Complementary Limb Motion Estimation for the Control of Active Knee Prostheses

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Abstract
To restore walking after above-thigh amputation, various actuated exoprostheses have been developed, which control the knee torque actively or via variable damping. In both cases, an important issue is to find the appropriate control that enables user-dominated gait. Recently, we suggested a generic method to deduce intended motion of impaired or amputated limbs from residual body motion. Based on interjoint coordination in healthy subjects, statistical regression is used to estimate missing motion. This Complementary Limb Motion Estimation (CLME) strategy has been proposed for rehabilitation of hemiparetic patients. Now, we extend the application of this method to controlled exoprostheses. A motor-driven prosthetic knee with one Degree of Freedom has been realized, and one above-thigh amputee has used it with CLME in a pilot study. Performed tasks are walking on a treadmill and stepping up and down stairs with alternating legs. The subject was able to walk on the treadmill at varying speeds, but needed assistance with the stairs, especially to descend. The promising results with CLME are compared to the subject’s performance with her own prosthesis, the C-Leg from O. Bock.

1 Introduction
Healthy human gait is a continuous control process, which allows adaptation to almost arbitrary environments on the basis of a broad experience. Human capabilities in the coordination of movements still outperform biped robots by far. After the loss of a leg due to amputation, the motor system is generally still capable of these complex control tasks, and the ideal of a prosthetic solution would be a seamless integration into the sensorimotor control loop. On this way, there are two challenges: One is to realize a portable hardware solution that is capable of generating the same forces and movements as a human leg. The second challenge is to interface the prosthesis with the human controller.

The first attempts for a hardware solution were passive mechanical joints. Using monocentric and later polycentric knee joints, stable stance and also knee flexion during swing were possible. A major advance was marked by the development of adaptively damped devices, namely the C-Leg by O. Bock and the Rheo Knee by Össur. These systems exploit the fact that knee joint power during physiological gait is mainly negative, meaning that the muscles are predominantly active to decelerate and to absorb energy. With very little power supply, microprocessor-controlled fluidic dampers can adapt the viscous torque according to the current gait phase, enabling a near-normal gait pattern. The C-Leg and the Rheo Knee show biomechanical advantages compared to passive mechanical joints, like smoother gait and less compensatory hip activity on the contralateral side [1]. Furthermore, the microprocessor-controlled joints show an improved behavior when descending stairs and negotiating rough terrain, and they can reduce the frequency of stumbling and falls [2]. However, knee joint power is low during gait, but it is not zero. Thus, purely dissipative devices are still a compromise and cannot enable a fully normal gait. Furthermore, they do not allow movements that intrinsically depend on positive knee power, like ascending stairs with alternating legs. Currently, with advancing actuator and energy storage possibilities, also active prostheses are being developed, which can generate positive joint power. The only commercial device is the Power Knee from Össur and Victom Human Bionics, Canada. Still in a research stage, there is also the pneumatic prostheses presented by Sup et al. [3].

The second goal, the integration into the human control apparatus, is still far away. To compensate for deficient interfacing with the human’s internal controller, diverse control strategies have been suggested, which let the prosthesis act intelligently based on its own knowledge base of physiological movements. The majority of algorithms change the prostheses behavior depending on the movement phase. The algorithm suggested in [3] cuts the gait pattern into a multitude of small units with different impedances (stiffness and damping values). The C-Leg also varies resistance depending on the gait phase. However, these strategies are optimized for a specific movement primitives like cyclic gait, and they require heuristic definitions of these primitives. For example, the Power Knee allows various movement primitives, but their number and type is limited by an explicit state machine [4]. This means that only pre-programmed, cyclic patterns and clearly defined transitions are possible. Sensors in the contralateral sole thereby detect the current state. This requires initiating new motions with the sound side, and the motion needs to be symmetric. Furthermore, this approach cannot be used for bilateral amputees. An important result of first clinical studies is that highly active patients can be deprived of...
their autonomy by intelligent prostheses [5]. Thus, a high level of internal intelligence in the prosthesis cannot compensate for the lack of proper interfacing between human controller and artificial joint, such that the user needs to get used to the technical aid, and adapt to its behavior.

On the way to cooperative devices that comply with the user’s motion intention, a major challenge is to detect this intention. Impulses can be drawn from other fields of research, especially from exoskeletons and haptic interfaces, as well as from arm prostheses. For these systems, various methods exist to estimate the user’s motion intention. Many of these concepts, however, cannot be transferred, because they aim to augment residual motion. One applicable strategy could be the use of electromyography (EMG), which measures motor commands sent to the muscles. This method has been applied to hand prostheses [6] and exoskeletons [7, 8]. However, transcutaneous EMG is very sensitive to noise, and it cannot be used for all patients. Especially for a leg prosthesis, safety is crucial, and an EMG-based approach would still have to be accompanied by a second method for plausibilization.

