Design and Evaluation of Robust Control Methods for Robotic Transfemoral Prostheses

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1 Introduction

1.1 Motivation

Six hundred thousand lower-limb amputees currently live in the United States according to recent estimates (**?**). People undergo amputations due to a variety of reasons including traumatic injuries from workplace accidents, traffic collisions, and as casualties of war. In addition, a large percentage (54%) suffer from the loss of a limb due to complications arising from dysvascular disease associated with diabetes. Consequently, largely due to the expected increase in diabetes in the coming years, **?** estimate that by 2050 the number of amputees living in the United States will likely double.

Currently, prosthetists often prescribe transfemoral amputees (those with amputations between the hip and knee joints) an energy storage and return composite foot such as the Thrive Foot (Freedom Innovations; Irvine, CA; fig. 1.1c) along with a microprocessor-controlled, mechanically-passive knee prosthesis. These knee prostheses feature control algorithms that adjust the knee's resistance in response to kinematic and force data measured by sensors embedded in the device. Examples of microprocessor-controlled prosthetic knees include the C-Leg (Otto Bock; Duderstadt, Germany; fig. 1.1a), which has an adjustable hydraulic damping system, and the Rheo Knee (Össur; Reykjavik, Iceland; fig. 1.1b), which achieves variable damping via a magnetorheological fluid. While **?** show these microprocessor-controlled knees can improve amputee gait characteristics by decreasing metabolic energy consumption and peak hip torque and increasing gait smoothness compared to that provided by fully-passive knee prosthesis, these prostheses still cannot fully replicate healthy leg behavior as they are incapable of providing positive net power during the gait cycle adn are may be limited to providing positive power only during fixed portions of the gait cycle.

Control of positive power generation is important as positive

(a) C-Leg™ Knee ©Ottobock

(b) Rheo™ Knee ©Össur

(c) Thrive™ Foot ©Freedom Innovations

Figure 1.1: Examples of microprocessor-controlled mechanically-passive knee prostheses (a,b) and a energy storage and return ankle-foot prosthesis (c).

power is evident in a number of locomotion tasks. In the knee joint, we see positive power during level walking (?), walking up stairs (?), running (?), and jumping (?). In addition, active knee flexion and extension muscle activations have been noted during stumble recovery (?). At the ankle joint, passive spring-like prostheses cannot replicate the positive net work seen in the ankle joint during level ground walking, which is essential for push-off and forward propulsion (?).

Consequently, lower-limb amputees and especially *transfemoral amputees*, those with above the knee amputations, equipped with mechanically-passive prostheses suffer from a number of issues including markedly increased energy consumption (?), abnormal gait kinematics (?), and an increased likelihood of falling (?). Specifically, large percentages of transfemoral amputees report they are unable to complete tasks such as walking outside in inclement weather (47.4%), walking while carrying a load (42.7%), walking up or down stairs without a handrail (38.5%, 37.9%), walking outside on uneven terrain (29.5%), picking up an object from the ground (28.1%) or getting up from the floor after a fall (22.8%) (?).

Importantly, these gait pathologies can lead to an avoidance of walking (?). This is especially true in the case of falls. **?** find 49.2% of lower limb amputees feared falling and that of those afraid of falls 76% avoided physical activity as a result. Avoidance of physical activity is eminently concerning as it may lead to reduced strength, endurance, and balance, feeding a positive feedback loop that causes further debilitation.

To help remedy this situation, in the past decade academic research groups and companies have developed robotic powered knee and ankle prostheses for lower-limb amputees. These prostheses feature actuators at the knee and/or ankle that, if controlled correctly, could potentially restore the kinetics, kinematics, and re-

(a) Generation 1 (b) Generation 2 (c) Generation 3

Figure 1.2: Vanderbilt University's Robotic Transfemoral Prostheses. Images courtesy of Michael Goldfarb.

actions of the healthy human leg. Notable examples include three generations of transfemoral prostheses developed by Vanderbilt University (fig. 1.2) (**???**) and the Biom powered ankle (fig. 1.3) (**?**). These powered prostheses have helped amputees walk on level ground more naturally and efficiently, as well as walk up stairs and slopes (**??**), run (**??**), perform sit-to-stand (**?**), and dance (**?**). These results illustrate the benefits of powered prostheses as many of these tasks require positive joint power and thus would be difficult to perform with mechanically-passive prostheses.

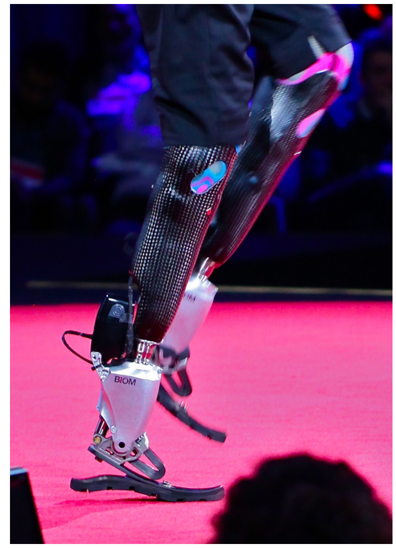

Figure 1.3: Biom Robotic Ankle Prosthesis. Photo by Steve Jurvetson, CC BY 2.0, Link (cropped from original).