Design of slender and lightweight rehabilitation orthotics based on Lines of Non Extension

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Abstract. The development of dynamic orthoses is a fast-growing field of research and has resulted in many different devices, where all of them try to solve or correct some motion pathology. As these devices are held on the human skin, it is of inspiration for the safety design of wearable devices [1]. Furthermore, to design a comfortable orthosis the joint motion must be considered. Based on this, the approach of this work for the design of rehabilitation orthotics is to analyse the skin strain field during a prescribed rehabilitation motion. Then, based on anatomical lines with minimum deformation, also called, Lines of Non-extension (LoNES) it is possible to design the structural parts of the orthosis. This LoNEs can be obtained from the recorded motion by Digital Image Correlation and different optimization criteria. The structural parts of the orthotic can be designed over these lines, and consequently these parts must be considered as slender structures. In this work, the complete process to obtain a functional orthotic device is presented. The design of the slender contours of the orthotic and the optimization (material selection, thickness, etc.) based on finite element analysis is also described. Different prototypes are analysed to determine the areas with major strain. The resulting prototype is optimize the design based on this information.

1. Introduction

The use of the human body as support environment, and must consider the interaction with the wearable device (J.L.Pons, 2008). The relative motion and tangential strains produced in the skin-device interface during everyday life, caused by the loads due to human motion, generate wounds and the formation of bedsores and chafing. Some recommendations have been made about the use skin strain analysis as criteria of design, such as the use of the areas with relatively low movement and minimum strain for support the structure of wearable devices (2,3).

A new engineering design trend has emerged around the idea that the products in contact the human body should be on minimum strain anatomical lines, namely Lines of Non-Extension (LoNEs). Different studies have used and explored the LoNEs for different purposes, such as the development of new space suits for improving the mobility of (4–6), pattern design of tight-fit of functional clothing (Seo et al. 2013) and design of socket prostheses and orthoses (7,8). From the perspective of wearable devices, there is still no transfer of results of the skin strain field and LoNEs to the design of these products. In this sense, we have developed a new methodology of design based on skin strain analysis and LoNEs to...
create wearable devices. To perform the skin strain analysis, a low-cost methodology using the principles of stereo digital image correlation (or also called 3D-DIC) has been implemented for this purpose. Based on this analysis, the basic structure, considered a slender structure, of a new design of wearable devices, such as an ankle-foot-orthosis (AFO) is presented.

2. Methods
The concept of “lines of non-extension” (LoNEs) introduced by Arthur S. Iberall (Iberall, 1964), defines lines or contours along of the human skin where there is a minimal strain during motion. Our design principle is based on the idea of analyse the skin strain field during a prescribed rehabilitation motion to obtain the LoNEs and to improve the placement of the structure of the orthosis in order to boost comfort and usability. This new methodological approach combines 3D-DIC algorithm to measure the skin deformation, LoNEs and CAD/CAE tools based on non-uniform rational B-spline (NURBS) to design the structural parts of the wearable orthosis with complex shapes due to the anatomy of the body segment.

DIC is a non-contact optical tool for surface deformation measurement that has been widely accepted and used in the field of experimental. The main advantages of this methodology are the simplicity of the data acquisition devices, the ease of measurement and also its application in large deformation cases. In essence, DIC is a technique based on digital image processing and numerical computing whose basic principle is to track the same physical points located in the undeformed and deformed images. In 3D-DIC (also called stereo-DIC), the 3D surface object is reconstructed by processing the images captured by two cameras with different perspectives. A random gray-value dot pattern is painted on the surface (in this case on the human skin) to perform a correspondence between points of the two images using the DIC algorithm. A comprehensive description of the metrological aspects can be found in (9,10). The zero-mean normalized correlation criterion (ZNCC) has been used in this study as it is robust against changes in the deformed image’s scale and intensity offset (Pan et al. 2007).

