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Biometrical Assistance: Adjusting the Motor Assistance of Pedal Electric Cycles to the Physiological Capabilities of the Cyclist

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ABSTRACT

Bicycles combine inexpensive, sustainable, and flexible mobility with physical activity. They can help counteract sedentary lifestyles as well as environmental and traffic problems. Human-electric hybrid vehicles (HEHVs), which integrate an electric motor into a human powered vehicle, enable persons with physical limitations to enjoy or rediscover the benefits of cycling.

The physiological and biomechanical causes that can complicate cycling for certain users are manifold. Individuals with physical conditions have to carefully monitor their strain to prevent exhaustion. Individuals with physical disabilities need special assistance to compensate their limitations. Customized assistance systems, which consider the cyclist’s individual physical constitution and adjust the motor assistance accordingly, would facilitate cycling for these users. The system has to act on a physiological as well as on a biomechanical level to prevent exhaustion and inappropriate strain, and to guarantee health improving effects of the activity.

This thesis describes the development process of control systems that automatically adjust the vehicle settings (motor assistance and transmission ratio) to regulate the heart rate of HEHV riders. First, the effect of the proportional motor assistance of conventional electric bicycles on the physiology and biomechanics of the cyclist is analyzed in an exploratory study with two experiments. The study shows that the electric motor assistance reduces physical strain, but the impact depends on the physiological constitution of the cyclist and increases with lower cardiorespiratory fitness. Then, the design process of a sliding mode controller (SMC) that maintains the heart rate of the cyclist at a user-specified level by adjusting the motor torque is presented. The SMC was implemented and tested on a conventional electric bicycle. Simulations and initial experiments with one subject indicated a valid control system. The SMC was then implemented on a four-wheeled human-electric hybrid vehicle prototype for further validation. Three scenarios were assessed by 42 subjects performing a 70 minute test cycle with the vehicle prototype on a stationary test rig. The results show the advantages of using heart rate as a control variable and that the SMC successfully automates the adjustment of the motor assistance to maintain a certain heart rate level. Finally, a model predictive controller (MPC) that uses both motor torque and transmission ratio to regulate the heart rate was developed. By manipulating two variables, the MPC increases the functionality of the system. Model predictive control also allows to integrate additional information about the environment, the cyclist and the vehicle, to estimate the riding resistances of the trip and formulate constraints for the energy consumption. That way, the energy consumption during the trip is improved and the risk of running out of battery is reduced.

Using these systems, cyclists are able to maintain their physical strain inside desired limits without having to monitor physiological parameters themselves. Therefore, they facilitate healthy physical activity and independent mobility for individuals with limited physiological capabilities. The systems also lay the foundation for new energy management systems for HEHVs that consider the individual needs of the cyclist and, in consequence, facilitate or enable cycling for individuals with physiological and biomechanical limitations. Ultimately, such systems contribute to the health, well-being, and quality of life of the user.

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1 Introduction

> *"Bicycling is a big part of the future. It has to be.*
> *There's something wrong with a society that drives a car to work out in a gym."*
> ~ Bill Nye

Physical activity describes *"…any bodily movement produced by skeletal muscles that results in energy expenditure"* (Caspersen, Powell, & Christenson, 1985, p. 126). Since obligatory[1] physical activity is decreasing, the resulting sedentary lifestyle[2] of our generation causes high burdens for healthcare systems worldwide (American Heart Association, 2016; Ding et al., 2016; Kohl et al., 2012; Oldridge, 2008). In the literature, the positive implications and numerous health improving effects of physical activity are well known (Chodzko-Zajko, 2014; Donnelly et al., 2009; Franco et al., 2005; Garber et al., 2011; Lee & Paffenbarger, 2000). Yet, new policies and action plans need to be enacted to counteract physical inactivity and to promote a healthy lifestyle (Mendis, Puska, & Norrving, 2011).

At the same time, receding fossil fuels, increasing traffic problems, and environmental pollution call for a rethinking of our current mobility behavior (Lienkamp, 2012). Most of our vehicles are oversized. Even with small cars, the ratio between vehicle mass (1000–2000 kg) and transported mass (100–200 kg) is out of proportion (Steinmaßl, Müller, & Lienkamp, 2015). Innovative vehicle concepts and transportation strategies need to be put in the spotlight of both academia and industry to tackle these problems (Ehsani, Gao, & Emadi, 2009).

