Characterization of Quasi-Stiffness of Lower Extremity Joints

Kamran Shamaei*, Gregory S. Sawicki**, and Aaron M. Dollar*
* GRAB Lab, Yale University, New Haven, CT USA, {kamran.shamaei, aaron.dollar}@yale.edu
** Joint Department of Biomedical Engineering North Carolina State University and University of North Carolina at Chapel Hill, Raleigh, NC USA, greg_sawicki@ncsu.edu

1. Introduction

Simple engineered mechanisms that can emulate human-like biomechanics are essential for robust performance of a number of engineered locomotion systems including anthropomorphic bipedal robots lower-limb wearable exoskeletons and biologically-inspired prosthetic limbs. Ideally, successful emulation of human locomotion in artificial systems is built upon a foundation of simple models (theoretical or empirical) that can accurately characterize the normal mechanical behavior of the human limb in the gait.

The most common modern ankle-foot and knee prostheses, such as the works of Prof. Herr at MIT and Prof. Kuo at Univ. of Michigan, employ a limited number of spring stiffnesses in their design. The gait of an amputee who uses these quasi-passive compliant prostheses could approximately mimic the unaffected limb. However, the current devices still need to exhibit user and task adaptability. The success in the field of exoskeletal devices has been even more limited [1]. Lower extremity exoskeletons have not yet been able to augment human performance, and advanced orthoses have been mostly limited to latching mechanisms that rigidly support the joints when loaded.

A better understanding of the biomechanics of joints could result in improvements in the design of these assistive devices. The findings of this study suggest that these devices could more closely mimic the behavior of human joints with a wider range of gait speeds and potentially less energy consumption, provided they exhibit stiffness tuned to the gait and body parameters. Indeed, the current work centers on development of mathematical models that characterize the quasi-stiffness of lower extremity joints for different gait conditions and body sizes.

2. Design Improvement by Characterization of Joints Quasi-Stiffness

The concept of quasi-stiffness has been explored to characterize the spring-like behavior of lower-limb joints in humans. Quasi-stiffness is defined as the stiffness of a spring that best mimics the overall behavior of a joint during a locomotion task. The concept of quasi-stiffness applies particularly well to the knee and ankle joint during the stance phase of gait (walking and running). Applying a quasi-stiffness analysis revealed nearly linear moment-angle behaviors for both the knee and ankle that change with gait speed, ground slope, and load carriage [2-3].

The overall goal of this study is to establish a series of mathematical models to characterize linear behavior of the knee and ankle in stance for adult humans. A well-developed general model of knee and ankle joints stiffnesses during walking promises to aid in development of biologically-inspired assistive devices (particularly quasi-passive orthoses and prostheses) to improve mobility. The stiffness of the knee and ankle joints of the assistive devices and bipedal robots will either need to be chosen in advance for the individual cases or in real-time for more complex active impedance controls. For these applications, generalized biomechanical models that can explain subject-specific variability of the behavior of lower extremity joints will be critical for properly tuning assistive devices (e.g. choosing spring stiffness) to individual users.

We extract the equations for the moment of joints through inverse dynamics analysis. These equations help us identify the important gait and body parameters that potentially explain the quasi-stiffness of the joints. Then, we employ experimental data to establish the mathematical models that characterize the joints quasi-stiffness based on the body and gait parameters. The mathematical models we established in this study could estimate the knee and ankle stiffness with $R^2 \approx 83\%$ using the body height and weight, gait speed, and joints' excursion.

3. Discussion

Our current research suggests that assistive devices (e.g. orthosis and prostheses) and bipedal robots could mimic biological ankle and knee in stance phase if they exhibit linear behavior. We have shown, however, that the stiffness, angle of engagement, and amount of excursion of the devices joints should be deliberately chosen based on the gait speed and the pilot/robot weight [2-4]. Ideally, a variable stiffness mechanism that adjusts its stiffness based on the gait speed and weight should be implemented to accurately mimic the behavior of the human joints. Nevertheless, the implementation of such devices is challenging in practice, particularly for the range of stiffness that the knee and ankle demonstrate (e.g. ~400Nm/rad). Moreover, our understanding of the interaction between the human and an external device is limited and the questions remain to be answered would be: How much external stiffness could be accommodated by the human body? How would the knee and ankle joints of the device interact? To what extent would stiffness-based assistance be successful?

References

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