Proceedings of the 2017 Design of Medical Devices Conference
DMD2017
April 10-13, 2017, Minneapolis, Minnesota, USA
DMD2017-3398

Hybrid Actuation Systems for Lightweight Transfemoral Prostheses

Tommaso Lenzi[1]
Marco Cempini[2]
Levi Hargrove[2,3]
Todd Kuiken[2,3]

[1] Department of Mechanical Engineering
University of Utah
[2] Center for Bionic Medicine
Rehabilitation Institute of Chicago
[3] Northwestern University

1 Background

Lower-limb amputation affects the ambulation ability and quality of life of about 600,000 individuals in the United States alone[1]. Individuals with transfemoral amputation typically walk slower, expend more energy, and have a higher risk of falls than able-bodied individuals[2]. Ambulation activities such as climbing ramps or stairs or standing up from a seated position are much more difficult than for able-bodied persons. Advances in prosthetic technologies are needed to improve the ambulation ability of above-knee amputees.

Passive knee prostheses are lightweight, robust, and quiet, but can only perform activities with dissipative dynamics. Powered prostheses[3] overcome this limitation by motorizing the prosthetic joints throughout the entire day, thus enabling the achievement of more activities. However, the prosthesis actuator must then accommodate a wide range of speed and torque to support the various activities, plus provide power over the course of the entire day. Consequently, powered prostheses provide the ability to perform more tasks at the expense of substantial weight, noise, and battery life, which in turn affect their acceptability and clinical viability.

To address these shortcomings, we propose a hybrid actuation design for prosthetic knees. The proposed hybrid actuation system uses a motor, transmission, and control only for those activities requiring net-positive mechanical energy, such as climbing on stairs and ramps or performing sit-to-stand transfers. For non-positive mechanical energy tasks, such as standing and walking, the motor and transmission are mechanically disconnected, and passive knee components are used alone, thus achieving improved joint dynamics, and avoiding any electrical energy consumption.

2 Methods

The proposed hybrid actuation system is based on an active mechanism that selectively connects the powertrain to the knee joint when positive net energy is needed. This task is accomplished by a novel actively variable transmission (AVT) that changes the effective transmission ratio of the powertrain from zero for level-ground walking to a maximum value for active tasks, such as stairs climbing, thus satisfying the needs of the hybrid actuation. The AVT was specifically designed to reduce the overall weight of the knee prosthesis.

The proposed knee kinematics consists of an offset inverted slider-crank mechanism, where the revolute joint R_1

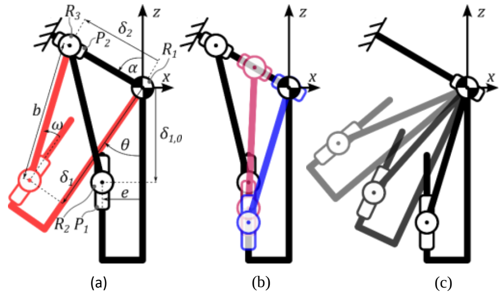

Figure 1. Proposed Hybrid Knee kinematics in (a) active mode, (b) mode transitions, and (c) passive mode.

corresponds to the knee joint. An additional prismatic joint P_2 is added along the crank member, realizing a five-bar mechanism with two degrees of freedom. Rather than being involved in the generation of knee motion, the joint P_2 is used to set a desired relationship between the motion of the prismatic joint P_1 and the motion of the revolute joint R_1 (knee joint position, Θ), which defines the transmission ratio of the proposed knee mechanism.

The proposed knee kinematics, based on inverted offset slider crank mechanism realizes an actively variable transmission thanks to its variable crank length (Fig1(b)). When the crank length is set to zero (Fig1(c)), the prismatic joint P_1 is fully decoupled from the knee joint. This degenerated configuration allows for a passive mode of operation where the knee joint can move freely, independently of the actuators (see Fig. 2c), and without any other mechanical motion involved.

In the final knee design (Fig. 2a), the prismatic joint P_1 is actuated by a brushless DC motor (Maxon Motor EC-4pole 22, 24 V, 120 W) connected to a roller screw (Rollvis) through a timing belt transmission (48:18 teeth ratio). The nut of the roller screw is connected to a linear guide (HMR9ML, Helix Linear Technologies), parallel to the roller-screw, which sustains it in the directions orthogonal to its axis. The motor is located inside the hollow prosthesis frame for protection and for enhanced heat dissipation. Two identical parallel bars connect the nut to the AVT, minimizing prosthesis size without interfering with the roller screw (Fig. 2). The AVT design comprises a custom non-backdrivable lead screw that allows changing the crank length between 0 and 45 mm. The screw nut moves on a slotted hole carved in the crank mechanical frame, sliding on dry bushings (L280 IGUS®

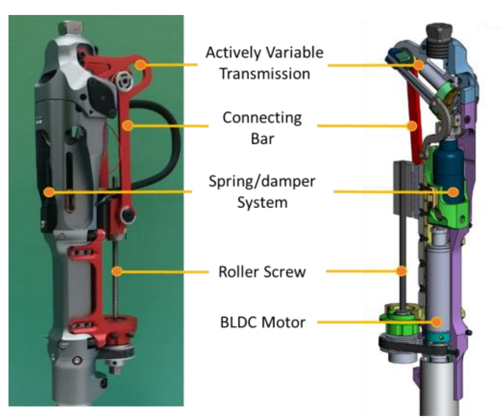

Figure 2. (a) Mechanical design and (b) CAD sectioned view of the hybrid-AVT knee prosthesis. (c)

Iglidur®). The leadscrew is driven by a miniaturized brushless motor (Maxon motor EC 10, 18 V, 8W, gear stage 16:1) through a 1:1 spur gear transmission

The hybrid knee prototype uses development electronics based on the System on Module (SOM) from National Instruments (MyRIO 1900, National Instruments), which is fully contained within the knee cover and powered through a 3000 mAh, 6S Li-Ion battery. Reciprocal gait stair ascent is achieved using the control algorithms previously described in [5]. This control approach divides the ambulation cycle into stance phase (i.e., foot in contact with the ground) and swing phase (i.e., foot off the ground), based on the ground reaction force readings. Then it enforces physiological quasi-stiffness profiles in stance [67] and minimum-jerk movements in swing [8].