A human-electric hybrid vehicle (HEHV)[3] combines reasonable transportation functionality with physical activity. HEHVs are propelled by two power sources simultaneously, the human muscles and an electric motor. Electric bicycles are currently the most prominent members of HEHVs and have become an emerging transportation modality in many countries. In Germany and Europe, sales numbers of electric bicycles have increased constantly over the past years. In 2015, about 535.000 electric bicycles were sold in Germany, an increase of 11.5 percent compared to 2014. About 2.5 million electric bicycles are in use already (Zweirad-Industrie-Verband, 2016). In Europe, over 1 million pedelecs have been sold in 2014, an increase of 25 percent compared to 2013 (Confederation of the European Bicycle Industry, 2015).

The electric motor assistance reduces the physical stress[4] significantly and in consequence the physical strain[5] of the cyclist, making electric bicycles an important means of transport to promote healthy activity (Gojanovic, Welker, Iglesias, Daucourt, & Gremion, 2011; Louis, Brisswalter, Morio, Barla, & Temprado, 2012; Simons, van Es, & Hendriksen, 2009). Despite the electric motor support, cycling can be a challenging task for older or inactive persons, persons performing rehabilitation or individuals with physical disabilities. These persons would

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[1] This includes activities in situations such as work, commuting and in the household (World Health Organization, 2004)

[2] A lifestyle that requires only little or no physical activity resulting in an energy expenditure of 1–1.5 METs (Garber et al., 2011)

[3] See Chapter 1.1.1 for a detailed explanation of the different vehicle types

[4] Physical stress: absolute measure of the intensity of a physical activity (e.g. in Watts)

[5] Physical strain: the reaction of the cardiovascular system to physical stress

particularly benefit from regular physical activity, but have to monitor their physical constitution closely to maintain a health improving intensity and to prevent negative implications (such as exhaustion, overexertion or even cardiac events). The individual limitation of their physical capabilities might therefore deter them from using the bicycle or even make cycling impossible (Aldred & Woodcock, 2008; Booth, Bauman, Owen, & Gore, 1997; Buffart, Westendorp, van den Berg-Emons, Rita J, Stam, & Roebroeck, 2009; Jaarsma, Dijkstra, Geertzen, & Dekker, 2014).

Adding the electric motor for propulsion unlocks extensive possibilities to intervene into the perceived physical strain and the biomechanics of the cyclist. This theses aims to provide control strategies for the motor assistance of human-electric hybrid vehicles that automatically adjusts the assistance according to the cyclist's individual physical capabilities. Such systems may encourage and enable persons with reduced physical capabilities to independently engage in regular physical activity, thus improving their health, well-being, and quality of life.

1.1 Human-Electric Hybrid Vehicles (HEHVs)

1.1.1 Definitions and Classification

The existing definitions for HEHVs are not consistent throughout the literature. Also, definitions and legal classifications of HEHVs vary between countries and regions. The following terms, which are also commonly found in the literature, are used in this thesis:

- **Human-Electric Hybrid Vehicle (HEHV):** Describes all types of vehicles that are propelled by two power sources—a human being and an electric motor (Fig. 1). The vehicle can be propelled either by both power sources simultaneously with varying ratios or by each power source separately.
- **Electric bicycle:** Describes the same type of vehicle as an HEHV, but is limited to two wheels. Electric bicycles have the design of conventional bicycles, but are equipped with an auxiliary motor unit. The motor is usually located in the bottom bracket or the wheels.
- **Pedal Electric Cycle (pedelec):** This type of vehicle, also called **Electrically Power Assisted Cycle (EPAC)**, is equipped with a pedal-assist technology. They provide power only, if the cyclist is pedaling at the same time. They are usually equipped with torque and/or cadence sensors to detect power output and/or pedal movement of the cyclist. The motor is either acting directly on the chain or cranks (mid-mounted motor) or located in the front or rear wheel (hub motor). The electric motor is limited to a maximum power output and assistance is only provided up to a maximum speed. In Europe, pedelecs are limited to a power of 250 W and a speed of 25 km/h (European Comittee for Standardization, 2015). Therefore, they are classified as bicycles (Regulation (EU) No 168/2013 of the European Parliament and of the council on the approval and market surveillance of two- or three-wheel vehicles and quadricycles, 2013) and do not require a driver's license, number plates or insurance and are allowed on cycle paths. Most pedelecs assist the cyclist with power proportional to the cyclist's own power output (proportional assistance).

