BMI Effects on the Biomechanics of the Knee Joint: Subject-Specific FE-musculoskeletal Approach

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INTRODUCTION: Osteoarthritis (OA) is a progressively painful disorder predominantly afflicting the knee, more so than the hip or ankle, and is a major cause of disability worldwide [1]. The last decade has seen a 25% increase in OA, correlating with soaring obesity rates—a key modifiable risk factor due to its exacerbation of joint loading and abnormal biomechanics during daily activities [2]. Despite its prevalence, the exact etiology of knee OA is elusive, entangled in the complex interplay of joint mechanics and metabolic changes. While obesity's impact on knee joint loading, especially in the frontal and sagittal planes, is acknowledged, its precise effect on joint biomechanics is less clear [3]. Most studies have fallen short of quantitatively dissecting the influence of obesity on muscle functionality and stress distribution within the joint. They've largely overlooked the passive resistance offered by soft tissues, simplifying muscles as force generators, and considering joints as mere kinematic constraints [4]. This oversight has led to a gap in understanding how stress and strain are distributed within the knee's structures in obese individuals. The accurate assessment of muscle forces is essential for precise calculations of joint stress and strain. However, the complexity of measuring these forces and their dynamics during movement hinders progress. Despite prior research, a comprehensive model combining experimental and computational data to elucidate the relationship between obesity, joint mechanics, and OA progression is lacking. Our study aims to bridge this gap by employing a systematic engineering approach to unravel how weight shifts affect mechanical responses in the knee, focusing on cartilage load distribution—a predictor of OA—thereby enhancing our understanding of degenerative joint disease onset and progression.

METHODS: In this research, 60 individuals with stable body mass and no history of knee issues were enrolled, following ethical consent. They were categorized into three BMI-based groups for gait and X-ray analysis. Knee X-rays were captured in a standing position, and motion capture with reflective markers mapped out lower limb movement. Walking trials were conducted to gather data. Participants' specific musculoskeletal models were created using a standard model adjusted to individual lower limb measurements [5]. The models, with 27 degrees of freedom and 92 muscle-tendon units, were analyzed using OpenSim's Python API for inverse kinematics and dynamics [6]. For the Musculoskeletal-FE analyses, a validated model was scaled to each participant, considering X-ray and OpenSim data [7]. Joints were modeled with varying degrees of freedom, while the knee joint included a range of anatomical structures. Material properties for soft tissues were carefully chosen based on prior studies, with the ligaments modeled as transversely-isotropic and the cartilages as fibril-reinforced hyperelastic materials. Loading and boundary conditions involved using participants' joint kinematics and ground reaction forces at five different stance instances (heel strike (HS), first loading peak (FP), midstance (MS), second loading peak (SP), and toe-off (TO)). Static optimization predicted muscle forces, which were iteratively refined using commercial software (Matlab & Abaqus). This detailed biomechanical analysis evaluated muscle, ligament, and contact forces, including stress distribution within the knee joint. Statistical comparisons utilized Python's NumPy library, with a two-sample t-test identifying significant differences between the groups at a 0.05 significance level.

RESULTS: Quadriceps force is similar across groups except at the first peak (FP), where the obese group's vastus lateralis force is 50% higher than that of healthy controls. This group also shows slightly higher rectus femoris peak force and significantly higher biceps femoris long head activation at FP. Obese participants' medial hamstrings and gastrocnemius muscles increasingly activate, especially at midstance and second peak (SP). Obese individuals' anterior cruciate ligament (ACL) stress peaking at 17.2 MPa at SP. Lateral collateral ligament (LCL) stress rises with BMI, while medial collateral ligament (MCL) stress is lower in obesity. The patellar tendon stress also increases in obesity at FP. Obesity leads to higher stress in the medial tibiofemoral joint compartment, peaking at 3.1 MPa at FP. Stress distribution in the tibiofemoral joint varies from anterior to posterior and lateral to medial throughout the stance phase (fig.1).

DISCUSSION: The study explores the connection between obesity and knee joint disorders like osteoarthritis, focusing on how walking patterns and joint forces differ in obese individuals and influence the progression of these conditions. It reveals that muscle forces around the knee, particularly from the quadriceps and hamstrings, increase with body mass index (BMI), with significant force spikes during peak load moments. The vastus lateralis and biceps femoris muscles exhibit heightened activity in obese subjects, likely to counterbalance increased knee flexion and adduction moments. During later stance phases, the gastrocnemius muscle becomes more active, suggesting a shift in muscle control for joint stability. BMI categories impact on ligaments stresses like the ACL and PCL, with the ACL bearing more load in obese individuals. This aligns with the increased muscle forces and altered knee joint angles in this group. The study also observed that obese individuals have higher compressive stresses in knee joint compartments, which may not immediately damage healthy cartilage but could exacerbate an already diseased joint. The study, however, has limitations, including a lower average BMI for the obese group than in previous studies, potential errors from skin-mounted markers, and assumptions in the modeling approach that may not account for individual variances in tissue properties. **SIGNIFICANCE:** Our findings contribute to understanding the biomechanical changes in obese individuals and their potential role in developing knee joint disorders.

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Figure. 1