Lecture Notes in Mechanical Engineering

Monica Carfagni · Rocco Furferi ·
Paolo Di Stefano · Lapo Governi ·
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Design Tools and Methods in Industrial Engineering III

Proceedings of the Third International Conference on Design Tools and Methods in Industrial Engineering, ADM 2023, September 6–8, 2023, Florence, Italy, Volume 2

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Editors
Monica Carfagni
Department of Industrial Engineering
University of Florence
Florence, Italy

Paolo Di Stefano
Department of Industrial and Information
Engineering and Economics
University of L'Aquila
L'Aquila, Italy

Francesco Gherardini
Department of Engineering "Enzo Ferrari"
University of Modena and Reggio Emilia
Modena, Italy

Rocco Furferi
Department of Industrial Engineering
University of Florence
Florence, Italy

Lapo Governi
Department of Industrial Engineering
University of Florence
Florence, Italy

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Foreword

It is a great honor and pleasure to welcome you to the International Conference ADM 2023 promoted by ADM, the Italian Association of Design Methods and Tools for Industrial Engineering, held in Florence, Italy, 6–8 September 2023. The conference, hosted by the University of Florence, a world-renowned university, provides a forum for researchers and students from industry and academia to share their latest findings and challenges and promote sustainable research.

First, I wish to thank all members of the ADM Executive Board and of the Scientific Council, especially the Coordinator, Prof. Paolo di Stefano, whose support made the organization of the ADM 2023 International Conference possible.

A special thank goes to the Conference Program Chair, Prof. Monica Carfagni, and to the members of the Organizing Committee for their tremendous efforts for making this conference successful and attractive.

The number of papers submitted was significant, and I also would like to thank all the authors and all the international and Italian reviewers for their continuous collaboration and commitment that led to the publication of this book of high scientific quality consisting of two volumes.

Finally, the conference is a great opportunity to meet all together and establish new collaborations and strengthen existing ones, and this is also thanks to all ADM members for their active engagement and support, which are essential to promote and organize these initiatives.

Caterina Rizzi
ADM President

Letter to Authors

These volumes collect the interventions carried out at the International Conference, ADM 2023, of the Italian Association of Design Methods and Tools for Industrial Engineering, held in Florence from 6 to 8 September 2023.

ADM is an association of researchers, mainly universities, who are at the service of scientific innovation in industry and the knowledge economy. Knowledge is a strategic resource for businesses and for society; whoever possesses it can gain a competitive advantage, especially in a context where the ability to innovate, design in time for the market, and generate high-quality products is essential to continue to exist in the markets.

The conference ADM represents a regular event that has been repeated for almost 50 years. The conference aims to discuss the latest advances in research and share knowledge, experience, and progress in advanced methods for the design and development of industrial products, providing links between educators, industry, and academic research. Its proceedings are the acme of cultural evolution and evidence of state-of-the-art technologies for the design and development of industrial products.

The documents presented here combine the contributions of the congressmen, collected in some sections according to a criterion of homogeneity, and include a wide variety of topics concerning design and manufacturing. About 10% of the contributions come from non-Italian research groups. It is a collection of papers rich in scientific speculations, all oriented, each in a different way, to the real needs of the professions and industry. It constitutes a cultural product and confirms a tangible link between industry and academia.

To introduce new research topics or fields of application of traditional methods and promote the continued evolution of the conference, following the development of new technology, five Special Sessions have been proposed in this edition of the ADM conference. In these sessions, 32 works have been presented at the conference and are now published in these volumes.

I want to thank all the authors and colleagues for the important scientific contribution they gave to the conference with their valuable work. The ADM association exists as long as there are motivated and qualified members with high scientific qualities; today, ADM is particularly vital! I also want to thank the reviewers of the papers who, with their work, have been the guarantors of the quality of the conference and of these volumes, which are the testimony for future memory. Special thanks go to the members of the Organizing Committee for their efforts in making this conference possible and for their hospitality in Florence and to the President of the ADM, Prof. Caterina Rizzi, for supporting the initiative.

September 2023 Paolo Di Stefano

Preface

This volume, together with Volume 1, collects the proceedings of the ADM 2023 International Conference, entitled "Design tools and methods in industrial engineering III" held in Firenze (Italy) from 6 to 8 of September 2023.

