an image registration algorithm that consists of measuring the degree of correlation between two pixels in matched images, and instead of comparing pixel by pixel for performing the correlation, it evaluates a straightforward matching between every pixel in both images but using a neighbourhood of pixels around the one in which correlation is to be performed (i.e. a *direct and local method*).

This method is usually designed to gather a dense disparity field [Cyganek and Siebert, 2011] between a set of two correspondent images. This application is useful in cases where continuous disparity fields are required, such as surface measurement. Thus, a displacement field is computed and a pixel correspondence between two images is created.

5. Experimental methodology

5.1. Stereo acquisition system and speckle pattern

The current stereo acquisition system consists of two Mikrotron EoSens MC-1363 cameras positioned so their FOV could intercept over the force platform present at the laboratory. They are hardware synchronised and configured to acquire 500 frames per second.

The speckle pattern quality is one of the key aspects to get a highly accurate measurement through digital image correlation. According to VIC-3D user manuals, it is necessary to use a non-repetitive, isotropic and high contrast pattern such that correlations are calculated without errors. Therefore, a random texture was chosen for this.

The application of the pattern consists in painting of foot with a white layer of water-based and washable paint using a normal paintbrush, from the top of the ankle, until the sole of the foot. Then, the plastic stamp is used to apply a random textured pattern of black paint, also water-based and washable. One should carefully apply the pattern, because the speckles shouldn't be too small (due to lack of paint) nor too big (due to blur effects and excess of paint).

5.2. Analysed ankle-foot motions

The performed experiments intended to cover the full range of motion that can be achieved by the ankle-foot complex. Therefore, it was necessary to separate the experiments into two major procedures: to acquire data from reference motions of the ankle-foot complex, with the subject placed in a static position-*static performance*-and to gather data about the skin deformation patterns that occur during the gait cycle-*dynamic performance*.

The static performance was recorded in four views of the left ankle-foot complex and for three distinct sets motions: anterior, lateral, medial and posterior views and the inversion/eversion, pronation/supination and plantarflexion/dorsiflexion sets of motions.

While the motion is being executed by the subject, is it crucial that he stands in a position as similar as possible to the anatomic reference position, in order to remain comfortable during the entire experiment so one can avoid jittering effects in the recorded video, due to lack of control and balance over his limb and body.

For the static performance, a 3 seconds video was recorded, corresponding to 1500 frames, that were afterwards extracted using MATLAB into *.tiff* images, in order to be processed in VIC-3D. The subject was also trained to be able to perform the several movements during this time window of 3 seconds. For example, in a plantarflexion/dorsiflexion static performance, the subject should start in the anatomic reference position, complete a plantarflexion, return to anatomic reference position and finally accomplish a dorsiflexion and back into the reference position. Likewise, the subject should perform an inversion, and go into an eversion passing through the anatomic reference position, and back to the anatomical reference position. An analogous procedure is executed in the pronation and supination set of motions.

The dynamic performance was captured from six different views to cover all the foot's surface during gait. All three Forward pathways in the dynamic performance made possible an analysis in the lateral view of the foot, and the three Backward pathways were set in order to permit a clear sight over the medial surface of the ankle-foot complex.

During the dynamic performance of the experiment, the video was recorded for 1.5 seconds, having a 750 frame time window to acquire a motion from State 1 to State 4.

5.3. VIC-3D and MATLAB processing

In order to get a 3D point cloud of the reference configuration (1^{st} frame) and all the remaining deformed configurations, it was necessary to use a commercial software (VIC-3D) to perform 3D-digital image correlation over the several frames extracted from the previously recorded experiments' videos.

MATLAB was the chosen tool to develop a framework that could help to visualize all data regarding skin deformation: strain magnitudes, principal directions and LONEs, The results can then be exported and therefore visualized in 2D, with the ROI superimposed on the picture or in 3D, with a mesh model implemented in MATLAB.

6. Results

6.1. Static performance

Three sets of the ankle-foot complex motions were acquired for 18 subjects: inversion/eversion, pronation/supination and plantarflexion/dorsiflexion. These motions are shown with respect to the four views in order to provide an accurate and complete description of the several local changes that occur on the skin's surface.

Although the patterns of skin deformation over different subjects show relevant and consistent configurations of the strain distribution on human skin, it is visible an inter-subject variability in what concerns to static performance experiments. Thus, it was recorded the maximum and minimum values of strain for the different static performance experiments in order to deliver a statistical analysis of those values (Table 1).

6.2. Dynamic performance

Six views of the gait of all the subjects were used to make the best detailed description of the human skin deformation during the gait. Three forward and backward views of the human gait allowed to see a 360°over the ankle-foot complex and to analyse the strain behaviour over the sagittal plane and in other regions of the foot such as around the malleolus or border of the sole of the foot (Figure 3).