- **S-Pedelecs:** A special type of pedelec, that allows a higher maximum speed (45 km/h) and motor power (500 W). These vehicles are classified as mopeds and therefore have to be type-approved, require number plates, a driver's license and insurance.
- **E-Bikes (or E-Scooters):** This type of vehicle does not require the cyclist to pedal and can be driven by motor power exclusively. These vehicles are very common in Asia, where they are often classified as bicycles (in contrast to Europe). The motor is usually controlled by a throttle mounted at the handlebars.

Figure 1: Different HEHV types: A three-wheeled cargo-bike (left), a Pedelec (middle) and a S-Pedelec (right) (ExtraEnergy e.V., 2014)

The terms "Electric bicycle" and "E-Bike" instead of HEHV are sometimes used in the literature as a collective term for all types of vehicles with an electric and a human power source. In Asia, the definitions "Bicycle Style Electric Bike (BSEB)" for pedelecs and "Scooter Style Electric Bike (SSEB)" for E-Scooters are common as well.

The motor of electric bicycles can be placed at three different positions which have different advantages and disadvantages (Fig. 2). Either it acts directly on the chain or cranks (mid-mounted motor) or it is located in the front or rear wheel (hub motors) (Muetze & Tan, 2007). Hub motors sometimes allow regenerative braking and can produce power to charge the battery.

✓ Good traction
✓ Direct power
- Complex cabling
- Difficult wheel change

✓ Compact
✓ Standard bicycle components
- Higher price
- No upgrade possible

✓ Low price
✓ Easy upgrade
- Long cabling
- Steering affected

Figure 2: Different motor types with selected advantages and disadvantages: Rear wheel hub motor (left), mid-mounted motor (middle) and front wheel hub motor (right).

1.1.2 Electric Bicycles as Alternative Means of Transport

Recently, electric bicycles have gained a lot of attention as alternative means of transportation with positive impacts on the environment, traffic, and health. The integration of human and motor power in a small vehicle permits fast transportation without emissions combined with physical activity at low costs.

In China, electric bicycles have been means of transport for many years already, mostly because of environmental and traffic reasons. High traffic volume and the resulting pollution made cities ban motorized vehicles with combustion engines from certain districts (Weinert, Ma, & Cherry, 2007), leading to an increase in electric bicycle sales. But also in districts where motorized vehicles are still allowed, people rely on electric bicycles to avoid traffic jams and complex traffic situations. Even on bicycle lanes, the faster speeds of electric bicycles can improve traffic flow (Jin et al., 2015). The direct environmental pollution of electric bicycles is very low, because they do not exhaust emissions. They only cause emissions during production, recycling and for generating the electric energy for the battery (if it is not produced from renewable energies). Still, the combined emissions are lower than those of other motorized vehicles like cars and motorcycles (Cherry, Weinert, & Xinmiao, 2009). Their small size and low carbon footprint makes electric bicycles an important form of conveyance to reduce traffic and environmental pollution.

Apart from the environmental advantages, there are many different reasons for people to use an electric bicycle (Fishman & Cherry, 2016). The main reason is the reduction of the necessary physical effort for the propulsion of the bicycle, which, in consequence, facilitates several tasks in the user’s daily life. First of all, the reduction of the physical effort enables persons with physical limitations to enjoy the physical activity and flexibility of cycling (again). Especially for elderly persons and persons with health conditions, this is the main reason for purchasing an electric bicycle (Cherry & Cervero, 2007; Dill & Rose, 2012; Johnson & Rose, 2013; Jones, Harms, & Heinen, 2016; MacArthur, Dill, & Person, 2014; Schleinitz et al., 2014; Weinert, Ma, Yang, & Cherry, 2007).

