Parametric analysis of bone variation to investigate future flatfoot surgery

Yanni Cai[1,2], Giulia Pascoletti[3], Sarah Junaid[2], Peter Zioupos[4], Elisabetta Zanetti[3], Trevor Ringrose[1], Basil Budair[5]
[1]Cranfield Forensic Institute, Defence Academy of the UK, Cranfield Univ. UK, [2]School of Mechanical, Biomedical and Design Engineering, Aston Univ. UK, [3]Department of Engineering, University of Perugia, Italy, [4]Biomedical Engineering, School of Engineering, Univ. of Hull, Kingston upon Hull, UK, [5]Royal Orthopaedic Hospital (ROH) Birmingham, UK
yanni.cai@cranfield.ac.uk

INTRODUCTION: Flatfoot is a condition commonly seen in children and adults, associated with foot arch flattening or lack of development of the foot arch and foot malalignment. Surgical corrective surgery is one option for symptomatic cases; however, outcomes can be variable and the multiple factors that affect surgical outcomes are still not clearly understood [1]. Due to a general disagreement on the clinical or radiographic criteria to define this condition, it is still considered by most to be a poorly understood topic and consequently all associated definitions are still somewhat superficial [2]. This explains why it is important to determine the key parameters which define the condition.
This research aims to develop a parametric model to improve understanding of bony anatomy of the calcaneum and medial cuneiform bones. The are the two bone that are usually reshaped to achieve surgical correction in adolescent flatfeet (Evans and Cotton osteotomy). There is no study currently that looked at variation in anatomical shape in these two specific bones, the calcaneus and the medial cuneiform, in skeletally mature adolescents with and without flatfoot deformity. There is also no available studies that look at anatomical changes in the pre- and post-operative shapes of these bones. The present paper outlines the methodology to achieve these goals within the context of this study.

METHODS: The methodology applied here is a proof of concept of the methodology based on the parametrisation paper and script written by Pascoletti et al. (2021) [3], which was used to analyse the morphological differences in the mandible and femur, while here will be applied on the calcaneus and medial cuneiform using five computed tomography (CT) scans of feet acquired from cadavers, assuming that they do not suffer from any foot related condition.
A key element of this methodology is the use of iso-topological meshes, meshes that have the same topology, where all nodes in the surface mesh can be treated as variables for the following statistical analyses. These are created by implementing some transformations in order to make the meshes comparable, which means all the information related to location, scale and rotation are eliminated in a way that only shape remains, through the use of the RBF (Radial Basis Function) method, with the help of placing 18 landmarks as location points for each calcaneus and 6 landmarks for each medial cuneiform. GPA (Generalised Procrustes Analysis) is applied to find the average shape and PCA (Principal Component Analysis), a widely used statistical analysis method to reduce data dimensionality, is applied on the database to find the variability model describing the dataset, which consists of modes (principal components), that explain a set percentage of total variation of the database, and related weights, that change depending on the sample they are explaining.

RESULTS SECTION: Applying PCA on a dataset of five calcanei and then five medial cuneiform bones found that three Principal Components (PCs) were needed to explain 98% (Figure 1) of the total variance of the dataset for the calcaneus and two PCs to explain 88% of the medial cuneiform. A qualitative analysis (Figure 2) using images and a quantitative analysis (Figure 3) comparing the landmarks coordinates of the singular shapes was made, showing observable correlations between different landmarks.

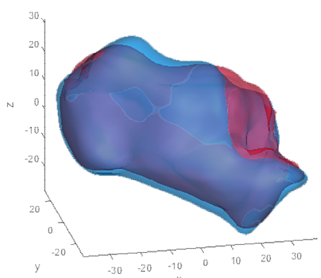

Figure 1 - PC1 of the calcaneus. Average shape is in red and the PC1 is in blue.

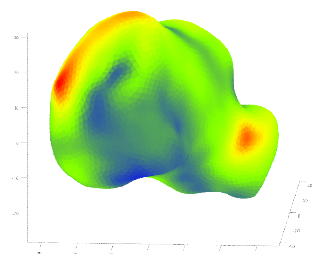

Figure 2 - Qualitative analysis of PC1 of the calcaneus compared to the average shape. Areas with the most differences are in red, while areas with fewer differences are in blue.

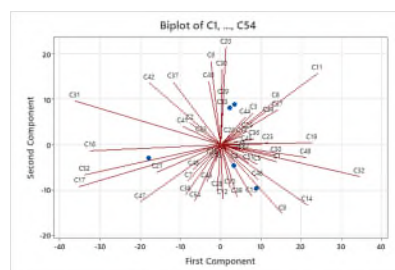

Figure 3 - Qualitative analysis of the 18 landmarks for the calcaneus in x, y and z.

DISCUSSION: Given the nature of this preliminary study, five CT scans are not statistically significant, and the acquired results are not relevant in any way. Although, applying PCA only on the selected 18 and 6 landmarks, correlations between specific medically relevant points can be discovered. This can give surgeons more information about the bones they are going to reshape during surgery that can hopefully lead to better surgical planning.
To expand the database in order to have better results, the New Mexico Decedent Image Database [4] is used to collect the lower limb CT scans of 10 men and 10 women (additional 40 calcanei and 40 medial cuneiform bones) that have been selected from a database of more than 15,000 subjects who died between 2010 and 2017, which also includes relevant medical history, that do not suffer from any foot or lower limb related condition or surgery. This is expected to give more reliable results from the PCA, which would better explain the specifics of medically relevant points in those two bones that are going to be reshaped by the Evans' surgery.

REFERENCES:
1. M. Myerson, Correction of Flatfoot Deformity in the Child, 2019.
2. K. Bauer et al., J Pediatr Orthop, 36(8): 865-869, 2016.
3. G. Pascoletti et al., Appl Sci, 11:1-14, 2021.
4. H. J. H. Edgar et al., New Mexico Decedent Image Database. Office of the Medical Investigator, University of New Mexico, 2020.

ACKNOWLEDGEMENTS: This work was supported by grant EP/R513027/1 from the EPSRC DTP 2018-2019.

SIGNIFICANCE/CLINICAL RELEVANCE: This methodology has the potential to be effective regarding the shape analysis of the calcaneus and medial cuneiform, once applied on the actual pre- and post-operative shapes, being able to tell what these bones have in common and being able to highlight what change has been made to the post-operative bone. More importantly it will make it possible at a later stage to relate the pre- to post-surgery shapes to parametric shape changes and relate these to the surgical outcomes.