# A PASSIVE IMPLANT THAT SCALES MUSCLE FORCE IN KNEE-REPLACEMENT SURGERY

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## I. Introduction

Diminished musculoskeletal function, such as reduced joint strength or reduced range of motion, result from a variety of causes such as old age, muscle or nerve trauma, chemotherapy, or even surgery [1]–[3]. While limb function can be partially restored with a significant amount of physical therapy, oftentimes full limb function never fully returns and has life-altering consequences. Inspired by robotics design technology, we are exploring the development of passive implants to reverse the problem of weak-joint function. Specifically, we are developing passive implants in the form of engineered mechanisms such as pulleys, gears, and levers that will scale up muscle force in order to increase joint strength or scale up muscle excursion in order to increase joint range of motion. The use of such devices offer an advantage because the devices can be custom designed based on the patient's desired post-surgery function.

In this paper, we present preliminary results from developing an implant to be used in conjunction with knee-replacement surgery. Knee replacement surgery is performed in nearly 600,000 patients a year in the U.S. alone [4]. The surgery replaces the biological knee joint with a single degree of freedom joint that mimics the knee's kinematics [5]. However, following the surgery, knee joint strength typically decreases by 30% for a variety of reasons, such as soft tissue disruption, implant pitting and fatigue, disturbance of the quadriceps mechanism (moment arms), tibiofemoral capsular dislocation, even though range of motion is unaffected [6]–[10]. This loss of knee strength affects the activities of daily living such as stair climbing and chair rising. We show through simulation that using a passive engineering mechanism in the form of a pulley between the quadriceps muscle and patella restores knee joint strength while sacrificing some knee range of motion (Figure 1). Losing some range of motion in this surgery is acceptable since only about 105° flexion is required at the knee joint for most activities of daily living [11], [12] and usually up to 160° of flexion is available after knee replacement surgery [12].

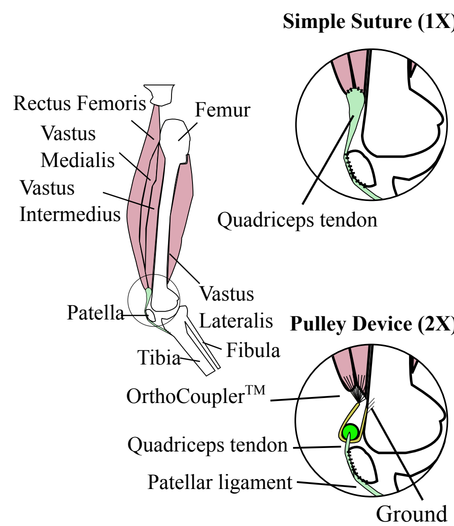


Fig. 1: Cross section of the knee joint. The top close-up shows the normal knee without an implant. The bottom close-up shows the knee with a pulley implanted for force scaling.

## II. Methods

A lower-extremity model and the dynamics engine available in an open-source biomechanical simulation program called OpenSim was used for this study [13]–[16]. In order to focus the study on the biomechanical effect of the implant on knee function, the model was simplified by removing all other muscles other the quadriceps. The original model was modified to insert a pulley between the quadriceps muscles and the patella joint (see Fig. 2). Movement was created by setting all four heads of the quadriceps to have a linear-ramp-and-plateau activation profile (linear ramp over three seconds from 0 to 75% excitation, and then held at 75% for three seconds. Force and joint rotation angle data from the simulation were collected. In both cases, the knee joint torque was measured using a same virtual spring attached to the tibia.

## III. Results

Fig. 3 shows results from the biomechanical simulation. The steady state part of the graph shows that the single pulley scaled the quadriceps force by a factor of 1.84 (expected 2X), while scaling the knee range of motion by a factor of 0.56 (expected 0.5X).

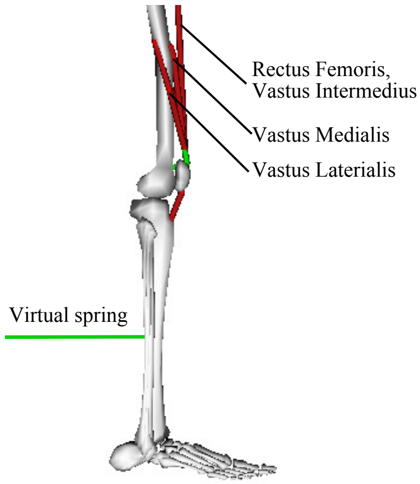


Fig. 2: Knee side view with implanted pulley system in OpenSim software.

## IV. Discussion

The key point in this paper is that simple robotics and engineering concepts may be used within the human musculoskeletal system just as in mechanical systems, since movement and force is transmitted in both systems using passive elements. Modifying the force and movement transmission inside the human body can significantly help restore human function for different medical conditions.

The results show that the force-scaling pulley works as intended to increase knee torque while sacrificing some range of movement. The small discrepancy in the force-scaling ratio arises from the irregular lines of action for muscles and ligaments in the human body when compared with mechanical systems. Note that the pulley device used in this study is only one possible embodiment of a force-scaling mechanism. Other mechanisms will be investigated in future work. Such force-scaling devices could also be applied to many other orthopedic surgeries for the hand, elbow, and ankle to improve joint function. Also, by changing the attachment configuration, the device may be use for range of motion scaling also. Specifically, by swapping the input and output cables from the pulley, the mechanism will increase range of motion while it is in the joint range of movement. Such devices will need to be designed specifically for each patient due to the fact that every person has different functional needs, musculoskeletal biomechanics, and medical conditions. Future work will entail validation of the mechanisms using cadavers.

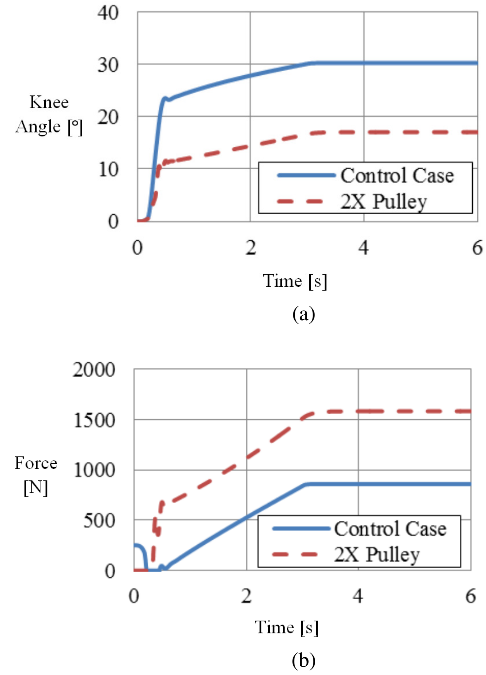


Fig. 3: Results from OpenSim biomechanical simulations of the lower extremity with and without a force-scaling pulley inserted: The biomechanical effect on (a) knee range of motion and (b) knee strength measured as force built up in virtual spring attached to tibia.

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