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A Longitudinal Cohort Study with Integrated Technologies to Inform Personalized Robotic Knee Arthroplasty

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Abstract

Many patients exhibit joint level biomechanics and mobility deficits after knee arthroplasty, which have been linked to patient dissatisfaction. Advancements in robotic-assisted surgery offer the potential for surgery personalization to address these deficits, yet the link between surgical planning and joint mechanics remains unclear. This research aims to comprehensively model the relationships among patient variability in joint mechanics, anatomy/morphology, physical activity, implant characteristics and post-operative outcomes to inform personalization strategies to address these deficits in joint mechanics. This is a five-year longitudinal patient cohort study with integrated data at several time points perioperatively including longitudinally during the pre-operative wait period, and post-operatively to one year. We combine patient-specific information from multiple domains including demographics and anthropometrics; patient-reported outcomes; three-dimensional gait kinematics through AI-driven markerless motion capture integrated into the clinic hallway; free-living physical activity (PA) and gait outcomes with inertial sensors; joint anatomy, morphology and OA feature modeling through custom CT image processing; and intraoperative robotic data. Longitudinal pre-operative outcomes have been collected for a subset (n=57) to date. There were no significant longitudinal changes in gait kinematics or objective PA outcomes on a population level pre-operatively. However, a subset of patients exhibited significant gait worsening, and worsening was significantly correlated with more advanced OA-related gait deficits at baseline. Unique free-living gait metrics were identified that moderately correlated with in-clinic gait kinematics. PA outcomes were not significantly correlated to gait outcomes, and significantly worse

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PA outcomes (step count, %sedentary, %light and moderate to vigorous PA) were identified for female patients.

1 Introduction

Continued evidence points to widespread deficits in joint level biomechanics and mobility outcomes for patients after knee arthroplasty (KA) surgery, which have been linked to early implant failure metrics and poor patient-reported outcomes including satisfaction. Poor joint mechanics are on their own a negative outcome of surgery[1]. Advancement in surgical technologies, such as robotics, enables heightened potential for innovation to restore joint mechanics on a patient-specific level. However, to do so we need more comprehensive evidence on the mechanistic links between anatomy, joint morphology, and joint-level biomechanics and clinical outcomes from prescribed KA surgical planning. The objective of this study as a preliminary step, is to characterize pre-operative KA patient variability longitudinally during the wait period for robotic KA by examining changes in knee kinematics and free-living outcomes through a KA cohort study that has integrated clinical markerless motion capture and wearable inertial sensor data capture at several time points peri-operatively.

2 Methods

Patients with end-stage knee osteoarthritis (OA) approved and scheduled for robot-assisted (Mako, Stryker KA surgery were recruited to participate according to the Nova Scotia Health Research Ethics board. This is a 5-year longitudinal cohort study that involves multi-domain data collections at several (5) time points in the peri-operative period including baseline (time of surgery decision), pre-operative (< 3 weeks before KA), surgery, 3 and 12 months post-operatively. Data collection domains include demographics and anthropometrics; patient-reported outcomes (pain, function, general health, mental health, satisfaction, physical activity); three-dimensional gait kinematics through AI-driven markerless motion capture[2] integrated into a clinic hallway (Theia Markerless, 60 Hz, 10 x Sony RXO II cameras); free-living physical activity (PA) and gait outcomes through lower extremity fixed inertial measurement units on patient tibias (IMUs; Axivity AX6, 100 Hz) with data collected for 7 days continuously after clinic visits; joint anatomy, morphology and OA feature modeling through custom CT image processing (Mimics, Materialise); and intraoperative robotic system surgical data (implant fit characteristics, alignment, soft tissue variables).

In this preliminary study, pre-operative clinical gait kinematics and free-living PA and gait outcomes are characterized. Video-based gait data were processed (Visual3D, C-motion) to calculate knee joint angles, and further processed using principal component analysis (PCA)[3] to define key magnitude and temporal patterns with previous evidence as important to arthroplasty[4,5]. Free living IMU data were processed for PA outcomes including average daily step count, %time spent sedentary (SED), and %time spent in light (LPA) or moderate to vigorous activity (MVPA). Steady state free walking bouts were also identified[6] to calculate free living joint kinematic outcomes including linear shank velocities[7] in the frontal plane and thrust accelerations[8] (related to knee adduction moment[7]). Correlations between pre-operative clinic gait and free-living PA and gait outcomes were examined, as well as changes in outcomes longitudinally during the wait period (α=0.05).

3 Results

To date, 57 patients awaiting robot-assist KA surgery have been recruited to participate in the longitudinal study. Thirty-eight of these had baseline in clinic gait analysis (19F/19M; age 68.2 +/-7.9 years; BMI 32.7 +/-7.3 kg/m^2), and a subset of 15/38 (6F/9M; age 69.8 +/-6.5 years; BMI 35.1 +/-7.6 kg/m^2) have had pre-operative follow-up gait testing 130+/-17.9 days later. Thirty-two patients had baseline IMU data for free-living PA outcomes (16F/16M; age 68.5 +/-6.4 years; BMI 33.8 +/-7.6 kg/m^2), 8 of whom have follow-up free living IMU data to date. Twenty-one patients have had IMU data processed for free living gait outcomes (8F/13M; age 69 +/-6 years; BMI 33 +/-8 kg/m^2).