The conference is organized and hosted by the Department of Industrial Engineering of Florence which, for the three days of the conference, we had the honor to represent.

Florence, a city renowned for its artistic heritage, rich history, and timeless charm, provided the perfect backdrop for our journey into the world of design methods. The picturesque streets and iconic landmarks of this cultural treasure inspired us all as we delve into the realms of research, innovation, and collaboration.

Throughout the conference days, our event served as a platform to exchange ideas, showcase breakthroughs, and foster connections that transcend borders and disciplines. Together, we explored the evolving landscape of the ADM compelling research field.

Almost 200 researchers joined the conference with an overall number of 183 papers arranged in the two volumes. More than 230 authors' authored papers were accepted at the conference, and more than 150 reviewers were involved to help the Scientific Committee in revising, scoring, and selecting accepted contributions. All papers were presented in 30 oral sessions which included also keynote speakers and session chairs. About 6 Special Sessions were organized by ADM Scientific Committee at this conference, namely Special Session on Design for Sports and Engineering, on Design Methods in Fusion Engineering, on Advanced Human Body Acquisition, on Artificial Intelligence in Design for Sustainability, on Design for Bioinspired and Sustainable Soft Robotics, and on Human Centered Design in Transportation Domain. All Special Sessions are covered in this volume. Other topics are:

Computer Aided Geometric Modeling and Design, Digital twin and digital factory, Knowledge and Product Data Management, Reverse Engineering, Digital Acquisition, Image Processing and Inspection, and X-Reality for Interactive Design.

We wish to thank the President of ADM, Prof. Caterina Rizzi, and Prof. Paolo di Stefano, coordinator of the Scientific Council of the ADM.

We also thank the whole Organizing Committee, with special thanks to Prof. Francesco Gherardini and Prof. Giuseppe Marannano for the management of the paper review procedure and to Eng. Francesco Buonamici for the precious help in organizing the Conference Sessions. Special thanks go to Doriano Giannelli and Patrizia Cecchi for the administrative and logistics management of the conference and side events. We wish to thank also all the colleagues who have supported us as members of the Scientific Committee and as reviewers and all the authors who gave their valuable contribution to the conference with their research.

Last, but not least, the publisher Springer Nature, who honored us by publishing the 2-volumes proceedings of this third edition in the series "Lecture Notes in Mechanical Engineering".

September 2023

Monica Carfagni
Rocco Furferi
Conference Program Chairs

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From Real-Time Acquisition to Mesh Morphing of Foot at Different Positions

Michele Calì[1], Elisabetta M. Zanetti[2], Francesco Bianconi[2], and Giulia Pascoletti[2](✉)

[1] Department of Electric, Electronics and Computer Engineering, University of Catania, Catania, Italy
[2] Department of Engineering, University of Perugia, Perugia, Italy
giulia.pascoletti@unipg.it

Abstract. This work is aimed to set-up a methodology for foot shape prediction at different flexion angles, overcoming limitations encountered when different poses are required but a limited set of acquisitions can be performed. The basic idea was to identify a fitting law able to interpolate positions of foot anatomical landmarks, and then use this information to guide the deformation of an average foot shape. First of all, mesh correspondence between foot geometries was accomplished by an established procedure based on mesh morphing. Then Procrustes analysis was applied to the dataset to remove rigid motions and estimate the average shape. Two interpolation laws (linear and quadratic) were investigated and the best one in terms of prediction of 3D landmarks' coordinates was identified. Finally, shape geometries at any flexion angle were predicted performing a second mesh morphing guided by interpolated landmarks' displacements from the average shape. These analyses proved that a limited number of interpolation angles provides a prediction accuracy comparable to that obtained using all the angles available in the dataset. Moreover, predicted shapes have been compared to the actual scans in terms of root mean square error between corresponding nodes, obtaining a mean value of 4.03 ± 1.39 mm, in accordance with data reported in literature.

