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Towards the generation of a parametric foot model using principal component analysis: A pilot study

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ABSTRACT

There have been many recent developments in patient-specific models with their potential to provide more information on the human pathophysiology and the increase in computational power. However they are not yet successfully applied in a clinical setting. One of the main challenges is the time required for mesh creation, which is difficult to automate.

The development of parametric models by means of the Principle Component Analysis (PCA) represents an appealing solution. In this study PCA has been applied to the feet of a small cohort of diabetic and healthy subjects, in order to evaluate the possibility of developing parametric foot models, and to use them to identify variations and similarities between the two populations. Both the skin and the first metatarsal bones have been examined. Besides the reduced sample of subjects considered in the analysis, results demonstrated that the method adopted herein constitutes a first step towards the realization of a parametric foot models for biomechanical analysis. Furthermore the study showed that the methodology can successfully describe features in the foot, and evaluate differences in the shape of healthy and diabetic subjects.

1. Introduction

Recently the development of Patient-specific models (PSMs) tailored to patient-specific data, has gained increasing attention in clinical applications [1–4]. PSMs could represent a solution to the growing awareness of personalized medicine [5]. PSMs have the potential of improving diagnosis and optimizing clinical treatments by predicting and comparing the outcomes of different approaches of intervention. Furthermore, they can provide information that cannot be directly measured, such as muscle forces or internal stresses and strains of the bones.

Given the considerable amount of diseases affecting motor ability, PSMs of the lower limbs have been broadly addressed in the literature [6]. One of the most popular techniques is the finite element (FE) analysis due to its flexibility and adaptability to model biological geometries and materials, and to simulate complicated boundary and loading conditions. FE modeling constitutes a useful tool to provide an insight of the internal behavior of the human body. However, despite the increasing attention, FE modeling has not yet been successfully integrated into clinical practice [2].

One challenge for the development of FE models is the time required to generate personal-specific models, which often involve the segmentation of MRI or CT images. In addition, this process requires high levels of user intervention due to the complexity of the human anatomy. The excessive effort and time required to generate 3D FE models has motivated the development of more effective mesh generation techniques based on reconstructed image data [7]. This may provide an alternative to the image-based segmentation process.

Common procedures used for this purpose are the Independent Component Analysis (ICA) and the Principal Component Analysis (PCA). Both are statistical techniques for analyzing multivariate data which identify features or variations within a population by highlighting their similarities and differences [8–11]. These features are ordered according to their relative significance and can be used to reconstruct the shape of different organs. PCA has been successfully used for several different applications like face recognition [8,12] characterization of the adult human femur [13,14] and

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Table 1
Demographic and clinical data of the healthy and the neuropathic subjects. # = number of subjects.

	HS1	HS2	HS3	DNS1	DNS2	DNS3
Gender	Female	Female	Female	Male	Male	Male
BMI [kg/m^2]	20.15	21.48	22.94	25.10	24.50	37
Age	31	26	39	65	59	71
Foot size [EU size]	40.5	38	43.5	42.5	42	43
Cavus foot	–	Right/left	–	Right/left	Right/left	Right/left
Flat foot	–	Right	–	–	–	–
Hallux valgus	–	Right	–	–	–	–
Foot deformities	–	–	–	Hammertoes/claw toes	Claw toes	Claw toes
Plantar callosity	–	Under metatarsal heads	–	–	Under metatarsal heads	Under metatarsal heads

sex determination from unidentified skeletal remains [15]. On the other hand, ICA has been extensively used in the ECG analysis [16–18].

To the authors' knowledge there are no studies focusing on the foot even though several 2 and 3-dimensional foot FE models have been proposed given their applicability in the design of therapeutic footwear and in the evaluation of the diabetic foot [19–24].

The latter is one of the most common consequences of diabetes and it implies the formation of ulcers which are major causes of disability in patients, often resulting in significant morbidity, extensive periods of hospitalization and mortality [25,26]. FE simulations can be used to predict the load distribution between the foot and different supports, and to provide additional information to the clinicians such as the internal stresses/strains of the ankle–foot complex [20]. Considering the complexity of the foot, the development of a parametric model would really benefit the field and make the translation into a clinical context easier.

