Autonomous Soft Exosuit for Hip Extension Assistance

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***Abstract*—In this abstract, we describe a mono-articular soft exosuit to assist with hip extension during overground walking. The system is comprised of a mobile Bowden-cable-driven electrical actuation unit, soft textiles, and a load cell and an inertia measurement unit per leg. The exosuit applies forces with a peak of 300N enabled by an IMU-based iterative control algorithm. This iterative controller detects the onset timing of the hip extension assistance based on an estimation of the maximum hip flexion angle. The timing and magnitude of the applied peak force is modulated by generating step-by-step actuator position profiles based on the previously measured assistive force. Results from a human subject during overground walking at self-selected speed indicate the robustness of the system to apply effectively forces with a high consistency in terms of magnitude and timing of the peak force profile.**

I. Introduction

Plethora of conventional rigid exoskeletons have been developed over the past decades to assist with human locomotion [1]. These devices can support the wearer's body weight and apply a substantial portion of the required biological torques [2]. However, such rigidly structured devices can restrict the user's movements and apply undesired forces resulting in discomfort. In addition to kinematic restrictions and joint misalignments rigid exoskeletons often have high inertias which can impede the user especially when control tracking deficiencies occur [3]. To overcome these limitations, we have recently proposed exosuits which are composed of soft materials such as textiles and elastomers to provide a compliant means to interface with the human [4]-[6]. Exosuits apply tensile forces to the body through load paths well defined by the textile architecture. As exosuits incorporate soft components they have extremely low inertia and eliminate the challenges associated to joint misalignments.

Several research groups have investigated the benefits of powering the hip joint using a wearable robot. In particular, in [7] it is proposed that providing external power to the hip joint could yield a greater reduction in metabolic cost, than providing the same amount of power at the ankle joint. Moreover, in [8] authors reported a reduced metabolic cost of ~18% compared to walking with exoskeleton unpowered when providing an assistive torque corresponding to 100% of the average torque of the human hip joint.

To this end, we present an autonomous exosuit system to assist hip extension during overground walking especially outdoors. The system is capable of consistently delivering mechanical power to the user across subjects, varied walking speeds and step lengths. In addition, it is intuitive and does not hinder other motion tasks (uphill/downhill walking, stair climbing/descending and walking over obstacles). It is also worth to mention that the robustness of each subsystem (i.e. actuation in terms of thermo-mechanical fatigue, suit in terms of component drifting, and controller in terms of tracking performance) has been successfully evaluated by several subjects testing during 3 miles hiking on rough terrains.

II. System Description

A. Actuation and Suit

The Bowden-cable-driven actuation unit is a two degree-of-freedom (DoF) system that actuates each leg independently and it is designed so that it can be simply mounted on top of a MOLLE II Large Rucksack as shown in Fig. 1. Each DoF consists of a Maxon EC 4-pole, 200W motor that is connected to a gearbox of ratio 51:1 and drives an 8cm diameter pulley. A motor controller unit (by Elmo Motion Control Inc.) controls each motor and is integrated into a custom electronic board. In addition, an Amtel microprocessor communicates with the Elmo motor controller through the CANOpen communication protocol and provides with the required position commands. A removable battery unit containing two 6-cell Li-Po batteries (5200mAh) is placed on the bottom of the rucksack and provides the device with an autonomy over approximately 6 miles. The overall system weight is 4.9kg (actuation, 3.1kg, suit, 0.4kg, and battery, 1.4kg).

The exosuit consists of a spandex base layer, a waist belt that wraps around the subject's pelvis, two thigh brace pieces and two IMU elastic bands (for IMU placement). The waist belt and the thigh brace provide with the two required anchor points. In particular, the Bowden cable sheath connects to the back of the waist belt and the inner cable connects to the back of the thigh brace. Therefore, when the motor retracts the cable a hip extension torque is created and when the motor feeds out cable the suit is slack.

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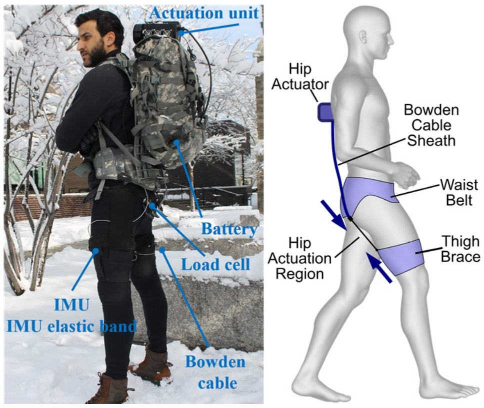

Fig. 1. A subject wearing the autonomous soft exosuit (left). Load path to actuate hip extension and components of the suit (right).

B. *IMU-based iterative controller*

The main goal of the mobile soft exosuit is to deliver consistent and robust hip extension force in sync with subject's gait dynamics. Based on our examination of the relationship between metabolic energy reduction and net work rate provided by actuators in previous study [5], the force profile was chosen to mimic the biological joint torque, with the assumption that this will allow the muscle activation to decrease proportionally and consequently reduce the metabolic energy.

