Preliminary Study on Dynamic Foot Model

Ameersing Luximon[1] and Yan Luximon[2]

[1] Institute of Textiles and Clothing, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[2] School of Design, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
tcshyam@polyu.edu.hk

Abstract. It is generally accepted that improper footwear design causes injuries and illnesses. Existing literature indicated that mostly static footwear fit has been studied to some extent, even though we are well aware that dynamic footwear fit is different. In addition to static fit, illnesses and injuries will occur due to dynamic pressure, friction, and foot movement beyond the normal range of motion. This study proposes a method for dynamic foot shape computation. The dynamic foot is generated by using multi-dimensional transformation of the 3D static foot based on the angular values of the foot movement. This provides a simple algorithm to deform the foot to create dynamic 3D foot shape. Result of this study is essential to build a model for dynamic fit computation.

1 Introduction

The human foot, an unsymmetrical object, consists of complex arrangements of 26 bones and other tissues namely cartilage, muscles, tendons, ligaments, nerves and blood vessels [1, 2]. Even though footwear has become more specialized these days, research on fit, especially during dynamic situation, have often been neglected [3], leading to foot-related problems such as bunions, calluses, corns, plantar forefoot pain, hallux valgus, metatarsalgia, and ankle sprain [4, 5].

The foot has size, shape and proportion variations within a person and among persons [6]. For specific individual there is considerable difference between right and left foot, weight-bearing, dynamic and thermal conditions [7]. Apart from the variation of the feet within a person, there are variations depending on gender [3-5, 8-9], age [4, 8] and race [5, 9]. In order to better understand the foot shape, feet have been classified [10] according to racial differences [5-7], arch type [11-12], flare angle [13-14], rear foot position [10, 15-20], big toe length [1] and foot print indices [20-24].

The variation in foot clearly indicates that development of better fitting footwear is a challenge. It is very important to understand the 3D foot shape. Currently footwear is produced in different sizes based on foot length and girth (or width). Since foot length and width are somewhat correlated and therefore current sizing methods are not optimal. Some studies have shown the importance of foot curvature (or flare angle) [25-27] and therefore an accurate and reliable method has been developed to quantify foot curvature (or foot flare) using principle component method [26]. Moreover analysis of footwear outline and footwear fit perception showed that differences in

V.G. Duffy (Ed.): Digital Human Modeling, HCII 2011, LNCS 6777, pp. 321–327, 2011.

footwear curvature can have differences in perception [25]. There should be a match between foot curvature and footwear curvature [27-29] Since foot outline and foot pressure distribution are important shapes that can influence fitting and foot outline was represented accurately using eight specially chosen landmarks [30] The accuracy was calculated based on dimensional differences [30] In addition to 2D shapes, 3D foot shape was predicted using three methods [25, 31-32]. The first method uses foot length, foot width, foot height, foot curvature and a standard foot shape to predict the complete food shape [31]. The second method uses foot outline, foot height, and a standard foot shape and the third method uses foot outline, foot profile and a standard foot shape [32]. The third method can predict foot shape to an accuracy of around 1mm. These techniques show that better foot prediction can be used for future developments of sizing based on 3D foot shape. Many of these studies are done using static foot shape data, dynamic foot data is still missing for better fitting footwear development.

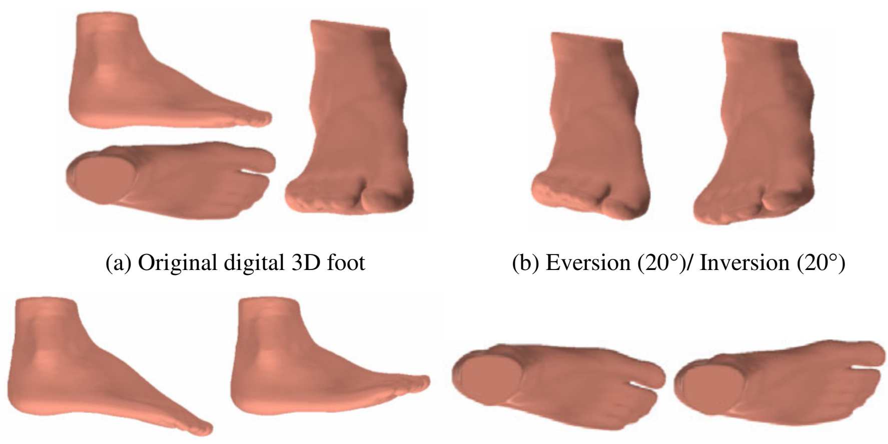
Several studies have been done for better quantification of foot shape and use of computational tools to capture foot shape. The foot height [33] and mid-foot shape [34] have been modeled to develop footwear without laces [35], boots [36] and ladies shoes [37]. The plantar foot shape changes under different load-bearing conditions have also been quantified [38-39]. The foot types (normal, pes cavus, and pes planus) were evaluated based on dynamic foot pressure distributions [40]. The foot contact properties were analyzed based on footprints and dynamic foot pressure distributions [41]. Recent studies have been aimed to develop comfortable plantar support for high heel shoes [42-43].

