Interaction Force Modeling for Joint Misalignment Minimization Toward Bio-inspired Knee Exoskeleton Design

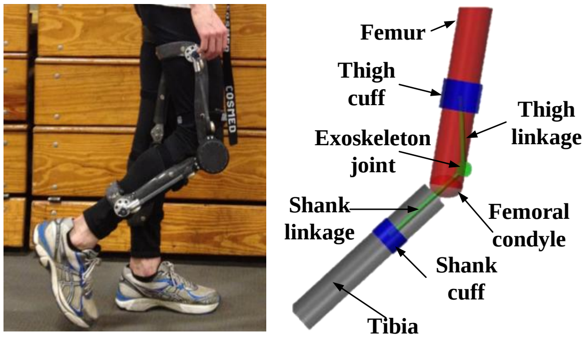
Yanjun Li[1], Shuo-Hsiu Chang[2], Gerard Francisco[2], Hao Su[1]*
Biomechatronics and Intelligent Robotics Lab, Department of Mechanical Engineering, City College of New York, NY, USA[1]
Department of Physical Medicine and Rehabilitation, University of Texas Health Science Center at Houston (UTHealth), Houston, Texas, USA[2]
*Corresponding author, hao.su@ccny.cuny.edu

1 Background

Roboticists have developed a diverse array of powered exoskeletons for human augmentation and rehabilitation over the last few decades. One of the key design objectives is to minimize the discomfort to enhance the user experience. The high inertia and joint misalignment of conventional rigid exoskeletons are two key factors that cause these problems. Different types of control algorithms have been developed to compensate the inertia and render low impedance to the wearers [1-2].

In addition to the high inertia, the misalignment between exoskeleton joints and musculoskeletal joints of wearers can cause detrimental forces [3-4]. Conventionally, the mechanical knee joints of rigid knee exoskeletons are typically treated as a simple 1 degree of freedom (DOF) hinge mechanism, but the biological knee possesses complex kinematic characteristics. When this kind of 1-DOF exoskeleton and wearer's limb form a closed kinematic chain, both kinematic and kinetic interference will inevitably occur.

There are two existing solutions to tackle the joint misalignment problems. One method aims to use complex mechanisms (e.g. cam mechanism or five-bar linkage) to alleviate the interference. However, these methods introduce additional inertia and largely increase the complexity of the system. The other method is to reduce the stiffness of interface between the exoskeleton and the wearer. Soft exoskeletons that use soft materials, like fabric [5] or elastomers [6, 7] have been proposed. Due to its compliance, the soft material undertakes the majority of deformation without generating excessive forces to the wearer.



(a) (b)

Fig. 1. (a) A representative knee exoskeleton developed by Herr et al. [11], (b) The computational model of the human-exoskeleton interaction. The red cylinder with an ellipsoid end (femoral condyle) and gray cylinder represent femur and tibia respectively. Green lines represent exoskeleton linkages. Green disc refers to the exoskeleton joint. Blue bands refer to the thigh and shank cuffs.

Irrespective of the design solutions, it is desirable to model and understand the interaction forces in the human-robot interaction model, e.g. between the biological joints and exoskeletons. The experimental approach can characterize such forces, but physical parameter measurement requires excessive effort [8]. The mathematical modeling approach [9, 10] aims to build the kinematic and kinetic model of the limb-exoskeleton loop to estimate both internal and external forces in simple movements (e.g. knee flexion and extension). However, for the convenience of analysis, [9, 10] neglected the hip joint.

Different with the experimental approach by Zanotto et al. [12] that investigated the impact of knee joint misalignment, this paper proposes a computational modeling framework to analytically understand the interaction forces, thus to guide the design of bio-inspired knee exoskeletons including both rigid and soft design solutions. *The contribution of our work is that we have developed a modeling and simulation framework to understand the interaction forces between the biological joint and the exoskeleton.* We particularly focus on the knee joint modeling as its unique anatomical structure is challenging but representative. Compared with the 1-Degree of Freedom (DoF) model in [10], our limb-exoskeleton model incorporates both hip and knee joints with five DOFs. This simulation framework has the potential to estimate the interaction forces for both rigid and soft exoskeletons during human locomotion. It will shed light on the bio-inspired soft knee exoskeleton design.