From an analysis of the hip biomechanics it can be found that the onset of the hip positive power concurs with the maximum hip flexion angle, and the hip extensor muscles start to activate slightly earlier to this [4],[6]. Therefore, we select to detect the maximum hip flexion using an IMU sensor mounted on the thigh of each leg. A force-based position control is then used to create the hip extension torque with onset, peak and offset timings similar to the one of the biological hip joint torque [5]. To ensure a consistent and robust delivered force given the variability in hip kinematics, kinetics, and suit positioning, the controller adjusts the pretension level and the maximum amplitude of the motor position command based on the force profile of the previous gait step.

III. RESULTS

To evaluate the performance of our proposed system and IMU-based controller, we conducted an overground walking experiment. A healthy subject (male, age 30, height 179 cm, weight 76 kg) wore the system and walked with the freedom to vary his walking speed as preferred. Our objective is to deliver constant and robust hip extension forces of 300N to the user (which corresponds to a hip torque of approximately 45Nm and a 60% of the nominal biological torque) regardless of his gait pattern. Thus, the performance of the assistive force has been evaluated using the following metrics on a step by step basis: the magnitude and timing of the peak force and the offset timing of the force waveform. Fig. 2 depicts the average and standard deviation of the measured forces and thigh angles for a trial of 10 minutes of walking, segmented based on the percentage of the gait cycle. Note that, the percentage of the gait cycle has been calculated based on the average onset timing (i.e maximum hip flexion) and 0% gait cycle corresponds to the heel strike. The average of the peak force was 294 ± 11 N, which results in an error of ~3%. In addition, the average of the peak and offset timing of the force profile were 16.4 ± 0.8 % and 28.2 ± 0.8 % gait cycle, respectively. These results demonstrate the ability of the system to accurately control the peak force and the peak force timing to the desired values.

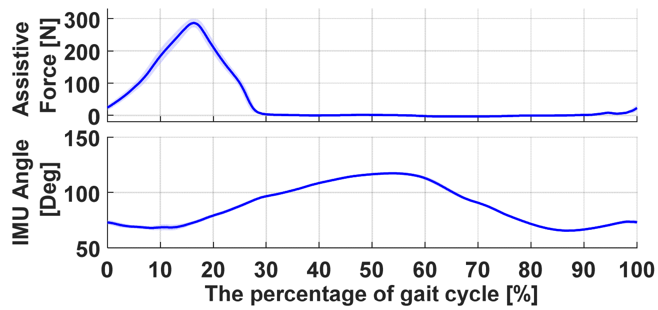

Fig. 2 Hip extension force (load cell) and thigh angle (IMU) based on the percentage of gait cycle (right leg).

IV. CONCLUSION

We presented an autonomous soft exosuit for hip extension assistance. The system is able to deliver constantly and repetitively mechanical power to the user with an error in the magnitude of the peak force of ~3% regardless of the kinematic and kinetic variations occurring during gait. In a previous study with an off-board actuation platform which applied similar force profiles with a peak of 200N, we found that metabolic energy is reduced by an average between 5.7-8.5% compared to the unpowered condition [6]. Thus, we expect that a greater reduction in metabolic energy will be achieved with a hip assistance of 300N. Future work will include investigation of the proposed system's benefit in energy expenditure among different subjects.

REFERENCES

[1] E. Guizzo and H. Goldstein, "The rise of the body bots", *Spectrum, IEEE* 42 (10) (2005) 50–56.

[2] R.J. Farris, H.A. Quintero, M. Goldfarb, "Preliminary evaluation of a powered lower limb orthosis to aid walking in paraplegic individuals", *IEEE Trans. Neural Syst. Rehabil. Eng.* 19 (6) (2011) 652–659.

[3] R. C. Browning, J. R. Modica, R. Kram, and A. Goswami, "The Effects of Adding Mass to the Legs on the Energetics and Biomechanics of Walking," *Med Sci Sport Exerc*, vol. 39, 2007.

[4] A. T. Asbeck, K. Schmidt, I. Galiana, D. Wagner, and C. Walsh, "Multi-joint Soft Exosuit for Gait Assistance," *IEEE International Conference on Robotics and Automation* (*ICRA*), May 2015.

[5] Y. Ding, I. Galiana, C. Siviy, F. A. Panizzolo, and C. Walsh, "IMU-based iterative control for hip extension assistance with a soft exosuit," *IEEE International Conference on Robotics and Automation* (*ICRA*), May 2016, to be published.

[6] Y. Ding, F. A. Panizzolo, C. Siviy, P. Malcolm, I. Galiana , K. G. Holt, and C. Walsh, "Effect of timing of hip extension assistance during loaded walking with a soft exosuit,", *J Neuroeng Rehabil*, in review.

[7] Sawicki GS, Lewis CL, Ferris DP, "It pays to have a spring in your step". *Exerc Sport Sci Rev*, 2009, 37:130–8.

[8] Ronsse R, Koopman B, Vitiello N, Lenzi T, De Rossi SMM, van den Kieboom J, van Asseldonk E, Carrozza MC, van der Kooij H, Ijspeert AJ,"Oscillator-based walking assistance: a model-free approach", *IEEE Int Conf Rehabil Robot,* 2011.