Feet First: Statistical Shape Modeling as a Basis for Developing Better-Fitting Footwear

Adam Bradshaw[1,2], Tao Liu[3], Taylor Leger[4], Aiden Hallihan[4], Evangelos Spyrou[4], Sandro Nigg[1], and W. Brent Edwards[1,2]
[1]Human Performance Laboratory, Faculty of Kinesiology, University of Calgary
[2]Department of Biomedical Engineering, Schulich School of Engineering, University of Calgary
[3]Department of Mechanical Engineering, Faculty of Engineering and Applied Science, Ontario Tech University
[4]CCM Hockey, Montreal
email: adam.bradshaw@ucalgary.ca

Summary

We have developed the largest-known statistical shape model (SSM) of the human foot using an expansive 3D foot scan dataset. In this study, six methods were examined to generate footwear fit shapes from the dataset, combining dimensionality reduction techniques and clustering algorithms. Calculated fit quality was similar between the six proposed methods, but all outperformed a model based on average foot shape. The SSM may represent a novel and viable statistically-driven technique for developing consumer footwear fits.

Introduction

Foot morphology can vary greatly, even within the same shoe size [1]. To accommodate this variation, footwear brands may offer multiple fit options within each size, with width and other simple 1D measures as the primary determining factor. While most analyses of foot shape use similar 1D or 2D anthropometric measures, the foot is a complex anatomical structure that varies in 3 dimensions. Statistical shape modeling provides a comprehensive understanding of a collection of shapes by representing the average shape and its 3D variation, which may help to design better-fitting footwear. Our objective was to compare six different methods for generating footwear fit shapes from the SSM.

Methods

20,096 anonymized 3D foot scans (foot length: 235-295mm) were collected in ice hockey equipment stores using the CCM 3D Fit Scanner (CCM Hockey) and Structure Sensor (Mark II). Each scan included 4542 points and was truncated 10-20mm above the malleoli after alignment and registration using a non-rigid Coherent Point Drift algorithm in MATLAB [2]. Principal component analysis (PCA) was then applied to extract principal variations of foot shape.

The dataset was divided into 15 size categories (based on foot length, with 4mm increments) and split into training (80%) and validation (20%) subsets. Six methods for generating representative footwear fit shapes were tested, combining three dimensionality reduction techniques (PCA, t-SNE, UMAP) with two clustering algorithms (k-Means, Gaussian Mixture Models). First, dimension reduction was applied to training data in each size (PCA: first 2 components; t-SNE and UMAP: 2 dimensions) followed by clustering to identify three foot shape groups. For each cluster, the average shape of the grouped scans was found, becoming Fits A, B, and C. The generated fits were subsequently compared against the average shape for each unclustered size subset (“Average Fit”).

Fit quality was assessed by comparing root-mean-squared-error (RMSE) between validation scans and the generated fits by size. Lower RMSE values indicate better fit. The lowest RMSE for each validation scan was determined across Fits A, B, and C for each method, and for the Average Fit shape.

Results and Discussion

The resulting statistical shape model was evaluated for accuracy, compactness, generalizability, and stability [3-4]. The first 50 principal components explained 95.24% of the variance in foot shape across all sizes, with the size- and length-dominant first PC accounting for 57.73%. Stability in the first 50 PCs was reached at around 4000 samples. With only the first 50 PCs, the model was generalizable at 200 samples to a reconstruction accuracy of 2mm. Further, all six tested fit generation methods successfully reduced mean RMSE values in comparison to the Average Fit method (Table 1).

Conclusions

A stronger understanding of foot morphology variance using the outlined statistical shape modeling approaches may help to design footwear that optimizes user fit and comfort, particularly in rigid footwear like ice hockey skates, ski boots, and work boots. These methods can also be applied more broadly in orthopedics, ergonomics, and apparel design to better understand anatomical differences across populations, and to develop products that accommodate a wider range of physical characteristics.

Acknowledgments

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References

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	Average Fit	t-SNE		UMAP		PCA	
		GMM	k-Means	GMM	k-Means	GMM	k-Means
RMSE [mm] (SD)	5.41 (0.13)	4.74 (0.11)	4.73 (0.12)	4.74 (0.11)	4.72 (0.12)	4.88 (0.22)	4.73 (0.11)

Table 1: Fit generation methods comparison, in terms of root-mean-squared-error (RMSE) to validation subset (mean across size categories).