Keywords: Real-time acquisition · Foot model · Statistical shape model · Statistical deformation model · Accurate geometric reconstruction

1 Introduction

In recent years, the acquisition of the body shape through scan techniques has quickly spread, thanks to the availability of more and more efficient and accurate technologies [1]. Nonetheless, many applications would require one step further since the outer geometry of body parts needs to be known at different poses; for example, there is a lot of interest in the individuation of lines of non-extension (LONES) in the skin, as required by the design of seams in sportswear [2] or to plan the best orientation of skin incisions in surgery [3]. Also prosthesis design [4] would take benefit from the simulation of different poses, resulting in a better fitting which can be achieved optimizing the location of flexible parts. The same issue is also of interest to ergonomists, since designing tools and devices that

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can be used at different poses has been demonstrated to be a successful strategy to improve operator health and safety [5]. Performing a high number of body scans at different poses is not always a viable perspective, considered the time required for an accurate scan and the need of high degree of subject compliance. The most common approach currently followed, for example by graphic animation [6], is based on the continuous acquisition of the position of a limited set of markers used to morph the base mesh in a second time; this method involves a complex set of video cameras for stereo-photogrammetry in dedicated laboratories. Another common approach produces the outer geometry modifications through an articulated inner skeleton [7]: the limit of this approach is setting fixed joints that should hopefully be coincident with natural joints, and actually approximate the physiological movement where the center of rotation is not perfectly fixed [6]. An alternative methodology has been here followed, based on the hypothesis that marker trajectories can be fitted by simple analytical models which are consistent among different subjects. This model allows predicting markers positions using the joint angle as predictor variable, and then using a mesh morphing technique to obtain the corresponding foot pose geometry.

2 Materials and Methods

The procedure has been tested setting up a prediction model from three different subjects: left foot geometries were scanned at five flexion angles, leaving from a configuration perpendicular to the tibia to a fully extended position. The considered subjects have non-pathological feet.

2.1 Foot Acquisition

The external geometry of the foot was scanned using three Azure Kinect devices arranged in a daisy-chain configuration (Fig. 1) with a master device synchronized with two subordinate devices. Each device includes a narrow field of view (NFOV) sensor, a wide field of view (WFOV) sensor, and a colour RGB sensor.

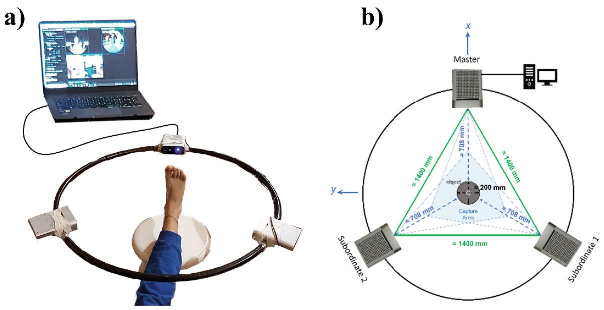

Fig. 1. a) Acquisition system setup; b) Daisy chain configuration and the reference system

Sensors were placed at the vertices of an equilateral triangle with sides of about 1400 mm while the hardware allowed the synchronization of depth images. The first step of the process is devices' calibration on a reference grid which takes about 80 s. In the next step, the plane of the triangle containing the three sensors is positioned parallel to the tibial bone and approximately perpendicular to the plantar surface (Fig. 1a) of the foot in order to optimize distance measurements; for this configuration the accuracy of kinect sensors has been estimated to be below 2 mm in the 1–2 m distance field [8].

The scene could be acquired in approximately 1.5 s for this single-loop configuration with an accuracy of just under a millimeter. Data are elaborated by RecFusion Pro software (ver. 2.3.0) which output an STL file of the foot surface with approximately 200.000 elements leading to a spatial resolution under 0.5 mm.

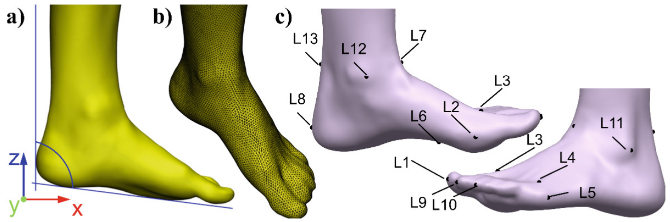

Fig. 2. a) Flexion angle definition; b) Geometry re-mesh; c) Anatomical foot landmarks

