Functional Knee Phenotypes Combined With Objective Motion Assessment Provide Novel Insights Into Patient-Specific Kinematic Patterns For Total Knee Arthroplasty

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INTRODUCTION: Current total knee arthroplasty (TKA) alignment techniques are primarily based on static evaluations of joint alignment and/or bone resections, with or without the incorporation of soft tissue balancing methods. Even with robotic technology improving implantation precision and gap assessment, it remains impossible to evaluate how the TKA will function throughout the full range of motion, and more importantly, during functional tasks. Given that three-dimensional (3D) knee kinematics have been linked with functional limitations and patient outcomes post-TKA, exploring their relationships with patients' individual bony profile could help better understand how to restore joint function. Therefore, the aim of this study was to combine functional knee phenotypes (FKPs) with weight-bearing gait analysis in order to seek patient-specific kinematic patterns.

METHODS: This retrospective analysis was conducted on 160 asymptomatic knees (89 subjects) in order to investigate patient-specific kinematic patterns. Most subjects (57%) were females and the mean age was 34 years (95%CI:32;35). All participants underwent full-length weight-bearing x-rays and the following radiographic angles were measured using a digital software. The hip-knee-angle (HKA) angle, femoral mechanical angle (FMA), and tibial mechanical angle (TMA) were extracted. The FKPs were described with the direction of alignment (NEU, VAR, VAL) followed by the mean standard deviation for each angle (e.g., $NEU_{HKA}0°-VAR_{FMA}3°-VAL_{TMA}3°$ for a neutral HKA, varus femur, valgus tibia). Deviations were used in 3° increments starting from the mean value of each angle (HKA:180°, FMA:93°, TMA:87°). Participants' 3D knee kinematics were assessed in clinic during treadmill walking with an optoelectronic medical device (Figure 1). Biomechanical markers describing knee kinematic behaviour in all three planes of motion were extracted (e.g., knee flexion angle at heel strike, mean varus-valgus alignment during stance, etc.). It included the dynamic HKA angle (dHKA) calculated by projecting hip, knee, and ankle centers in the coronal plane throughout gait. This 2D representation was used to first investigate whether coronal knee alignment was maintained throughout motion and defined patients who changed their dHKA alignment orientation (i.e., varus or valgus) during stance as CHANGERS. We then sought to determine how each FKP behaves dynamically during gait in terms of extension/flexion (°), varus/valgus (°), and internal/external tibial rotation (°). Chi-square and T-tests were used to compare the proportions of CHANGERS and assess 3D kinematic differences between FKPs on biomechanical markers.

RESULTS:

A total of 45 FKPs were identified. Knees of the NEU0°-NEU0°-VAL3° phenotype were the most likely to be CHANGERS (50% prevalence) followed by NEU0°-NEU0°-NEU0° (35%). On the opposite, there were significantly less in VAR3°-NEU0°-NEU0 ° (12%, both $0.03<p<0.1$), while none of the participants in the VAR3°-VAR3°-VAR3° phenotype changed their dHKA during stance (i.e., stayed varus aligned). The VAR3°-VAR3°-VAR3° phenotype was the one phenotype presenting with the most dynamic varus alignment during stance (5.0° on average), but also the one with the highest knee flexion at heel strike (10.7°) and the most internal tibial rotation during swing (-4.0° on average between 60% and 100% of the gait cycle, see purple line in Figure 2, 3, and 4). Interestingly, the VAR3°-VAR3°-VAL3° (green) and the VAR3°-VAR3°-NEU0° (red) phenotypes, which only differ from the VAR3°-VAR3°-VAR3° phenotype in terms of tibial alignment, displayed significantly different 3D kinematics (i.e., higher valgus alignment during push-off/swing for valgus tibia, lower flexion-extension range of motion for neutral tibia, more internal tibial rotation at heel strike and during swing for varus tibia, all $p<0.05$).

DISCUSSION AND CONCLUSION:

Functional knee phenotypes combined with dynamic objective motion assessment revealed distinct, phenotype-specific kinematic patterns, offering valuable insights into patient-specific dynamic behaviour. These findings suggest that subtle variations in coronal alignment, particularly tibial orientation, may significantly influence knee function, making it more challenging to predict dynamic behaviour based on static measures alone. Further analyses exploring FKPs kinematic behaviour on larger sample sizes could help refine these preliminary results, which could ultimately be considered in personalized TKA planning.