Recently, we suggested an alternative approach to motion intention estimation of missing or paralyzed limbs, which is based on close observation of the user. This approach, Complementary Limb Motion Estimation (CLME), uses residual body motion, and it complements this motion continuously for missing limbs. This is possible because healthy human motion exhibits strong interjoint coordination, enabling statistical estimation of missing movements. CLME should not be confounded with echo-control approaches, which replay the recorded motion of one leg with a time shift on the other side [9]. In contrast, CLME offers a continuous and instantaneous complementation of motion. Initially developed for robot-aided gait rehabilitation of hemiparetic patients, CLME has been successfully tested on a rehabilitation robot [10, 11].

In this paper, we show how CLME can be transferred to active prostheses. The aim is to offer an intuitive interface to the user and to reduce the device to a simple tool that executes his/her intention. The goal is to use the superior human control capabilities again for the limb. To allow a first practical evaluation, an actuated prosthesis has been built. Using this device in combination with sensors to measure angles and velocities of the user’s sound limbs, walking on a treadmill, as well as ascending and descending stairs has been investigated.

2 Control Strategy and Experimental Setup

2.1 Complementary Limb Motion Estimation (CLME)

The goal of Complementary Limb Motion Estimation is to find a mapping function that outputs the states of missing limbs (angles and velocities) in dependence of the states of sound limbs. To obtain this function, interjoint coordination patterns are extracted from recorded healthy movement trajectories. Then, a reference motion is generated on-line for exoprosthetic joints, using the current motion of the sound limbs. There are numerous approaches in statistical regression to tackle this problem. As it has shown acceptable results in past experiments in robot-aided gait rehabilitation [11], conventional Best Linear Unbiased Estimation (BLUE) is used here as the baseline approach to regression [12].

The states of the sound limbs are known variables, they are normalized and subsumed in the vector $x_s$:

$$x_s^T = \left( \varphi_s^T \, \dot{\varphi}_s^T \right). \quad (1)$$

The normalized states of the prosthetic joint(s),

$$x_p^T = \left( \varphi_p^T \, \dot{\varphi}_p^T \right), \quad (2)$$

are to be estimated. Here, the sound joints are contralateral hip and knee, and only knee motion is to be estimated. This shows that the state vectors of sound and impaired limbs do not have to be of equal size. The ipsilateral hip had been included in preliminary experiments, but it led to unstable oscillating behavior during stance. This effect is probably due to the mechanical coupling between hip and knee. There could be other limbs involved, for example trunk motion as part of $x_s$.

Now, the statistical coupling between joints is used to find an estimate of $x_p$ as a function of $x_s$. In the linear case, this is equivalent to finding a solution to the optimization problem

$$||x_p - Cx_s||^2 \rightarrow \min$$

in terms of the matrix $C$. Using the covariance matrices $M_{ss}$ and $M_{sp}$ of the respective data vectors containing the recorded motion, the matrix and the estimator are given by:

$$C = (M_{ss}^{-1}M_{sp})^T, \quad \hat{x}_p = Cx_s. \quad (4)$$

The outputs are augmented by mean and standard deviation of the healthy motion, which gives reference angle and velocity for the knee. The estimates are subject to uncertainty, and the estimated velocity can differ from the differentiated estimated angle. To merge the two pieces of information, a Kalman filter is used, which is designed based on the model of a double integrator [13]. The outputs provide the reference for a stiff position controller.
Preliminary attempts included not only the states, i.e. angles and velocities, but also accelerations of healthy and prosthetic joints as inputs and outputs of the regression, respectively. However, simulations revealed that the accelerations hardly improve performance [13]. Furthermore, providing accelerations of the healthy limbs would rely on additional sensors or noisy numerical derivatives.

In summary, a recorded reference motion is reduced to the regression matrix, the Kalman gains, and mean values and standard deviations of the states. Based on these parameters and driven by sound limb motion, on-line estimation provides a position reference for the prosthetic joint(s). Thus, CLME only exploits the phenomenological coupling between limbs, no explicit knowledge of the motion (e.g. the gait phase) is needed.

2.2 Experimental Setup and Data Acquisition

The experimental setup consists of an actuated knee joint, as well as angle and angular velocity sensors attached to the contralateral hip and knee. The knee joint is actuated by a Maxon RE 40 DC motor with a planetary gear with transmission ratio $i = 91$. The knee joint can be attached easily to the patient’s individual prosthetic shaft and foot using standard pyramidal adapters. The motor is equipped with an optical quadrature encoder, and it is controlled via MATLAB/Simulink and real-time Linux. As the focus of this project is not on hardware development, but on control, the device depends on an external power supply. To obtain the mapping matrices for the CLME controller, a healthy 23-year-old female subject walked on a treadmill at a speed of 3 km/h, as well as up and down stairs, equipped with angle and velocity sensors on both legs. Then, the interjoint couplings and statistical variables were extracted from the recorded data.