In dynamic situation such as normal gait, the foot is undergoes different stages including pronation during heel strike and supination during push-off. Supination is a combination of inward rotation at the ankle, adduction of the hindfoot, inversion of the forefoot, and plantarflexion, while pronation is a combination of abduction of forefoot, eversion of hindfoot and dorsiflexion [44]. The foot has 28±6.9° abduction and 28±4.8° adduction [44]; 37±4.5° inversion and 21±5.0° eversion; and 13±4.4° dorsiflexion and 56±6.1° plantarflexion [45]. The dorsiflexion/plantarflexion is different for gender and age group [46]. The foot range of motion is used for foot evaluation [47], and it is widely accepted that foot movement beyond the normal range causes foot injury, mainly ankle sprains [48]. Van Rijn [49] provides a detailed review of ankle sprain injury. Therefore knowledge of dynamic and static foot shape is essential, in medical as well as footwear design.

During the last decade, emergence of 3D laser scanners and digital imaging technologies [50-51] are enabling the quantification of 3D foot shape. Even though 3D laser scanning technology is widely used [52], capture of dynamic foot shape is still at its infancy. So far, few studies used projection pattern and digital camera to capture dynamic foot shape while walking [53-54]. This study uses simple multi-dimensional deformation to model dynamic foot shape. Once the dynamic foot has been generated, it can be used for fit evaluation and for complex computational models.

2 Dynamic Fit Model

Let P be the data point set representing 3D foot shape. The points p_i is the i^{th} data point denoted as $\{p_i = (x_i, y_i, z_i) \in P, \text{ where } i = 1, \ldots n\}$. In order to have non-linear 'shear' or deformation, an interface plane is required. The interface plane separates two regions. One region will be deformed while the other is not deformed. Let assume the interface plane is plane *A*. The equation of the plane *A* is given by Equation (1). If we want to consider the toe side, then *S* is the point set of the selected part is denoted as $\{ s_i = (x_{s,i}, y_{s,i}, z_{s,i}) \in P \mid ex_i + fy_i + gz_i < h,\ i = 1,\dots n_s \}$. For a given point s_i, the point a_i is computed, where $d_{s,i}$ is the shortest distance from point s_i to the plane *A* (Equation (2)). The vector $\bar{t}_s$ indicates the shear direction. The offset of the point s_i is $o_{s,i}$ and is influenced by $\bar{t}_s$ and $d_{s,i}$. If a cubic hermite spline function is used, the relationship between $d_{s,i}$ and $o_{s,i}$ is given in Equation (3). $O_{s\max}$ is the maximum offset for $o_{s,i}$ and $D_{\max}$ is the maximum of $d_{s,i}$. The new position s_i^* of the point s_i after a non-linear shear transformation along vector $\bar{t}_s$ is given in Equation (4). The shear transformation will be used to calculate plantar-flexion/dorsiflexion, and with some modifications foot shape for different heel height and shank curve. Similar to non-linear shear, non-linear rotation can be used to calculate forefoot or rear foot everted/inverted foot shape. Non-linear scaling will be used to generate changes to foot shape due to different weight bearing. Preliminary results are shown in Figure 1. Currently the data has not been validated. The prediction error between predicted and measured foot can be calculated using average and standard deviation of dimensional differences [30-32].