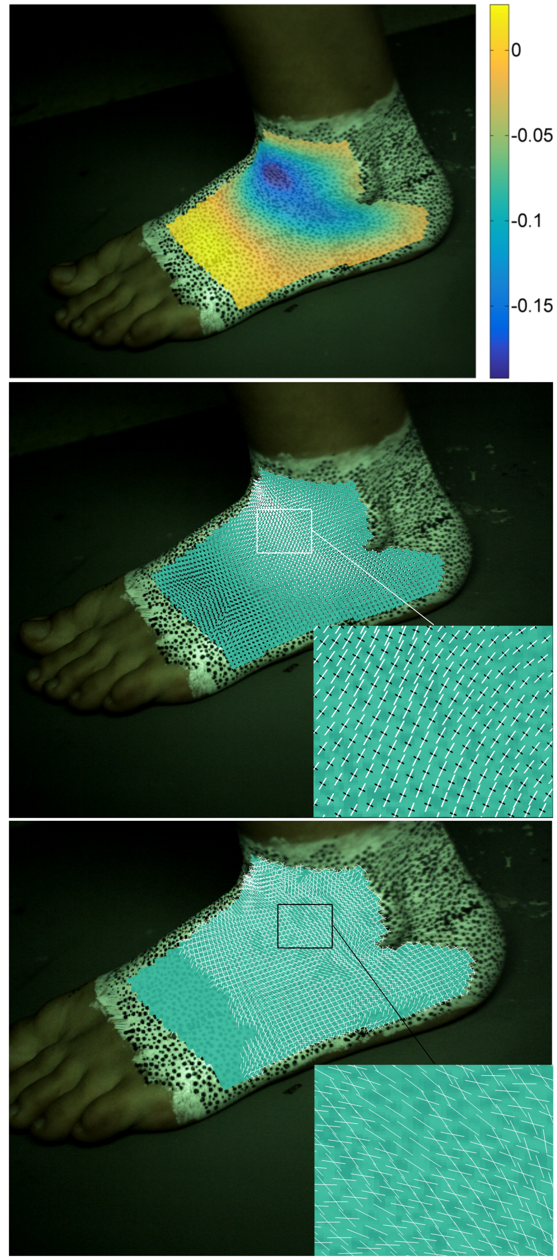


Figure 3: *Analysis on the skin deformation during the gait (State 3). Top: Anterior view of the Minor strain component; Middle: Anterior view of the Minor direction of deformation; Bottom: Anterior view of the LONE's.*

As for the static performance experiments, the dynamic ones also show an inter-subject variability which is expressed in the maximum

Table 1: *Mean and Standard Deviation of Major and Minor strain components of the static performance experiments (IE-Inversion/eversion; PS-Pronation/supination; PD-Plantarflexion/dorsiflexion; m-mean; sd-standard deviation)*

View & strain/Experiment	IE-m	PS-m	PD-m	IE-sd	PS-sd	PD-sd
Anterior-Major	11,6	15,3	24,3	4,6	8,1	10,3
Anterior-Minor	-15,9	-14,5	-21,1	6,4	6,3	5,6
Lateral-Major	15,8	22,2	20,6	6,6	14,2	7,2
Lateral-Minor	-19,8	-17,6	-17,7	6,0	5,8	4,4
Medial-Major	29,2	11,8	17,5	5,6	6,2	5,9
Medial-Minor	-23,0	-20,3	-19,1	7,1	6,7	3,5
Posterior-Major	12,8	11,9	15,8	5,4	7,3	5,4
Posterior-Minor	-12,3	-10,8	-16,6	7,2	6,3	5,0

and minimum strain values obtained for different subjects. During the Backward experiments, it was necessary to divide the analysis in two distinct blocks, the first one until the opposite toe-off and the second one from the heel rise to the moment where the foot is outside of the cameras' FOV.

Those strain values are presented in the following table in the same way they were presented for the static performance experiments (Table 2 and Table 3).

Table 2: *Mean and Standard Deviation of Major and Minor strain components of the dynamic performance experiments (FD1-Forward Normal 1; FD2-Forward Normal 2; FN-Forward Normal)*

	Mean	S. Deviation
FD1-Major	20,6	9,8
FD1-Minor	-15,3	5,5
FD2-Major	11,4	7,2
FD2-Minor	-16,3	4,6
FN-Major	10,5	3,9
FN-Minor	-17,8	6,3

Table 3: *Mean and Standard Deviation of Major and Minor strain components of the dynamic performance experiments (BD1-Backward Diagonal 1; BD2-Backward Diagonal 2; BN-Backward Normal; TO-Toe off; HS-Heel strike)*

