New 3D Foot Measurements in Weight-Bearing Condition: In-Vitro and In-Vivo Applications

Belvedere C. [1], Sacchetti G. [1], Conconi M. [2], Sancisi N. [2], Ortolani M. [1], Leardini A. [1]
[1]Laboratory of Movement Analysis, IRCCS Istituto Ortopedico Rizzoli, Bologna, Italy.
[2]Department of Industrial Engineering - DIN, University of Bologna, Bologna, Italy.
Email: belvedere@ior.it

Summary

Novel 3D foot measures of joint surface coverage and plantar vault volume under loading conditions, here performed by weight-bearing CT, prove fundamental to understanding foot biomechanics. Initial results confirmed procedural feasibility and original observations in the presence of foot deformity and after correction surgery.

Introduction

Advanced 3D medical imaging of the foot under loading conditions is fundamental to understanding related biomechanics, diagnosing pathologies, and supporting/monitoring treatments [1]. Traditional techniques allow 2D imaging under loading conditions, or 3D imaging in supine. To address these limitations, weight-bearing computed tomography (WBCT) has been recently developed, which allows detailed 3D morphological foot models generated under actual loading conditions, and still with limited radiation dose emission [1]. Despite these advances, research is lacking to explore the full potential of WBCT for in-depth assessment of the foot. To this end, analyses via 3D bone-to-bone coverage mapping and volumetric measures of the plantar vault could help to understand joint interactions in normal and pathological feet, and after surgical or orthotic treatments. This study aims to analyze, through original WBCT-based measurements, the extent to which loading conditions change 3D bone-to-bone relationships in the foot. In-vitro tests were performed, as well as in-vivo applications in a flatfeet population, before and after surgical correction.

Methods

Three frozen cadaveric normal lower limbs were tested for methodological feasibility after a 36-hour thawing period and being cast to maintain full knee extension [2]. These received WBCT scans (slicing: 0.26-mm, matrix resolution: 884x884x960) in an upright position both without loads and by vertically applying a weight, equal to half of the donor's body weight. A semi-automatic segmentation procedure was used for 3D foot model reconstruction of each bone. Distance mapping was performed on the relevant models to generate color-coded bone-to-bone maps used to derive bone coverage for the talonavicular, calcaneocuboid, and subtalar joints (Fig. 1). The plantar foot vault was defined with a 3D polygonal structure based on a number of plantar bony landmarks; its entire volume was split in rear-, mid- and forefoot, and also under the metatarsal bones (Fig. 1). This methodology was also applied before/after surgery at 1-year follow-up to 11 flatfoot patients operated for deformity correction via the Grice-Green surgery [3]. A control-group of 7 normal feet was analyzed. Paired Student's t-test and correlation analysis were performed for in-vivo pre/post-operative data comparisons.

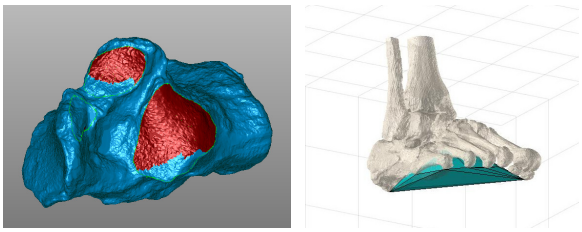

Figure 1: Calcaneal coverage in the subtalar joint (left); polygonal structure encompassing the volume of the foot plantar vault (right).

Results and Discussion

In-vitro tests confirmed overall methodological feasibility. Moving from unloading to loading conditions, total plantar volume reduction and joint coverage changes were observed as expected, with marked volume and coverage reduction in the rearfoot and subtalar anterior joint facet, respectively.

In the in-vivo analyses, pre-operative vault volume was ~50% of total foot bone volume, which increased to ~55% ($p<0.05$) postoperatively, with control data being about 60%. Postoperatively, a 35% ($p<0.05$) improvement was observed for the coverage in the anterior facet of the subtalar joint; a decrease from 46% to 41% for the talonavicular joint was observed, likely due to prior realignment of the talus-calcaneal joint; the calcaneocuboid joint coverage compared with the control (~80%).

Conclusions

These findings demonstrate the potential of WBCT in achieving new foot measurements in 3D and under real-life loading conditions. Expected in-vitro changes demonstrated overall procedural feasibility and reliability. In-vivo coverage and volumetric 3D investigations under loading conditions support the understanding of the mechanisms underlying the interactions between the foot bones, both in the presence of deformity and after corrective surgery, and can contribute to careful surgical planning. Examinations of larger cohorts of healthy subjects and patients are underway to consolidate statistically these preliminary findings.

Acknowledgments

This study was partially funded by the Italian Ministry of Health under the “5 per mille” program.

References

[1] Leardini A et al. (2019). *Semin Muscul Rad*, **23**: 643-55.
[2] Conconi M et al. (2024). *J Orthop Res*, **42**: 148-63.
[3] Sacchetti G et al. (2024). *Appl Sci*, **14**: 8521.