\[
\psi = \frac{\sum_{\xi} \sum_{\eta} [f(\xi,\eta) - \tilde{f}] [g(\xi',\eta') - \tilde{g}]}{\sqrt{\sum_{\xi} \sum_{\eta} [f(\xi,\eta) - \tilde{f}]^2 \sum_{\xi} \sum_{\eta} [g(\xi,\eta) - \tilde{g}]^2}}
\]  

(1)

where $\psi$ is the ZNCC, and $f(\xi,\eta)$ are the greyscale values at the pixel $g(\xi',\eta')$ in the reference and shift window, respectively. $\tilde{f}$ is the mean value of $f(\xi,\eta)$ over the reference subset of dimension a x b pixels and $\tilde{g}$ is the mean value of $g(\xi',\eta')$ over the subset of current image. The maximum value of $\psi$ is the best match between two images. Three primary steps are differentiated in the proposed methodology: stereo-system calibration, know control points, image recording and matching and, finally, 3D reconstruction and computation of the strain field (figure 3).
2.1. Experimental Setup

2.2. In this study, the skin strain field at the ankle joint was measured for one subject. Two DSLR cameras (Nikon D3300, Full HD-1080p) was used to create the stereo system and to obtain simultaneously the images of ankle-foot during the support phase of the human gait. A 22mm focal length lens with low-distortion and F-number of 14 (f/14) was used to provide a good depth of field. The setting of both camera was manually changed to obtain the best shutter speed (about 1/250) given the lighting conditions. A LED light to illuminate the ankle-foot was used. To calibrate the system, a specialized frame to calibrate stereo systems with different size of black and white pattern of dot was used. All image acquisition and 3D-DIC procedure was performed in MATLAB (Mathworks Inc.) using an own developed toolbox. Tangential component of strain, principal strain magnitudes and LoNEs corresponding to the support phase heel contact, mid-stance and toe-foot was analysed. Both sides of the foot, both lateral and medial sides were recorded. The subject was instructed to keep a natural gait during and random step were selected to the study. Image of reference was captured standing in a static position.

3. Results and Conclusions

Tangential component of strain, principal strain magnitudes and LoNEs corresponding to the support phase heel contact, mid-stance and toe-off was analysed. Both sides of the foot, both lateral and medial sides were recorded. In figure 6 shows the tangential and principal strains values in lateral and medial view during different stages of stance phase.
Based on this analysis, LoNEs can be identified applying the strain ellipse theory and polar decomposition theorem. The directions of the LoNEs can be calculated by the following expression:

\[ \theta = \tan^{-1}\left(\sqrt{-\frac{\lambda_f}{\lambda_{II}}}\right) \]  \hspace{1cm} (2)

where \( \lambda_f \) and \( \lambda_{II} \) are the principal strain magnitudes (eigenvalues).

Once obtained the LoNES and skin strain field, the orthoses design is created in a CAD/CAE environment. To begin the design of the virtual prototype, the triangular mesh (.obj file format) of body segment, previously obtained from the cloud points, is imported to a CAD/CAE software. Based on this mesh, section curves with B-spline can be constructed and converted in a mathematical NURBS surface (Concheiro et al. 2014; Inoue, Kikuchi, and Masuyama 2005). An offset of 2 mm is applied to the triangular mesh to avoid discomfort and to prevent the physiological swelling. From the NURBS shaped cut of the CAD surface it is transformed into IGES format for input to a CAD/CAE environment and then the virtual 3D model of wearable orthosis is constructed.

To check the structural integrity, a static analysis in a CAD/CAE environment was performed to obtain the mayor stress zones of orthosis during human gait. The direction of the loads was chosen based on the reaction force direction’s vector in the stance phases of a human gait (figure 4). The material applied was ABS due to is the principal material of the convectional 3D printers and use in other work of the bibliography (Faustini et al. 2008; Papi et al. 2015).
Figure 4. Static analysis of orthosis in CAD/CAE environment.

In figure 4 can be seen that the major stress areas are situated around the thinner parts connecting the sole with the calf shank. Thus, a major reinforce in these zones must be done to ensure the structural integrity of the orthoses.

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