2 Methods

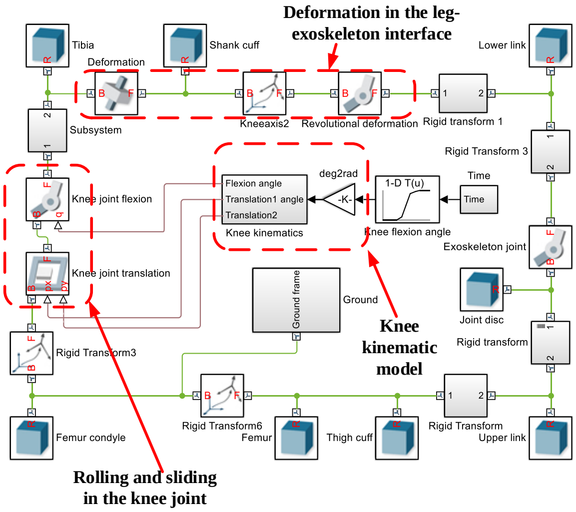


Fig. 2. Block diagram of the limb-exoskeleton system. By the combination of a rectangle joint and revolution joint, the model is able to realize the rolling and sliding motion of the biological knee. A prismatic joint and revolution joint describe the relative motion between the shank and lower link. Due to the

space limit, the modeled pelvis and hip joints are not shown here.

Table 1. Physical parameters of the lower limb in the model

Parameter	Value
Femur length (mm)	39
Tibia length (mm)	36
Tibia mass (kg)	3.6
Femur inertia (kgm^2)	0.14
Tibia inertia (kgm^2)	0.05
Semi-major axis of femoral condyle (mm)	33.6
Semi-minor axis of femoral condyle (mm)	23

The limb-exoskeleton interaction model has 5 DOF, namely the 2-DOF pelvis translation, 1-DOF pelvis tilt, 1-DOF hip joint rotation and 1-DOF knee joint rotation.

Fig. 1 (a) illustrates one representative quasi-passive clutch-spring knee exoskeleton [11]. Fig. 1 (b) depicts the limb-exoskeleton interaction model in a computational multi-body dynamics environment. Fig. 2 illustrates the detailed implementation in Simscape Multibody (MathWorks, MA, USA). We choose this environment because it has the capability to define the kinematic and kinetic models of limb-exoskeleton. The limb movements in our model are defined in the sagittal plane, and the frontal plane knee motion are ignored. Table 1 illustrates the parameters obtained in [13] for one representative biological knee joint used in the model.

The wearable robotics literature typically treats the biological knee joint as a 1-DOF hinge mechanism. In fact, the contact between the femoral condyle and tibial condyle forms a planar high pair mechanism (2 DOF) in which kinematic constraints between the rolling and sliding exists [14]. In this paper, we have developed a biological knee joint model [15] that describes the relative motion of femoral condyle with respect to the tibial condyle as an ellipse rolling and sliding along a flat surface in Simscape Multibody (MathWorks, MA, USA). The sliding ratio in this model, which is defined as the ratio between rolling distance and sliding distance can be adjusted to emulate the complex movements in the biological knee joint.

In the current framework, the rigid exoskeleton is modeled as articulated linkages. As described in [12], the thigh linkage is fixed on the femur while the shank linkage can rotate and slide relative to the tibia. Such relative motion between the tibia and the shank linkage will generate undesired forces. The offset between exoskeleton pin joint and center of femoral condyle ellipse is also considered in this model, as can be seen in Fig. 1 (b).

3 Results

We have successfully reproduced similar kinematic results of the biological joint by parameter optimization in the knee joint model. Simulation results illustrate that trajectory of contact points between the femoral condyle and the tibial condyle generated by this model is consistent with the experimental data in [14] as shown in Fig. 3. The motion of the biological knee is neither pure sliding nor pure rolling, but a combination of rolling and sliding with a certain sliding ratio. Fig. 4 shows the trajectories of the two different models (pure rolling vs. rolling with sliding) in the -5°~120° knee flexion range. The solid blue ellipses represent the rolling and sliding model adopted in our simulation framework, while the dotted red ellipses denote the trajectory if the femoral condyle purely rolls along the tibial condyle. At the initial position (-5°), the red and blue ellipses overlap with each other and share the same contact point. Compared with pure rolling, the combination of rolling and sliding allows the center of the femoral condyle to have a smaller locomotion, which is more similar to the observed data in the experiment.