Also, the reduced effort allows users to travel longer distances, ride at faster speeds or in hilly terrain, and transport more goods. As a consequence, people use an electric bicycle to replace trips they would otherwise conduct by car. For leisure activities, users enjoy the combination of fast mobility and physical activity (Cappelle, Lataire, Maggetto, van den Bossche, & Timmermans, 2003; Fyhri & Fearnley, 2015; Haustein & Møller, 2016; Johnson & Rose, 2013; Jones et al., 2016; MacArthur et al., 2014). When used in bike sharing systems, the reduced physical effort motivates people to use the electric bicycle more often and to replace car trips, because it allows users to arrive at a destination without sweating (Langford, 2013; Langford, Cherry, Yoon, Worley, & Smith, 2013; McLoughlin et al., 2012).

Compared to the many advantages of electric bicycles, there are only few disadvantages. The main disadvantages reported by the users are the electric bicycles’ higher weights (compared to regular bicycles) and their limited range (Haustein & Møller, 2016; Jones et al., 2016; Schleinitz et al., 2014). However, the disadvantages are only experienced by a small percentage of users. Trip distances, travel times and necessary motor power vary largely for the many different application purposes as well as user types of electric bicycles. For instance, trip duration can vary between 40 minutes for commuting and 2 hours for leisure activity (An, Chen, Xin, Lin, & Wei, 2013). To explore new application purposes for electric bicycles and to improve their usability for the current ones, new vehicle types and designs are constantly developed.

1.1.3 The Vehicle Concept “QuadRad”

The different application purposes for electric bicycles make it indispensable to create customized vehicles. Not surprisingly, there is already a huge variety of different electric bicycle concepts, which are specifically designed for their respective task. Three- or four-wheeled cargo-bikes are an emerging type, because they can fill the gap between bicycles and cars in terms of payload, purchasing price, and range (Gruber, Kihm, & Lenz, 2014).

For this purpose, the so called “QuadRad” was developed. The QuadRad is a type of pedelec with four wheels (Fig. 3). It is designed in particular for commercial applications, but variations for private use, touristic applications and sports are also possible. The vehicle concept is powered by a mid-mounted motor (that acts on the cranks) with a maximum power of 250 W and a maximum torque of 70 Nm. The vehicle provides motor assistance up to a velocity of 25 km/h, following the requirements of a pedelec within German legislation. Equipped with a battery with a capacity of 1.0 kWh at 44.4 V, the range of the vehicle under ideal conditions (flat terrain, no payload, lowest assistance mode) is about 90 km. The vehicle weighs 60 kg and an additional load of 180 kg is possible. A modular design was used for the QuadRad to reduce the vehicle complexity. In consequence, parts like the loading area can be customized and replaced easily depending on the intended application (Steinmaßl et al., 2015). Experimental testing and questioning of potential customers of this type of vehicle indicate that the design and specifications meet requirements for everyday use (Steinmaßl & Lienkamp, 2016a, 2016b).

The vehicle is equipped with a human-machine-interface (HMI) at the handlebars that displays important information like speed, distance, and assistance level as well as vital parameters like the heart rate, in case a heart rate chest strap is connected. Additionally, a smartphone can be attached to the handlebars to display and log the data that is gathered during a trip.

Figure 3: QuadRad prototype (left) and mechanical design (right). The QuadRad has four wheels and is equipped with a mid-mounted motor. It fulfills the legal requirements for pedelecs and therefore is categorized as a bicycle.

Great potential for this type of vehicles is expected in highly touristic areas. In small communities with environmentally protected areas, the infrastructure cannot cope with the mobility needs of the tourists. The resulting traffic jams and high particle and noise emissions contradict the tourists' expectations of a relaxing environment. Also, the surrounding nature reserves are directly (by emissions and road constructions) and indirectly (by acid rain and the climate change) affected.

Compared to an electric car, regular pedelecs are associated with much lower costs because of a low purchasing price and lower running as well as maintenance costs. However, they do not offer the same amount of comfort, safety and transporting capacity as four-wheeled vehicles. The QuadRad concept combines the advantages of both vehicle types, making it an important alternative mean of transport for business purposes, leisure activities, commuting, and other applications. Persons with physical limitations or disabilities can benefit from the increased safety and comfort of the four-wheeled vehicle concept, to manage everyday activities independently.