2.2 Pre-processing

Scanned feet geometries were pre-processed prior to the subsequent analysis. As a first step, spaces between toes geometries have been closed in order to reach more consistent meshes. After this, the feet were imported into the 3-Matic software (by Materialize) to align feet's axes to a common reference frame and isolate the volume of interest. The registration procedure aligned the long axis of the calf portion with the global vertical direction (z-axis, Fig. 2a), and a Cartesian reference system was established defining the x-axis on the symmetry plane of the calf along the anatomical antero-posterior direction and perpendicular to the z-axis. This registration allowed computing the foot flexion angle as the angle, in the x-z plane, between the z-axis and a line tangent to the two most prominent regions of the sole (Fig. 2a) [9]. Finally, the feet geometries have been re-meshed to obtain a uniform and looser mesh distribution, reaching an average number of nodes equal to about 10.000 (Fig. 2b); this decimation was considered to produce enough accurate results while limiting computation times.

2.3 First Mesh Morphing Analysis

The 3D geometries dataset must include consistent meshes with one-to-one correspondence between nodes to be able to perform the subsequent analyses. To do this, a mesh morphing procedure was implemented, arbitrarily selecting a 'reference foot' and morphing its mesh on all the other geometries of the dataset. 13 anatomical landmarks (Fig. 2c) have been identified in 3-Matic for all feet geometries, according to literature [10, 11]. These landmarks were used to guide the morphing procedure, through a dedicated code written in MATLAB [12], based on linear RBF morphing, nodes projection and smoothing. Four more landmarks have been added in the calf region to optimize the accuracy of the reconstructed mesh. At the end all geometries had 9636 nodes.

2.4 Interpolation Analysis

The aim of this analysis was to identify the best regression law for landmarks position prediction, based on the foot flexion angle. Given the 15 feet available in the dataset, 10 feet, with ten different flexion angles (80°, 91°, 97°, 102°, 109°, 118°, 124°, 133°, 140°, 151°), were retained for this analysis, and 5 feet were used as control set for the evaluation of prediction error. Two different laws have been investigated (linear and quadratic), based on a preliminary analysis of landmarks displacements over the dataset (Fig. 3). The regression has been set up considering g input angles ($g = 2,\ldots,10$) as the independent variable, and exploring many different combinations k of g angles, $C_{g,k}$ ($k = 1,\ldots,K_g$); the two extreme positions (80° and 151°) were always included so that each mesh could be obtained as an interpolation between meshes rather than an extrapolation. For example, the explored 3-angles combinations were 8 ($C_{3,k}$, $k = 1,\ldots 8$): each combination included the two extreme angles and one of the 8 middle angles.

A Procrustes analysis was performed on the dataset to align and center all feet which were also normalized with respect to the foot length, so that the different sizes would not bias the analysis. In the next step, the average foot shape was obtained (Fig. 3) to be used as a reference to compute landmarks displacement. Regression coefficients for both linear and quadratic laws have been so calculated for every landmark and for each combination of flexion angles $C_{g,k}$. The goodness of fit was assessed through Euclidean distances between the actual landmarks positions and the predicted ones ('p' in Eq. 1) over the dataset [12]: for a foot i ($i = 1,\ldots, N_f$) the deviation of the j-th landmark ($j = 1,\ldots, N_l$) was evaluated as:

$$d_{ij} = \sqrt{\left(x_{p,ij} - x_{ij}\right)^2 + \left(y_{p,ij} - y_{ij}\right)^2 + \left(z_{p,ij} - z_{ij}\right)^2} \tag{1}$$

A vector whose elements are the sum of squared (SS) distances d_{ji} was obtained for each foot i and for every combination k of g angles:

$$SS_{gki} = \sum\nolimits_{j=1}^{N_l} d_{ij}^2 \tag{2}$$

The optimum combination $C_{g,k*}$ for each group of g input angles was established as the one that minimizes the mean SS_{gki} over all feet, that is:

$$\mu_{SS_{gk*}} = \min\left(\sqrt{\left(\frac{1}{N_l \cdot N_f} \sum\nolimits_{i=1}^{N_f} SS_{gki}\right)}\right) \tag{3}$$

2.5 Second Mesh Morphing Analysis

Predicted landmarks coordinates were then used to perform a second mesh morphing of the average shape. Two different RBFs have been investigated (linear and thin plate).