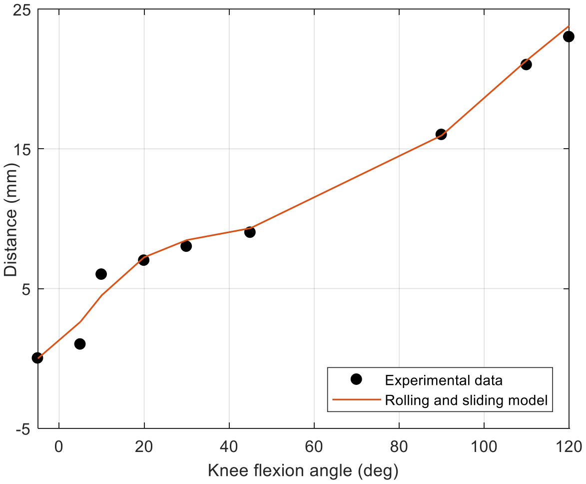


Fig. 3 A kinematic comparison between the rolling and sliding model and real biological knee. The vertical axis represents the distance between the initial contact point and the contact point at a certain flexion angle. The experimental data measured by MRI was the average rolling and sliding distances for six knees [14]. The raw data between 45° and 90° of the flexion angle was not included in the experimental database.

Fig. 5 shows one gait cycle generated from the animation of the limb-exoskeleton model. Databases in OpenSim Gait2392 [16] provide the biological trajectories of the pelvis, hip, and knee joints. The gait kinematics generated from our model resembles the biological data indicating that our model can accurately capture the characteristics of human hip-knee biomechanics.

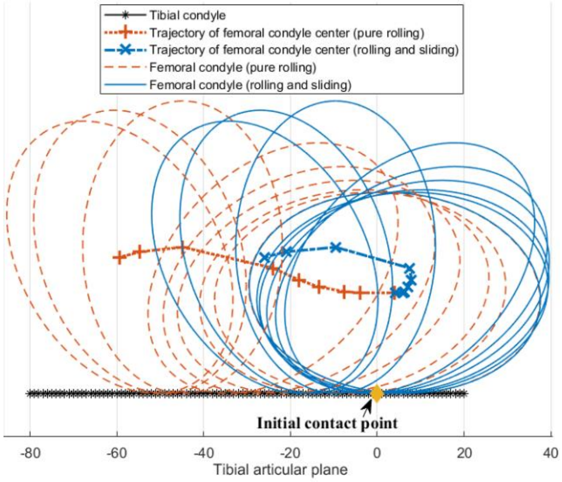


Fig. 4 The positions of the femoral condyle (solid red lines) calculated by the rolling and sliding model are plotted with respect to the tibia (solid black line) in the -5°~120° knee flexion range. Compared with the pure rolling model (dotted

blue line), the rolling and sliding model has a much more similar trajectory to the biological knee.

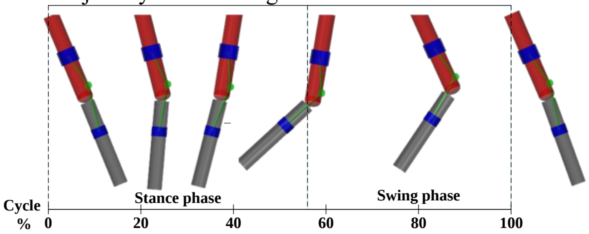


Fig. 5 A limb kinematics generated with the computational model in a gait cycle. 0% is the heel strike event. Swing phase starts at approximately 55% of the cycle. This diagram demonstrates that our model is able to produce biological gait.

4 Interpretation

This paper presents a computational modeling framework to study the kinematic characteristics of the mechanical interface between the knee joint and the exoskeleton. This model captures the main characteristics of the biological knee. The simulation result demonstrates that this framework has the ability to emulate the complex knee joint motion in one gait cycle.

The future work includes dynamics analysis and the soft exoskeleton model development within this framework. We will use this model to evaluate different design solutions. The insight gained from the interaction forces will facilitate the design and optimization process of the bio-inspired soft exoskeletons.

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