3 Results

The weight breakdown of the Hybrid Knee prototype is shown in Table I. Knee mechanics weight 1130 g. The AVT and passive spring/damper system accounts for 2.68% and 7.44% of the total weight respectively. In active mode, the knee prosthesis can provide 125 Nm repetitive peak torque, as required by a 90 kg person for reciprocal stair climbing [4].

Preliminary validation of prosthesis performance during ambulation was conducted by an able-bodied subject wearing a bypass orthosis; all experimental procedures were approved by the Northwestern University Institutional Review Board. The subject performed level-ground walking and reciprocal stair climbing on a walkway and stairwell that each allowed for five full strides on the prosthesis side. Experimental results (Fig 4) show that the subject could ambulate on level ground and climb stairs with close to physiological knee kinematics.

Table I Weight Breakdown

Part	***Mass (g)***	***(%)***	
Primary motor	170	10.1	
Primary tranmission	250	14.9	
AVT	45	2.7	1130g (67.3%)
Passive spring/damper	125	7.4	
Frame	480	28.6	
Bolts and screws	60	3.6	
Cover	100	5.9	
Electronics and control	150	8.9	550g (32.7%)
Battery	300	17.9	
Total			**1680g**

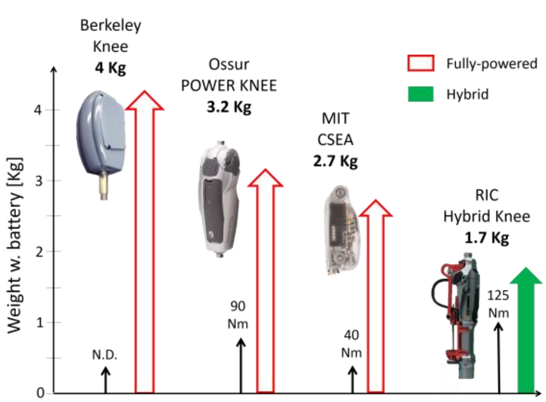

Figure 3. Weight and torque performance of fully powered (open arrows) and hybrid knee prostheses (solid arrow)

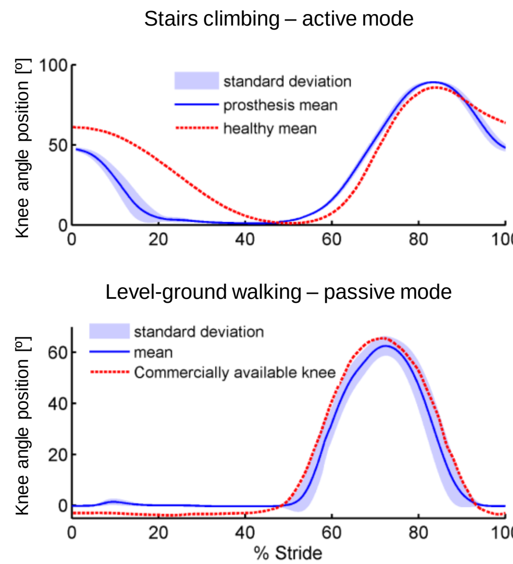

Figure 4. Averaged knee position trajectory during level-ground walking and stairs climbing with the Hybrid Knee.

4 Interpretation

A novel actively variable transmission allows for significant weight reduction compared to conventional powered prostheses. To the best of our knowledge, our knee prototype is the lightest powered knee prosthesis to have been developed so far. Future work will focus on validating the proposed design in individuals with transfemoral amputations.

References

1. Adams PF, Hendershot GE, Marano MA. Current estimates from the National Health Interview Survey, 1996. *Natl Heal Surv Vital Heal Stat*. 1999;(200):1-203.
2. Schmalz T, Blumentritt S, Jarasch R. Energy expenditure and biomechanical characteristics of lower limb amputee gait: The influence of prosthetic alignment and different prosthetic components. *Gait Posture*. 2002;16(3):255-263.
3. Goldfarb M, Lawson BE, Shultz AH. Realizing the promise of robotic leg prostheses. *Sci Transl Med*. 2013;5(210):210ps15. doi:10.1126/scitranslmed.3007312.
4. Winter DA. *Biomechanics and Motor Control of Human Movement*. Vol 2. (Edition W, ed.). Wiley; 1990.
5. Lenzi T, Sensinger J, Lipsey J, Hargrove L, Kuiken T. Design and preliminary testing of the RIC hybrid knee prosthesis. In: *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE; 2015:1683-1686. doi:10.1109/EMBC.2015.7318700.
6. Lenzi T, Hargrove L, Sensinger J. Speed-adaptation mechanism: Robotic prostheses can actively regulate joint torque. *IEEE Robot Autom Mag*. 2014;21(4):94-107.
7. Lenzi T, Hargrove L, Sensinger JW. Preliminary evaluation of a new control approach to achieve speed adaptation in robotic transfemoral prostheses. In: *IEEE/RSJ International Conference on Intelligent Robots and System, 2014*. ; 2014.
8. Lenzi T, Hargrove LJ, Sensinger JW. Minimum jerk swing control allows variable cadence in powered transfemoral prostheses. In: *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. 2014:2492-2495.