The aim of this preliminary study was to develop a new method for generating a parametric foot model based on PCA. The statistical technique was applied to 6 foot meshes for a preliminary feature analysis, 3 of which were of diabetic subjects and the rest were of healthy subjects. Such an approach can be useful for reducing current drawbacks of model generation, as well as allowing variations and similarities between the two populations to be identified. A similar method was applied on the meshes of the levator ani muscle [27] but never to a complex structure like the foot. It has the potential to markedly reduce the time required for FE model generation, providing an opportunity for rapid generation of a large population of geometries that can be used for simulations.

2. Methods

2.1. Subjects

Three healthy subjects (HSs) and 3 diabetic subjects (DBs) were enrolled. Clinical and demographic characteristics are reported in Table 1.

DBs were recruited among the patients attending the outpatient Clinic at the Department of Metabolic Disease of the University of Padova (Italy). The criteria of inclusion were type 1 or 2 diabetes, no history of neurological disorders (apart from neuropathy) or ulcers, orthopaedic problems, lower limb surgery or cardiovascular disease. They should also have intact walking ability. HSs were enrolled among the personnel of the Department of Engineering Information of the University of Padova. Written informed consents were given by all subjects. The protocol was approved by the local Ethic Committee of the University Clinic of Padova.

All the DBs underwent a neurological evaluation that included the assessment of symptoms, and signs compatible with peripheral nerve dysfunction. The Michigan Neuropathy Screening Instrument was used [28,29]. Furthermore they underwent a physical examination as in Sawacha et al. [30].

Each DBs had at least one urinary albumin-to-creatinine ratio measured (0–30 mg/g normal, 30–300 mg/g microalbuminuria, 4300 mg/g macroalbuminuria), one ophthalmologic examination, one 12-leads electrocardiogram collected in the three months preceding the study, and one carotid artery Doppler ultrasound examination and HbA1c values from the preceding ten years.

2.2. Data acquisition

A right feet MRI was acquired with 1.5 T devices on each HS and DB in a completely unloaded condition. More details are provided in Table 2. The grey scale images were then segmented with Simpleware-ScanIP software (v.5.0) into both the skin and 30 bones to represent the overall shape of the foot. The triangulated mesh was then generated from the bitmapped data with the Simpleware-ScanFE module (algorithm FE-Free, minimum and maximum edge length respectively of 6/8 mm, 0.4 mm target maximum error – smaller than the MRI resolution).

First of all, only the geometry of the first metatarsal bone (FMTB) was extracted from each mesh to perform the PCA, as the area underneath it has been proven to be at a higher risk for the development of foot ulcers [25] (Fig. 2). In the paper this will be referred to as Case A.

In order to analyse the geometrical variations of the whole foot, the outline of the skin of the feet was also extracted for every DBs and HSs. The toes were removed from the skin meshes due to large inter-subject variations. This allowed us to focus on the evaluation of features of the overall foot between DBs and HSs (Fig. 3). In the paper this will be referred to as Case B.

2.3. Geometric feature extraction

The application of the PCA has two requirements: the meshes have to be aligned to eliminate spatial variations and they must have the same number of vertices. In order to achieve this, MeshLab (http://meshlab.sourceforge.net/) was used to control the number of elements coupled with NMSBuilder [3] for performing the mesh co-registration. NMSBuilder implements a standard rigid vertex-to-vertex iterative closest point (ICP) algorithm to align a moving mesh with a fixed one [31].

Then the elements of the meshes were reordered using k-nearest neighbor algorithm (k-NN). K-NN is a non-parametric method used for classification and regression. It solved the problem of finding the closest vertices given a reference so that the nodal numbers were consistent across all the meshes. Nodal coordinates of the meshes were then extracted to form a matrix M where each row corresponded to one individual. After this procedure was completed on all the meshes, PCA was performed by first computing the mean nodal coordinates M_{mean} across the population and then subtracting it from M to obtain $M_{\mathrm{adjust}} = M - M_{\mathrm{mean}}$. The covariance matrix of M_{adjust} was evaluated and an eigenvalue analysis was performed [8].