The Rotational Configuration of the Lower Limb: Machine Learning Insights Using Weight Bearing CT

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INTRODUCTION:

Understanding the interrelationships of lower-limb alignment parameters has been a challenging endeavour. Historically, the coronal configuration was mostly considered and the global rotational profile of the whole lower limb was not considered. In 1993, Prof. Giacomo Pisani proposed a compensatory relationship between femoral anteversion and subtalar configuration during development, aimed at optimizing biomechanical efficiency. However, it is not known which of the subtalar joint, the ankle joint of the talus accounts for this compensation mechanism. The introduction of CT enabled to investigate the rotational configuration of the limb from hip to ankle. Recently introduced weight-bearing cone beam CT enabled to investigate the 3D alignment of the hindfoot. In the present study, we investigated the rotational profiles of the femur, tibia, talus and 3D hindfoot alignment using weight-bearing cone beam CT. We hypothesized, as in the coxa-pedis concept, that talar-femoral rotational axes would be correlated.

METHODS:

We retrospectively analysed 59 lower limbs from 82 patients who underwent full lower limb WBCT for unrelated causes, excluding prior lower limb surgery, fractures, or systemic conditions affecting physiologic rotational anatomy. Using 3D Software (3D Slicer, https://www.slicer.org/), two independent readers assessed femoral neck anteversion (FNA), tibial torsion (TT), talar neck adduction angle (TNA), and Foot and Ankle Offset (FAO) (Fig.1). Male-to-female ratio was 2:1, with a mean age of 37.3 years. Statistical analysis was conducted using Easymedstat for descriptive and inferential statistics. Significance level was set at 5%. Python v 3.11 in a Google Colab environment was used for machine learning. An unsupervised model using KMeans clustering after PCA dimensional reduction. A supervised logistic regression model was then used to validate the cluster assignments and the model tested using and 80/20 split and 5 fold cross-validation. Receiver Operative Caracteristic curves were given for each cluster definition and performance was evaluated using AUC, precision, recall and F1 scores.

RESULTS:

The overall inter-operator agreement was moderate (ICC: 0.60). The mean values obtained were 16.74° ± 7.22 for FNA and 20.04° ± 9.28 for TNA. Although, non-significant linear correlation was found between FNA and TNA ($p = 0.42$), a significant correlation emerged between FNA and TT in relation to gender. The machine learning algorithm identified 3 distinct morphological patterns (Fig.2). Cluster 1 (22 limbs) was defined by high femoral anteversion (22.4° +/- 5.2), moderate tibial torsion (25.88° +/- 7.2), low talar neck adduction (13.43° +/- 4.7), neutral FAO (2.81+/- 4.2) and a significant correlation of FNA and TNA ($r=0.46$, $p = .032$). Cluster 2 (10 limbs) showed no significant association between FNA and TNA ($r=-0.12$, $p = .73$). Cluster 3 (21 limbs) exhibited intermediate femoral anteversion (15.8° +/- 4.4), similar tibial torsion (25.06° +/- 6.5), high talar adduction (28.23° +/- 6.3), and mean FAO of 1.77 (+/- 3.4) and a significant correlation of FNA and TNA (r, 0.46, $p = .032$) ($r=0.52$, $p = .017$) (Fig.3). Repeated ANOVA's showed significant differences between the three clusters in FNA ($p<0.0001$), TNA ($p<0.0001$) and FAO ($p<0.04$), but not in TT ($p=0.2$)

DISCUSSION AND CONCLUSION:

Machine learning revealed 3 distinct patient groups for which the separation was driven primarily by femoral and talar torsion, while tibial torsion did not seem to drive morphotype definition. Hindfoot alignment seemed to act as compensatory, relative to proximal (FNA) and distal (TNA) rotational alignments which varied together. FAO was similar and neutral when associated with high talar adduction and neutral femoral anteversion, or with high femoral anterversion and low talar adduction. In the intermediary group, where FNA and TNA were not correlated, FAO was significantly more valgus, which may suggest that the lower limb may organize as an internally symmetrical structure around the shin segment. In this case, FNA and TNA would vary together and self-compensate, without need for further compensation from hindfoot alignment or tibial torsion. In the scenario where FNA and TNA are decoupled, hindfoot alignment seems to be the only compensating variable. These findings provide further insight in the understanding of the rotational profile of the lower limb. Future studies should aim at applying these findings to improve surgical guidance.

Fig 1:3D Rotational parameters were measured for femur, tibia and talus

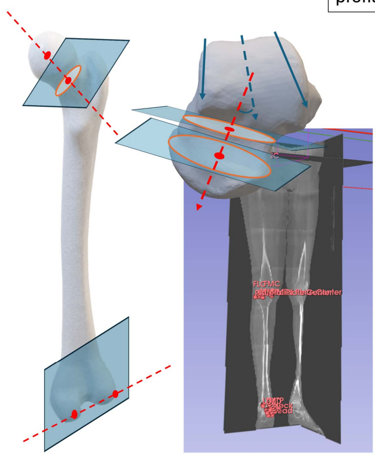
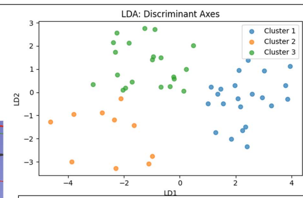


Fig 2: Machine Learning distinguished 3 distinct morphotypes depending on rotational profile



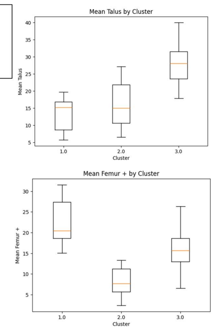


Fig.3: Talus Neck Adduction and Femur Neck Anteversion were correlated in 2 morphotype clusters