Digital Twins for Personalized Knee Reconstruction
Hamidreza Jahandar, MS, Zaid Zayyad, MS, Thomas Fraychineaud, BS, Jennifer Vazquez, MS, Andrew Pearle, MD, Thomas Wickiewicz, MD, Carl Imhauser, PhD
Hospital for Special Surgery, New York, NY

Introduction: Common, traumatic knee injuries, such as rupture of the anterior cruciate ligament (ACL), are often treated via surgical reconstruction. Unfortunately, up to 18% of these reconstructions fail for technical and biomechanical reasons [1]. For example, incorrectly positioned tunnels for fixing the ACL graft may overload the surgical construct causing graft rupture [2]. Treatments decisions are based on the empirical intuition of the surgeon, who primarily utilizes qualitative and subjective exams to assess the tightness or looseness (i.e., stability) of the knee. This rudimentary approach cannot account for the complex interaction of surgical variables (e.g., tunnel location, graft stiffness) and tissue loading, which may lead to the scenario where the graft is overloaded and fails. The goal of this work was to use the concept of a digital twin to reduce risk of graft failure by integrating the following two tools: 1) an objective and quantitative tool to measure knee stability in multiple planes of motion; and 2) a physics-based digital twin of the instrument and the patient’s knee to optimize surgical treatment via prediction of knee stability and the loads carried by the ACL graft.

Materials and Methods: The measurement tool is an instrumented spatial linkage (i.e., an arthrometer), which measures the translations and rotations of the tibia relative to the fixed femur in response to known applied loads (Fig. 1). The digital twin consists of multibody dynamics computer models of both the arthrometer and the patient’s knee (Fig. 1). The workflow for optimizing surgical treatment includes the following steps: first, the patient undergoes physical assessment using the arthrometer prior to surgical treatment. Second, the patient receives magnetic resonance imaging (MRI) as part of their clinical standard of care. Third, a physics-based, virtual model of the knee is developed in the multibody dynamics framework based on 3D reconstructions of the bones and soft tissues (cartilage, menisci, ligaments) of the knee from the MRI. Fourth, the soft tissues of the digital twin are calibrated to the mechanical response of the patient via measurements obtained from the arthrometer. Finally, the digital twin is used to optimize surgical variables by assessing numerous what-if scenarios and selecting the one that is most feasible to implement (e.g., based on cost, time, surgical complexity) and does not overload the ACL graft.

Results and Discussion: We have applied the concept of a digital twin to orthopaedic care as part of a pipeline for personalized surgery following common, costly, and debilitating knee ligament injuries. These surgeries still have an unacceptably high failure rate and therefore impose a large financial burden on the health care system. Challenges remain; they include scaling the workflow to larger patient populations, efficiently and accurately extracting image data, and capturing the complexity of the soft tissues. The strength of the digital twin approach is the ability to optimize treatment by rapidly filtering through numerous what-if surgical scenarios and by estimating the loads carried by the soft tissues, which are otherwise extremely difficult to measure in the clinic.

Translational Impact: Digital twins in orthopaedic surgery may help mitigate the substantial physical and financial burden of patients at high risk of graft failure by decreasing revision rates and by improving function.

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Figure 1. Arthometer (on left) used to assess knee stability with operator loading the knee through handles. Digital twin (on right) used to evaluate treatment scenarios and estimate soft tissue forces to optimize therapy. Red arrows indicate forces carried by the ACL and forces applied to the handles of the arthrometer.