(a) Original digital 3D foot (b) Eversion (20°)/ Inversion (20°)

(c) Plantar-flexion (20°)/ Dorsi-flexion (20°) (d) Abduction (5°)/ Adduction (20°)

Fig. 1. Preliminary results for 3D dynamic shape prediction using non-linear multidimensional transformation

$$ex + fy + gz = h \tag{1}$$

$$d_{s,i} = |s_i - a_i| \tag{2}$$

$$o_{s,i} = \left[-2\left(\frac{d_{s,i}}{D_{\max}}\right)^3 + 3\left(\frac{d_{s,i}}{D_{\max}}\right)^2 \right] \times O_{s\max} \qquad 0 \le d_{s,i} \le D_{\max} \tag{3}$$

$$s_i^* = s_i + o_{s,i} \times \hat{t}_s \tag{4}$$

3 Discussion and Conclusion

This study attempts to generate dynamic foot shape using static foot shape and simple multi-dimensional scaling. Further research is needed to create a comprehensive model, but the results seem promising. Although dynamic foot scanners are being developed, there will be a need for developing a model for dynamic foot shape that can be generated from static foot shape. Currently foot scanner can capture the 3D foot shape, usually in static state. Similarly, it is fairly easy to capture location of landmarks on the foot in dynamic situation (for example in normal gait or running) using motion capture systems. Using motion capture system landmarks on the foot can be located in dynamic situation. The relative position of the landmarks can be used to find angular values of the foot movement in terms of plantar-flexion/dorsi-flexion; eversion/inversion; and adduction/abduction. The dynamic foot is generated by using multi-dimensional transformation of the 3D static foot based on the calculated angular values of the foot movement. Preliminary results indicate that the static foot shape can be deformed. Further studies are still required to validate our results.

Acknowledgment. This work was supported by The Hong Kong polytechnic grant (A-PH98).

References

1. Morton, D.J.: The Human Foot. Columbia University Press, New York (1935)
2. Sarrafian, S.K.: Anatomy of the Foot and Ankle: Descriptive, Topographic, Functional. JB Lippincott, Philadelphia (1993)
3. Rossi, W.A.: The Futile Search for the Perfect Shoe Fit. Journal of Testing and Evaluation 16, 393–403 (1988)
4. Pfeiffer, M., Kotz, R., Ledl, T., Hauser, G., Sluga, M.: Prevalence of Flat Foot in Preschool-Aged Children. Pediatrics 118, 634–639 (2006)
5. Hawes, M.R., Sovak, D., Miyashita, M., Kang, S.-J., Yoshihuku, Y., Tanaka, S.: Ethnics Differences in Forefoot Shape and the Determination of Shoe Comfort. Ergonomics 37(1), 187–196 (1994)
6. Cavanagh, P.R.: The Running Shoe Book. Anderson World, Mountain View (1980)
7. Cheskin, M.P.: The Complete Handbook of Athletic Footwear. Fairchild Publications, New York (1987)

