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„Complementary Limb Motion Estimation (CLME): Experimental Results“

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Complementary Limb Motion Estimation (CLME): Experimental Results

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INTRODUCTION

Rehabilitation robots facilitate early and extensive therapy, which promotes effective rehabilitation after brain injury [Sinkjaer2005]. Control strategies for these robots can be based on recent studies concerning motor learning and rehabilitation. These have shown that active movements performed by the subject are much more effective than guided motion along the "correct" path, and that robots support motor learning best if they only provide "assistance-as-needed" [Emken2007]. For gait rehabilitation, this would imply to provide assistance only when essential for the walking task, and to leave the patient otherwise undisturbed, an approach similar to new tendencies in upper limb rehabilitation [Oldewurtel2007].

Therefore, a controller has to fulfill two requirements: It has to ensure stable walking, and it has to remain "invisible" if the patient walks correctly. The challenge lies in the definition of "correct", because a simple comparison to the gait of another healthy subject by impedance control would imply forcing both legs on fixed trajectories. Such a procedure might interfere with the subject's motion intention, whereupon the interference manifests itself in altered EMG patterns and interaction forces between leg and exoskeleton [Hidler2005].

Interference can be lowered if the patient's motion intention is known, such that the robot can anticipate and adapt the reference trajectory. In some cases, the intention can be deduced from muscular activity in the impaired limbs, either by observation of the generated motion [Jezernik2004], or by EMG measurements of the muscle activation. However, these techniques require sufficiently coordinated activity in the brain regions controlling the impaired limbs.

An alternative approach is to observe the patient's sound limbs, which might reveal the motion intention. We have presented an automated, generic method ("Complementary Limb Motion Estimation", CLME), which infers from the motion of sound limbs to the intended motion of paretic or amputated limbs [Vallery2006]. The idea is based on the observation that during functional movements such as grasping or walking, there are strong couplings between Degrees of Freedom (DoFs), called "synergies" [StOnge2003]. This indicates a subset of manipulated variables; it seems as if our brain has developed such refined control methodologies to deal with the abundance of human DoFs. Based on these couplings in healthy synergistic motion, CLME estimates the motion of paretic limbs that corresponds to a patient's current sound limb motion.

CLME thus defines "correct" walking only on the basis of interjoint couplings, such that a much wider range of movements is allowed compared to a predefined gait pattern. Furthermore, sound limbs are not influenced in their motion at all.

The strong inter-limb coordination during human walking allows for a very accurate right leg - left leg inference (as needed for hemiparetic subjects) using prerecorded trajectories in simulations [Vallery2006]. However, the suitability for control of gait rehabilitation robots can only be answered by practical experiments, where the human closes the loop. The pilot studies to be presented here therefore address the two requirements above: a) In the case of a high level of paresis, is functional gait ensured by the controller? b) In the case of voluntary activity in the impaired leg, will the controller produce only minor interference?

COMPLEMENTARY LIMB MOTION ESTIMATION

The goal of CLME is to find a mapping function, which outputs the states of impaired limbs (angles and velocities) in dependence of the states of sound limbs. To obtain this function, joint synergies are extracted from recorded healthy gait trajectories. Then, reference motion can be generated on-line for inoperable joints, using the current motion of the sound limbs.

There are numerous approaches in statistical regression to tackle this problem. We have investigated 2 among them: One approach using Principal Component Analysis (PCA), and one using the standard Best Linear Unbiased Estimator (BLUES).

The outputs of the regression are angles and velocities for the impaired joints, yet both angles and velocities are subject to uncertainty. Thus, the estimated velocity is quite different from the differentiated estimated position. Therefore, an additional Kalman filter is used to merge the two pieces of information, yielding the most plausible motion intention.

EXPERIMENTAL EVALUATION

We conducted two pilot studies on the LOPES gait rehabilitation robot addressing the questions above. LOPES consists of a light-weight 9-DoF actuated exoskeleton for the lower extremities in combination with a treadmill [Veneman2006].

Ensuring Functional Gait: For this first rather qualitative proof of concept [Vallery2007], 8 healthy subjects were recruited, and a one-sided impairment was simulated using the exoskeleton leg as a prosthesis. Subjects were asked to ”sit” with their left buttock on a small board mounted to the LOPES frame. Furthermore, a foot was attached to the exoskeleton leg on this side, such that the left LOPES leg became a prosthesis. Subjects thus walked with their own right leg and the robotic left leg, the motion of which was commanded by CLME in dependance of the right leg motion. Each subject walked based on the extracted coupling and scaling of a physiologically comparable person (criteria were gender, height and weight), whose gait pattern had previously been recorded.

*Results:*All subjects were able to walk after a very short time of practice. Some of the gait patterns were asymmetric: Subjects tended to prolong their right stance phase, probably due to low confidence in the robotic left leg. This shows that CLME allows a range of possible functional gait patterns. Furthermore, signs of adaptation to the gait pattern of the reference person have been found.

Interference with Voluntary Activity: We conducted a pilot study with two healthy subjects, who walked in LOPES with 4 different control modes: a) position control for both legs along the gait pattern of a different subject, b) CLME control based on PCA, i.e. right leg in zero torque, left leg in position control, c) CLME control based on BLUES, d) Zero torque mode for both legs. These control modes directly followed each other in the experiment (using a slow blending). The time duration was 1 minute for each mode. We did not measure interaction torques directly, but the torques between actuators and exoskeleton. Due to the light weight of the exoskeleton, these torques do not differ much from the interaction torques. To rate the approaches, a performance index is calculated for each mode and joint, which is the sum of squared interaction forces divided by the zero torque value (the best possible result).

Results: The results are similar for both subjects: Interaction torques with the left leg are high in position control, low in zero torque mode, and intermediate in CLME gait. When comparing PCA and BLUES, results are not consistent, neither among joints nor subjects, but both controllers always yield better performance indices than position control. Fig. 1 exemplarily shows left hip flexion interaction torques of one subject.

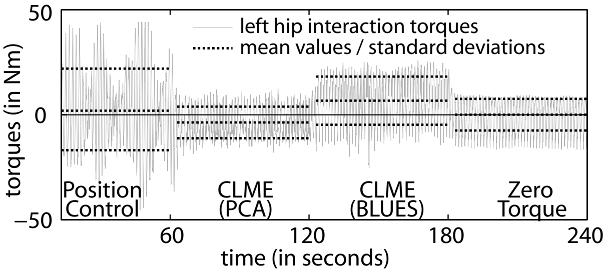

Fig. 1: Left hip interaction torques of a subject walking in LOPES with position control, CLME and zero torque

CONCLUSION

This paper presented two pilot evaluation studies of Complementary Limb Motion Estimation concerning its suitability to control gait rehabilitation robots. The results show that CLME enables functional walking controlled by one leg. It also lowers the interference with voluntary patient activity in the impaired leg compared to position control using fixed reference trajectories.

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