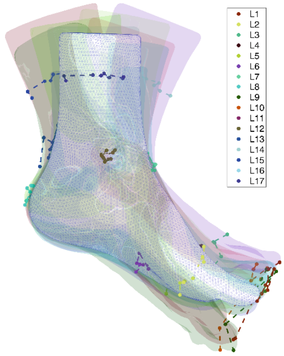

Fig. 3. Dataset after Procrustes; the average shape is represented as wireframe geometry. Dashed lines represent trajectories of anatomical landmarks (dots) over the flexion range

Morphing results were then re-scaled based on the original foot length to restore the actual foot size, and the deviation between the predicted shape and the actual foot geometries of the training set was evaluated to assess the goodness of morphing: an error distribution map was obtained considering the root of the mean squared error (RMSE), between corresponding nodes, averaged over the feet dataset. Finally, the full procedure was tested on five feet (five different flexion positions) belonging to the control dataset.

3 Results

3.1 Interpolation Analysis Results

The optimum combination of flexion angles to be used for the regression was identified for both the linear and quadratic laws. Table 1 reports the respective root of the mean squared distance for the best combination groups $C_{g,k*}$. As expected, all ten flexion angles are required to minimize the landmarks prediction error (8.29 mm and 7.13 mm, respectively) both for linear and quadratic laws.

3.2 Shape Prediction on the Training Dataset

The average shape was deformed based on respective landmarks displacements, as predicted by regression models. The best results were obtained with the quadratic landmarks' fitting, coupled to linear RBF, with an RMSE 4.03±1.39 mm and 90th percentile equal to 5.94 mm. Figure 4a shows the morphing result at 133° flexion along with the actual and predicted landmarks positions; the mean RMSE distribution colormap, plotted over the average shape geometry is depicted in Fig. 4b.

3.3 Shape Prediction on the Control Dataset

The complete interpolation and morphing procedures were then evaluated on feet that had not been included in the original dataset (control dataset). Landmarks coordinates were

Table 1. Mean errors of the linear and quadratic fitting for the optimum angles' combinations

g		C_{gk*}	μ_{SSgk*} [mm]		C_{gk*}	μ_{SSgk*} [mm]
2	**Linear**	80° 151°	11.19	**Quadratic**	-	-
3		80° 133° 151°	9.37		80° 124° 151°	8.74
4		80° 124° 133° 151°	8.75		80° 109° 118° 151°	7.78
5		80° 109° 118° 133° 151°	8.60		80° 109° 118° 140° 151°	7.49
6		80° 109° 118° 124° 140° 151°	8.46		80° 109° 118° 124° 140° 151°	7.34
7		80° 109° 118° 124° 133° 140° 151°	8.37		80° 109° 118° 124° 133° 140° 151°	7.29
8		80° 91° 97° 102° 124° 133° 140° 151°	8.35		80° 91° 97° 102° 124° 133° 140° 151°	7.22
9		80° 91° 97° 102° 109° 124° 133° 140° 151°	8.32		80° 91° 97° 102° 109° 124° 133° 140° 151°	7.22
10		**80° 91° 97° 102° 109° 118° 124° 133° 140° 151°**	**8.29**		**80° 91° 97° 102° 109° 118° 124° 133° 140° 151°**	**7.13**

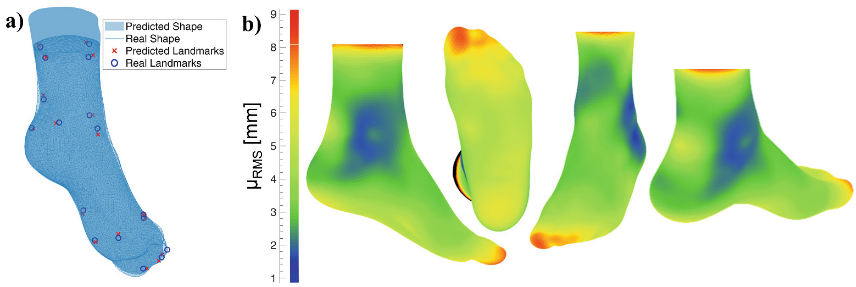

Fig. 4. a) Morphing result for θ 133°; b) Mean RMSE distribution colormap on the average foot

predicted using the quadratic interpolation model, followed by linear RBF morphing and rescaling. RMS errors for all nodes were computed at each flexion angle.

