Exoskeletons on the move

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1 Motivation

Wearable exoskeletons are becoming a reality with increasing application in the medical environment.

Different companies already commercialize their exoskeletons to clinics and privates, with the key leaders of the market being Ekso bionics, Rewalk and Indego. All these devices have at least hip and knee joints flexion/extension actuation. However, all these devices also rely on crutches for guaranteeing locomotion stability. Another characteristics of these first commercial exoskeletons are a limited ability to move quickly and easily, and notably, a limited ability to adapt or be adapted to many different functions or activities.

The goal of the research going on at the TUDelf group (University of Twente), under the direction of Prof. Herman van der Kooij, is to allow robust, versatile and agile walking for SCI subjects, enabled with exosuits, without the use of crutches.

This goal is reached by the completion of four main phases. A first phase is constituted by the identification of balance strategies and the study of the neuromechanics of human movements. In a second stage, mathematical models are obtained to formalize these strategies. Next, the models are implemented in controllers to integrate the intelligence into robot movements. Finally, the last phase consists in the validation of the controller with ad-hoc evaluation experiments.

2 How humans maintain balance: three strategies

Three strategies are used by humans to maintain balance: the modulation of Center of Pressure (CoP, namely the point of application of ground reaction forces) location by ankle torque, the modulation of CoP location by foot placement, and the exertion of moment by utilising inertial forces. In the ideal stable standing situation, Center of Mass (CoM) and CoP position are the same. After the application of a small unexpected antero-posterior perturbation acting from the back to the front body's CoM is displaced frontally. To recover the stable position, humans will exert a torque with the ankle which pushes the CoP to the front to recover stability. Similarly, if the intensity of the perturbation is higher, the ankle strategy may not be enough and the hip joint is used to recover the stable position. Finally, to face an ever stronger perturbation, stepping strategy can be used: with the step, the CoP instantaneously moves forward to recover stability. However, while these mechanisms are known in literature, the question that rises is if humans utilise foot placement to maintain balance while walking, or whether they use also other strategies.

3 How we maintain balance during gait: Experimental results

Novel walking models and exoskeleton control approaches are based on aforementioned CoM control strategies. Since changes in CoM position during walking depend on the movement itself as well as on external perturbations in the anterio-posterior (AP) and medio-lateral (ML) plane, recent studies on walking patterns investigated a foot placement strategy humans involuntary undertake which tailors compensatory mechanisms according to the specific applied perturbation.

In particular, rightward/leftward perturbations in the ML plane induce an automatic stepping reaction in the leading foot (i.e. foot in swing during perturbation) respectively towards backward-right-hand and backward-left-hand direction, whereas disturbance in the AP plane does not show such a significant compensatory pattern. Moreover, linear relationship has been found between ML-perturbation velocity and ML-foot position, as well as between ML-perturbation velocity and Centre of Pressure (CoP) position, which are however specific to the ML plane only.

4 Regular approach to control exoskeletons: finite state machine (Mindwalker)

Further studies implemented an innovative controller for walking-exoskeleton based on the aforementioned CoM adaptive strategies for optimal locomotion and balance practise. The controller (Finite State Machine control, MindWalker EU project) is based on the well-known sequential phases of walking (i.e. stance-swing) as represented by five different states that the controller is able to subsequently activate in order to perform an ideal walk. Each state activates a set of actuators in the joints specifically needed in the related walking phase to perform the associated motion. Moreover, elastic springs and recording sensors are embedded in each joint in order to respectively monitor joint force production and record joint angles as feedback control error (e.g. monitoring mismatched steps). The switching from one state to the next is currently reliably conveyed by simply pushing a button, setting timing of motion (passive conditions), or by monitoring CoM position (active condition). The latter is currently the most common used state-switching technique and has been proved to reliably support healthy subjects walking with exoskeleton, although tests on SCI patients weren't fully successful.

Two different tests on SCI patients were performed: using automatic control external aid was still needed (e.g. crutches, physiotherapist), whereas CoM control gives better results. Given the current state of the work there is still room for improvement of the controller automation as well as for investigation of more advanced state-switching techniques, for example using real-time EMG sensors and individual EEG brain activity.

5 Biological inspired approach: evaluation and implementation of NeuroMuscular-based locomotor Controllers (NMC)

Nowadays, scientific society is continuously moving towards more complex neural algorithms to control human gait. Nevertheless, locomotion requires little control if dynamics of legged systems are maintained and, in this direction, muscle reflexes play a vital role. Principles of legged mechanics have been encoded into a model of human locomotion. This model, equipped with this reflex control, stabilises walking gait with its dynamic interplay with the ground, reproduces human walking dynamics and leg kinematics, tolerates ground disturbances, and adapts to slopes without parameter interventions. The results suggest that human motor output could for some muscles be dominated by neural circuits that encode principles of legged mechanics.

This control algorithm has been subsequently implemented in two different robots in order to validate its applicability. The first one is an Achilles exoskeleton, which is intended to provide push-off assistance during walking. Assistance is provided by a series elastic actuator that has been optimized to provide maximal push-off power. It has been proven that subjects walk at faster speed with NMC. Moreover, NMC could provide tailored assistance and, finally, differently from the most common robotic devices, subjects felt comfortable walking in Achilles. The second robot device is the LOPES II, which can provide sufficient support to let severely affected patients walk. It showed a reliable speed modulation and swing foot perturbation rejection.

6 Conclusions

Experimental results showed that external perturbations in the AP plane do not induce any foot placement strategies and that the control of CoP location is made by the modulation of ankle torques, whereas disturbances in the ML plane induce a specific foot placement strategy. Some tests on complete SCI subjects demonstrated that decentralised reflex based on NMC support allows subjects to walk in LOPES II. However, controlling and sensing CoM velocity is important to maintain balance control.

In conclusion, the results of this work evidenced some implications for the design and the control of exoskeletons.

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