8. Adrian, K.C.: American Last Making: Procedures, Scale Comparisons, Sizing and Grading Information, Basic Shell Layout, Bottom Equipment Standards. Shoe Trades Publishing, Arlington (1991)
9. Fessler, D.M.T., Haley, K.J., Lal, R.D.: Sexual Dimorphism in Foot Length Proportionate to Stature. Annals of Human Biology 32(1), 44–59 (2005)
10. Razeghi, M., Batt, M.E.: Foot Type Classification: a Critical Review of Current Methods. Gait and Posture 15, 282–291 (2002)
11. Nachbauer, W., Nigg, B.M.: Effects of Arch Height of the Foot on Ground Reaction Forces in Running. Med. Sci. Sports Exerc. 24(11), 1264–1269 (1992)
12. Williams, D.S., Mcclay, I.S.: Measurements Used to Characterize the Foot and the Medial Longitudinal Arch: Reliability and Validity. Phys. Ther. 80(9), 864–871 (2000)
13. Freedman, A., Huntington, E.C., Davis, G.C., Magee, R.B., Milstead, V.M., Kirkpatrick, C.M.: Foot Dimensions of Soldiers (Third Partial Report Project No. T-13). Armored Medical Research Laboratory, Fort Knox, Kentucky (1946)
14. Yavatkar, A.S.: Computer Aided System Approach to Determine the Shoe-Last Size and Shape Based on Statistical Approximated Model of a Human Foot. Unpublished Masters Thesis. Tufts University, Medford MA (1993)
15. Kouchi, M., Tsutsumi, E.: Relation Between the Medial Axis of the Foot Outline and 3-D Foot Shape. Ergonomics 39, 853–861 (1996)
16. Sell, K., Verity, T.M., Worrel, T.W., Pease, B.J., Wigglesworth, J.: Two Measurement Techniques for Assessing Subtalar Joint Position: A Reliability Study. J. Orthop. Sports Phys. Ther. 19(3), 162–167 (1994)
17. Smith, L.S., Clarke, T.E., Hamill, C.L., Santopietro, F.: The Effects of Soft and Semi-Rigid Orthoses upon Rearfoot Movement In Running. J. Am. Pediatr. Med. Assoc. 76(4), 227–233 (1986)
18. Kernozek, T.W., Greer, N.L.: Quadriceps Angle and Rearfoot Motion: Relationships in Walking. Arch Phys. Med. Rehab. 74(4), 407–410 (1993)
19. Kernozek, T.W., Ricard, M.D.: Foot Placement Angle and Arch Type: Effect on Rearfoot Motion. Arch Phys. Med. Rehab. 71(12), 988–991 (1990)
20. Mcpoil, T.G., Cornwall, M.W.: Relationship between Three Static Angles of the Rearfoot and the Pattern of Rearfoot Motion During Walking. J. Orthop. Sports Phys. Ther. 23(6), 370–375 (1996)
21. Cavanagh, P.R., Rodgers, M.M.: The Arch Index: a Useful Measure from Footprints. J. Biomech. 20(5), 547–551 (1987)
22. Staheli, L.T., Chew, D.E., Corbett, M.: The Longitudinal Arch. A Survey of Eight Hundred and Eighty-Two Feet in Normal Children and Adults. J. Bone Joint Surg. Am. 69(3), 426–428 (1987)
23. Chu, W.C., Lee, S.H., Chu, W., Wang, T.J., Lee, M.C.: The Use of Arch Index to Characterize Arch Height: a Digital Image Processing Approach. IEEE Trans. Biomed. Eng. 42(11), 1088–1093 (1995)
24. Hamill, J., Bates, B.T., Knutzen, K.M., Kirkpatric, G.M.: Relationship between Selected Static and Dynamic Lower Extreminy Measures. Clin. Biomech. 4, 217–225 (1989)
25. Luximon, A.: Foot Shape Evaluation for Footwear Fitting. Phd Thesis, Hong Kong University of Science and Technology, Hong Kong (2001)
26. Goonetilleke, R.S., Luximon, A.: Foot Flare and Foot Axis. Human Factors 41, 596–607 (1999)
27. Luximon, A., Goonetilleke, R.S.: Critical Dimensions for Footwear Fitting. In: IEA 2003 Conference, Seoul, Korea (2003)