Figure 5 reports the predicted shapes and landmarks, and the RMSE colormaps for every foot position. Mean and standards RMS error for each foot ranges between 3.06 ± 1.20 mm to 4.25± 2.41 mm (Table 2), showing values comparable to the mean values obtained on training dataset predictions. The highest errors of landmarks prediction in

Table 2. Mean and 90th percentile RMSE shape prediction for the control set

Foot	$\mu_{RMS} \pm \sigma_{RMS}$ [mm]	q_{90} [mm]
1	3.06 ± 1.20	4.52
2	2.86 ± 1.25	4.67
3	3.98 ± 1.90	6.47
4	4.46 ± 2.28	8.09
5	4.25 ± 2.41	7.36

the flexion plane were associated to L9, L6 and L13 (reaching 11 mm), while all other landmarks exhibit errors below 7 mm.

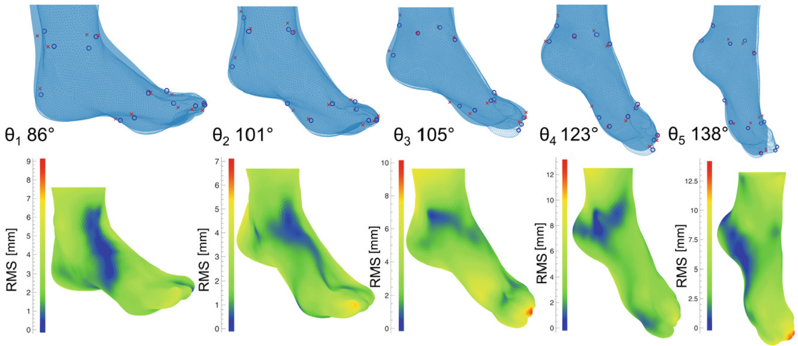

Fig. 5. Control Database: Morphing prediction (top) and RMS error distribution (bottom)

4 Discussion and Conclusions

A procedure to obtain 3D reconstructions of foot morphology at different flexion angles has been set up, having as input data foot scans obtained at a limited number of positions. More specifically, results have pointed out that using scans at extreme angle positions (90° and maximum extension) and two more intermediate scans, produces a mean error less than 0.5 mm higher compared to the 10 flexion angles fitting, while the benefit in terms of time, experimental and computational effort is significant.

The core of the procedure is the regression of landmarks displacement versus foot flexion angle. In the flexion plane (x-z plane), the most critical landmarks were those placed at the toes ends (L1, L9, L10) which resulted in errors up to 12 mm, and landmarks L13 and L6 with 8.84 mm and 8.38 mm errors. All other markers positions could be predicted by the regression with less than 6 mm errors. The cartesian axis along which the highest errors take place is the z axis with 7.5 mm and 9.3 mm respectively for markers L6 and L13; markers L9, L6 and L10 were affected by the highest errors along the x axis (6 mm).

The performance of the methodology has been tested on the training and control datasets and resulted to produce average RMS error in line with those reported by other authors who employed continuous scanning of landmarks position (5.2 ± 2.0 mm [13]). On the contrary, a lower RMS error has been reported by Schuster et al. [1] (maximum RMS equal to 4.74 ± 0.40 mm and average value <0.89 mm), however this author analyzed one single foot and variations where due to load-bearing rather than to flexion.

Considering morphed foot meshes, the highest errors were found at the toe tips and at the Achilles tendon area (Figs. 4 and 5); these areas are in correspondence of above reported landmarks, affected by the highest errors. From the control set predictions, it was shown that errors grow as flexion angles grow, and this is particularly true at the toe tips, due to a significant bias given by the added effect of meta-carpal joint (Fig. 5), not consistent among subjects. Errors measured for the training dataset are not significantly different from those reported for the control dataset; therefore, the first one can be considered as representative of physiologic variability.

Dealing with mesh morphing, thin plate function is better suited to the instep region, while the linear RBF produced better performances at the calcaneus and sole areas.

Only non-pathological feet were considered in this study, ensuring that pronation/supination effects were not so relevant to affect the results, also considering that datasets underwent a preliminary registration through Procrustes analysis.

Next steps of this research will include widening of the feet dataset and using PCA (Principal Component Analysis) to reduce the dimension of the problem. Other joint movements will be taken into account as inversion/eversion and internal/external rotation, considering both the ankle and the meta-carpal joint angles as input data.

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