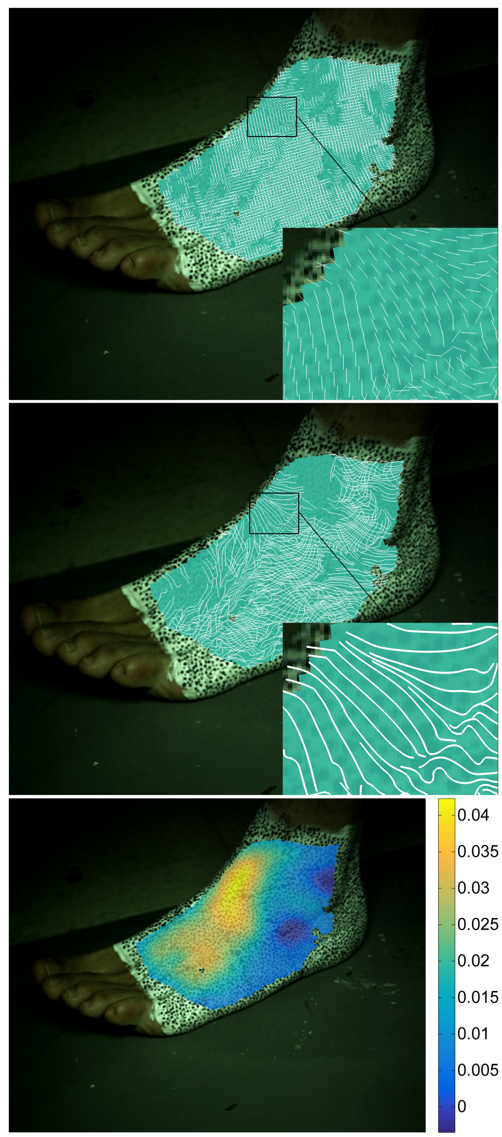
	Mean	S. Deviation
BD1-HS-Major	12,4	9,4
BD1-HS-Minor	-4,3	2,7
BD1-TO-Major	8,4	4,9
BD1-TO-Minor	-11,7	3,7
BD2-HS-Major	10,7	3,6
BD2-HS-Minor	-7,1	2,1
BD2-TO-Major	7,1	3,2
BD2-TO-Minor	-12,0	4,9
BN-HS-Major	9,3	2,8
BN-HS-Minor	-5,5	2,2
BN-TO-Major	8,7	4,6
BN-TO-Minor	-12,4	4,4

7. Conclusion

With respect to the results of the magnitude of strain, the principal directions of deformation and the LONEs, the present results can be related to those obtained by Sara Marreiros [Marreiros, Novembro de 2010] and Rita Domingues [Domingues, 2014] for the plantarflexion/dorsiflexion results. The strain tensor used in that experiment is different (Biot) from the one used in this work (Lagrangian) and that, together with the explicit differences in the methods, leads to the difference of a much higher strain value obtained in Rita Domingues' experiments. Furthermore, principal directions of deformation and LONEs are obtained with much more detail using digital image correlation based methods.

With respect to LONEs, it was also found that usually LONEs follow the direction of the principal ligaments of the dorsum of the foot: *Superior extensor retinaculum* and *Inferior extensor retinaculum* . This is supported by the fact that oblique pairs of LONEs aligned with the circumferential direction of the ankle-foot complex were found in that very same place on many experiments. Also, the skin on top of the tendons that connect toes to the dorsiflexors of the foot are considered regions of the skin where no extension occurs, since they crease the skin during some motions of the foot. The heel-strike during the gait is a good example, since the toes in a dorsiflexed position produce that effect in the skin.

One real and direct application of this tool is the aid on the development of soft orthosis for the correction of the drop-foot pathology by identifying the places in the foot where to put the actuators since places of zero extension and places of maximum extension are known and are considered the best location to anchor them. The knowledge about maximum value of strain and the direction of principal directions of deformation is also important, specially in the moment right after heel strike, an until the foot lays flat on the ground during controlled plantarflexion. LONEs identified in Figure 4 (Middle Top) can support the actuators, which should perform a controlled extension of about 5%, aligned with the Major direction of deformation observed in Figure 4 (Bottom) (black lines).



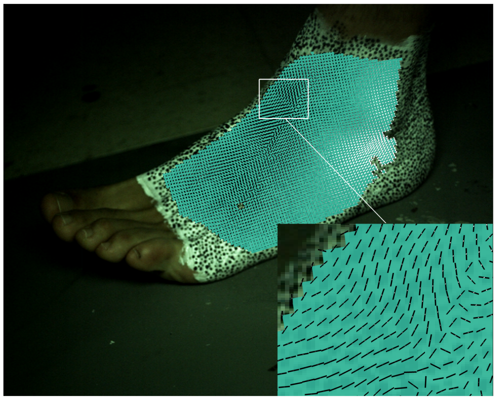


Figure 4: *Applications of the skin strain field analysis on the development of a soft orthosis device. Top: Anterior view of vectorial LONE's representation; Middle top: Anterior view of interpolated LONE's representation; Middle bottom: Anterior view of the Major strain component; Bottom: Anterior view of the Major direction of deformation.*

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