28. Witana, C.P., Goonetilleke, R.S., Feng, J.J.: Dimensional Differences for Evaluating the Quality of Footwear Fit. Ergonomics 47(12), 1301–1317 (2004)
29. Luximon, A., Goonetilleke, R.S.: A 3-D Methodology to Quantify Footwear Fit (Chapter 28, pp. 491–499). The Customer Centric Enterprise- Advances in Customization and Personalization by MM Tseng and F Piller (2003)
30. Luximon, A., Goonetilleke, R.S., Tsui, K.L.: Foot Landmarking for Footwear Customization. Ergonomics 46(4), 364–383 (2003)
31. Luximon, A., Goonetilleke, R.S.: Foot Shape Prediction. Human Factors 46(2), 304–315 (2004)
32. Luximon, A., Goonetilleke, R.S., Zhang, M.: 3D Foot Shape Generation from 2D Information. Ergonomics 48(6), 625–641 (2005)
33. Xiong, S., Goonetilleke, R.S., Witana, C.P., Au, E.Y.L.: Modelling Foot Height and Foot Shape-Related Dimensions. Ergonomics 51(8), 1272–1289 (2008)
34. Witana, C.P., Goonetilleke, R.S.: Midfoot Shape when Standing on Soft and Hard Footbeds. In: HFES 50th Annual Meeting, San Francisco, California (2006)
35. Xiong, S., Goonetilleke, R.S.: Can We Do away with those Cumbersome Shoe Laces? In: Eighth Pan-Pacific Conference on Occupational Ergonomics (PPCOE 2007) Bangkok, Thailand (2007)
36. Xiong, S., Witana, C.P., Goonetilleke, R.S.: The Use of a Foot Dorsal Height Model for the Design of Wellington Boots. In: Agriculture Ergonomics Development Conference (Aedec), Kuala Lumpur, Malaysia (2007)
37. Xiong, S., Goonetilleke, R.S.: Midfoot Shape for the Design of Ladies' Shoes. In: BME2006 Biomedical Engineering Conference, Hong Kong (2006)
38. Tsung, Y.S., Zhang, M., Fan, Y.B., Boone, D.A.: Quantitative Comparison of Plantar Foot Shapes Under Different Weight Bearing Conditions. J. Rehab. Res. Dev. 40(6), 517–526 (2003)
39. Xiong, S., Goonetilleke, R.S., Zhao, J., Li, W., Witana, C.P.: Foot Deformations under Different Load Bearing Conditions and their Relationships to Stature and Body Weight. Anthropological Science 117(2), 77–88 (2009)
40. Leung, A.K.L., Cheung, J.C.Y., Zhang, M., Fan, Y., Dong, X.: Contact Force Ratio: a New Parameter to Assess Foot Arch Function. Prosthet Orthot Int. 28, 167–174 (2004)
41. Tsung, B.Y.S., Zhang, M., Mak, A.F.T., Wong, M.W.N.: Effectiveness of Insoles on Plantar Pressure Redistribution. J. Rehab Res. Dev. 41(6A), 767–774 (2004)
42. Luximon, Y., Luximon, A., Yu, J., Zhang, M.: Foot plantar pressure evaluation for different heel heights and with different weight-bearing. Acta Mechanica Sinica (in press, 2011)
43. Witana, C.P., Goonetilleke, R.S., Au, E.Y.L., Xiong, S., Lu, X.: Footbed Shapes for Enhanced Footwear Comfort. Ergonomics 52(5), 617–628 (2009)
44. Roaas, A., Andersson, G.B.: Normal Range of Motion of the Hip, Knee and Ankle Joints in Male Subjects, 30-40 Years of Age. Acta Orthopaedica Scandinavica 53(2), 205–208 (1982)
45. Boone, D.C., Azen, S.P., Lin, C.M., Spence, C., Baron, C., Lee, L.: Reliability of Goniometric Measurements. Physical Therapy 58(11), 1355–1390 (1978)
46. Nigg, B.M., Fisher, V., Allinger, T.L., Ronsky, J.R., Engsberg, J.R.: Range of Motion of the Foot as a Function of Age. Foot Ankle 13, 336 (1992)
47. Rome, R.: Ankle Joint Dorsiflexion Measurement Studies. A Review of the Literature. Journal of the American Podiatric Medical Association 86(5), 205–211 (1996)
48. Kaufman, K.R., Brodine, S.K., Shaffer, R.A., Johnson, C.W., Cullison, T.R.: The Effect of Foot Structure and Range of Motion on Musculoskeletal Overuse Injuries. The American Journal of Sports Medicine 27(5), 585–593 (1999)

49. Van Rijn, R.M., Van Os, A.G., Bernsen, R.M., Luijsterburg, P.A., Koes, B.W., Bierma-Zeinstra, S.M.: What is the Clinical Course of Acute Ankle Sprains? A Systematic Literature Review. The American Journal of Medicine 121(4), 324–331 (2008)
50. Wang, J., Saito, H., Kimura, M., Mochimaru, M., Kanade, T.: Shape Reconstruction of Human Foot from Multi-Camera Images Based on PCA. In: Proceedings of the Fifth International Conference on 3-D Digital Imaging and Modeling (3DIM 2005) (2005)
51. Amstutz, E., Teshima, T., Kimura, M., Mochimaru, M., Saito, H.: PCA Based 3D Shape Reconstruction of Human Foot using Multiple Viewpoint Cameras. In: Gasteratos, A., Vincze, M., Tsotsos, J.K. (eds.) ICVS 2008. LNCS, vol. 5008, pp. 161–170. Springer, Heidelberg (2008)
52. Nácher, B., Alcántara, E., Alemany, S., García-Hernández, J., Juan, A.: 3D Foot Digitizing and its Application to Footwear Fitting. In: Proc. of 3D Modelling 2004, Paris (2004)
53. Kimura, M., Mochimaru, M., Kanade, T.: Measurement of 3D Foot Shape Deformation in Motion. In: PROCAMS 2008, Marina Del Rey, California (2008)
54. Kimura, M., Mochimaru, M., Kouchi, M., Kanade, T.: 3D Cross-Sectional Shape Measurement of the Foot while Walking. In: Proceedings of the 7th Symposium on Footwear Biomechanics, International Society of Biomechanics, pp. 34–35 (2005)