A 42-year old female subject with transfemoral amputation took part in the study and walked on a treadmill, as well as up and down stairs with the previously extracted couplings of the healthy subject. The subject was allowed to hold on to the bars during treadmill walking and to the handrail of the stairs, respectively. Furthermore, an assisting person secured her on the stairs. Reflective markers were attached to the hip, knee, heel, forefoot, and ankle, in order to allow later motion analysis. One camera was used to record the marker positions of left and right side during treadmill walking (subsequently), and also to capture the stair trials. To compensate for changes in perspective in these two-dimensional recordings (e.g. due to slightly different camera angles on left and right side), a linear transformation of the recorded data points was performed, using known side-symmetric landmarks on the treadmill and Least-Squares optimization. Treadmill walking and stair descent was compared to the same movements with the C-Leg, alternating stair ascent is not possible with the C-Leg. In addition to qualitative observations, the level of symmetry was assessed by comparing the stance-to-swing ratio between legs, which denotes the time ratio spent for each leg with and without ground contact. “Toe off” and “Heel Strike” events were detected by off-line analysis of the kinematic data in Cartesian space.

3 Results

The subject was able to walk smoothly after a few minutes of practice. She noticed how left and right leg were coupled, and she also managed to alter her gait voluntarily. She was able to walk at varying velocities (tested up to 5 km/h) with the same controller. Compared to walking with the C-Leg, the subject made longer steps with her sound leg, such that asymmetry slightly increased. This is reflected in the stance-to-swing ratio. For the C-Leg, this ratio was 1.09 and 1.36 for right and left leg at 4 km/h, respectively. For the CLME-controlled prosthesis, the corresponding values were 0.98 and 1.41. A qualitative observation was that the subject vaulted slightly on her sound leg when walking with the C-Leg. This did not occur with the CLME-controlled prosthesis. In the trajectories of the heel marker during walking with the two devices (Fig. 1), the vaulting can be seen, as well as the increased step size with CLME.

![Figure 1: Cartesian trajectory of the sound leg’s heel during treadmill walking with the C-Leg (left) and with a CLME-controlled active knee joint (right). Vaulting can be observed with the C-Leg.](image-url)
The subject also quickly learned how to ascend the stairs smoothly and with alternating legs (Fig. 2), starting on either leg. However, she did need assistance with balance, and correct placement of the foot on the next step required some compensatory motion with the hip. In stair descent (Fig. 3), the performance of the CLME-controlled prosthesis was less satisfactory, as it did not match the subject’s smooth stair descent with her C-Leg. The subject reported that she felt insecure, and she hesitated to initiate the next descend with the prosthesis, prolonging the time spent on the sound leg.

Figure 2: Stair ascending with a CLME-controlled prosthetic knee joint. An assisting person (right) helps with balance. Time between adjacent frames: 40 ms.

Figure 3: Stair descending with a CLME-controlled prosthetic knee joint. An assisting person (left) helps with balance. Time between adjacent frames: 40 ms.

4 Discussion

The results show that it is generally feasible to control an actuated exoprosthesis using Complementary Limb Motion Estimation. Using a simple mapping function from sound limb motion to the prosthesis, the test subject was able to achieve an almost physiological gait pattern. In contrast to walking with the C-Leg, no contralateral vaulting occurred, which can be explained by the fact that the active prosthesis can generate positive power to flex the knee during swing. This eliminates the need for contralateral compensation to clear the foot. The observation
that the subject was able to walk at different speeds without change of the mapping function shows that interjoint coupling does not vary much for a large range of speeds in level walking. CLME also exploits another advantage of an actuated system that can generate positive power, which is to enable alternating stair ascent.

There are still some issues to be addressed, for example concerning prolonged stance phases on the sound leg. To some extent, the results can be explained by a lack of training of the subject. For example, physiological stair descent is an almost ballistic motion consisting of successive phases of controlled falling. This requires a high level of confidence in the knee joint, which can probably not be achieved in the first minutes with a new device.

5 Conclusion and Outlook

This first proof of concept shows that the minimization of “autonomous intelligence” in an actuated prosthesis combined with close observation of the user allow to incorporate the human’s superior motion control in a cooperative and intuitive way. Future research will focus on generalizing CLME and adapting it to practical requirements of exoprostheses. To enable more accurate mapping and seamless transitioning between different activities, the method will be extended to the nonlinear domain, possibly using techniques such as Generalized Principal Component Analysis [14] or Correlation Clustering [15].

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References


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