On a population level, there were no significant changes in clinic-based knee kinematics during gait, nor in free living PA outcomes from baseline to follow-up in the pre-operative period ($P>0.05$). However, 5/15 patients exhibited significant gait worsening (Figure 1), with worse (ie distance from healthy) baseline kinematics (but no other patients factors) associated with greater deterioration in gait mechanics while waiting ($p <0.005$). There were no significant correlations between PA outcomes and knee kinematic gait outcomes at baseline ($P>0.05$), but female patients had significantly lower total step counts, higher %SED, lower %LPA and %MVPA and higher pain than males. Significant correlations between free-living (IMU) and clinic-based gait metrics were found including moderate correlations between peak knee flexion angles in stance (clinic) with thrust acceleration ($r=0.50$, $p=0.02$) and frontal plane velocity range ($r=0.43$, $p = 0.05$).

4 Discussion and Implications

Our results characterize the variability, longitudinal changes in and correlations among in-clinic knee kinematic gait outcomes and free-living outcomes during the pre-operative wait period for KA surgery in a preliminary analysis of data from a longitudinal cohort study to inform patient-specific robotic KA prescription. Characterizing patient variability and relationships among key domains in the pre-operative period is an important step in our overarching objectives. Gait mechanics did not change significantly while waiting for surgery on a population level, however there was variability among patients, with a subset identified as worsening. Similarly, free living outcomes did not change significantly on a population level, but demographic differences were noted. Our data suggest relationships exist between in-clinic and free-living gait outcomes, however relationships were not strong, indicating the need for their potential separate and unique integration into clinical decision-making.

5 Conclusions and Significance

Understanding pre-arthroplasty patient gait biomechanics and physical activity levels and their relationships with other outcomes may help clinicians make more-informed surgical decisions for patient-specific planning. Laboratory (or in-clinic) gait assessments have been used extensively in this population and are well defined with associated evidence, however the role of free-living gait mechanics is less well defined for arthroplasty decision-making. Sensor data present an opportunity to define different, free-living gait outcomes through simple technologies, providing complementary insight into gait mechanics. A better understanding of patient functional variability may be gained, potentially relevant to arthroplasty patient care and decision-making. This longitudinal cohort study is continuing, and we will be integrating patient-specific anatomy, joint morphology with robotic surgical data (and computational modeling) to continue to examine how and which patient factors are most relevant for optimizing arthroplasty outcomes through robotic surgery.

6 References

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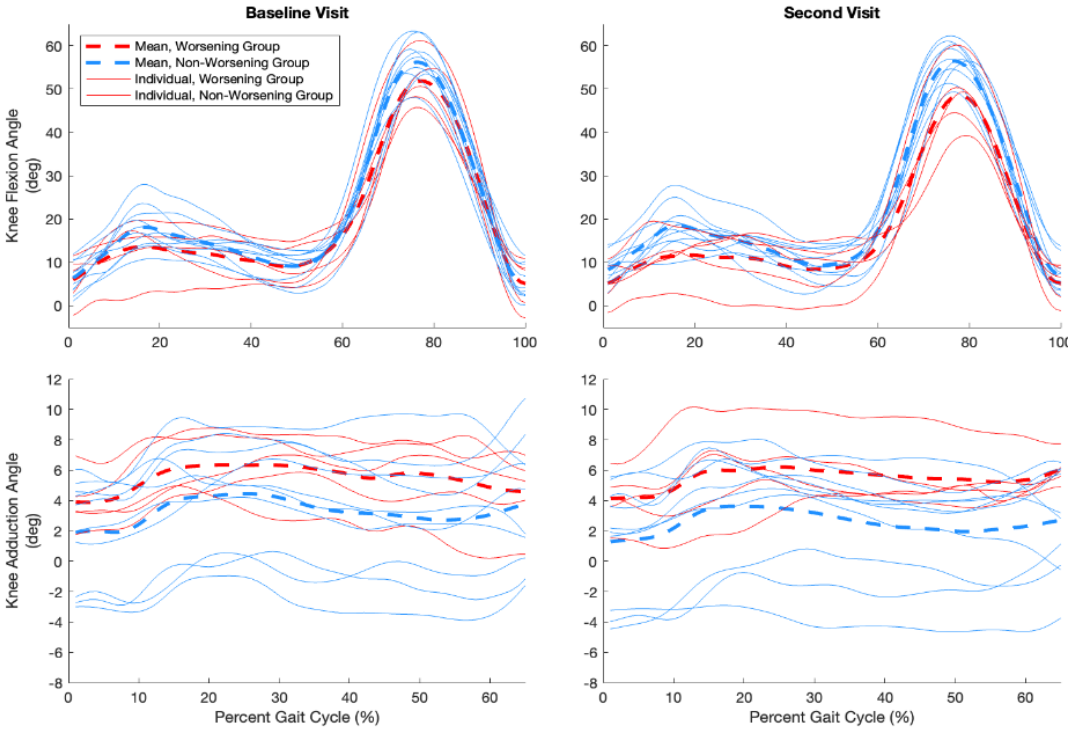

Figure 1. Clinic-based knee flexion(+ve)/extension (top) and ad(+ve)/abduction angles during gait at baseline (left) and follow-up (right) clinic visit during the wait period for KA for patients who exhibited worsening (n=5, red) gait kinematics and those (n=10, blue) who did not while waiting.