1.2 The Need for Customized Assistance Strategies for Pedelecs

Regular physical activity and exercise[6] are associated with numerous health improving effects (Physical Activity Guidelines Advisory Committee, 2008; U.S. Department of Health and Human Services, 1996). It can reduce feelings of fatigue and low energy (Puetz, 2006) and help with weight loss (Donnelly et al., 2009). It can prevent and limit chronic diseases (Chodzko-Zajko, 2014; Garber et al., 2011), improve the quality of life of healthy as well as ill individuals (Conn, Hafdahl, & Brown, 2009; Gillison, Skevington, Sato, Standage, & Evangelidou, 2009; Oldridge et al., 1991; Rejeski & Mihalko, 2001) and increase life expectancy (Franco et al., 2005; Lee & Paffenbarger, 2000).

Active commuting to work, for instance, is an effective way to include physical activity into one's daily life and already a moderate amount leads to increased aerobic fitness (Geus, Smet, Nijs, & Meeusen, 2007; Gordon-Larsen et al., 2009; Hendriksen, Zuiderveld, Kemper, & Bezemer, 2000; Oja, Vuori, & Paronen, 1998; Pucher, Buehler, Bassett, & Dannenberg, 2010; Shephard, 2012; Terzano & Morckel, 2011). In consequence, the bicycle has always played an important role in maintaining the independence and well-being of individuals, because it combines inexpensive and flexible mobility with physical activity.

For certain individuals, such as sedentary persons, elderly, and persons with chronic diseases or physical disabilities, using a regular bicycle can pose a challenge. Their condition often requires to pay careful attention to avoid exhaustion, injuries and inappropriate physical strain. In some cases, the individual physical limitation even makes cycling impossible. For these users, a four-wheeled vehicle design such as the QuadRad, which offers increased stability and safety, and which is equipped with an electric motor assistance, means healthy physical activity and increased independence through personal mobility. Nevertheless, their sensitive physical

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[6] *"Exercise is a subset of physical activity that is planned, structured, and repetitive and has as a final or an intermediate objective the improvement or maintenance of physical fitness"* (Caspersen, Powell, & Christenson, 1985, p. 126)

constitution not only requires customized vehicle designs, but also a motor assistance that is customized to their individual physical limitation.

1.2.1 Considering the Physiology of the Individual for Customized Motor Assistance

About 150 minutes of moderate or vigorous exercise per week are recommended for most healthy adults to maintain health. For sedentary persons, even less exercise is already beneficial (Garber et al., 2011; Tremblay et al., 2011). Older adults, overweight, and obese persons often suffer from reduced exercise capacities (Chodzko-Zajko, 2014; Divitiis et al., 1981). Therefore, it is recommended that they start exercising at lower intensities (Cress et al., 2005; Donnelly et al., 2009).

Individuals who suffer from cardiovascular diseases (CVD) are also encouraged to engage in physical activity (Thompson et al., 2003). The amount and intensity of the exercise depends on the severity of the condition. For instance, persons with congestive heart failure (HF) have limited exercise capabilities (Franciosa, Ziesche, & Wilen, 1979). They experience symptoms like fatigue or shortness of breath, because the nutritive flow to the skeletal muscles is limited by the disease (Wilson, Martin, Schwartz, & Ferraro, 1984). Exercising at a low or moderate intensity is recommended to improve physical fitness of these persons (Piña et al., 2003). For individuals who suffered a stroke or for persons with coronary artery disease (CAD), physical activity and exercise at a moderate intensity is recommended to increase aerobic function (Fletcher et al., 2001; Gordon et al., 2004).

Limiting the physical exertion of individuals with chronic diseases or symptoms for it reduces the risks of sudden cardiovascular events (Pescatello et al., 2004; Thompson et al., 2007; Thompson, Arena, Riebe, & Pescatello, 2013). Particularly individuals who do not exercise regularly have an increased risk for such events (Mittleman et al., 1993; Willich et al., 1993). Keeping the exercise intensity at a low or moderate level therefore increases the safety of the physical activity and guarantees health improving effects (Foster & Porcari, 2001; Siscovick, Laporte, & Newman, 1985).

Low, moderate and vigorous exercise intensities describe an intensity that is measured relatively to the cyclist's state of cardiorespiratory fitness (CRF). In consequence, the state of CRF of the individual has to be known in advance. During cycling, the individual has to monitor physiological parameters, to keep the intensity at the desired level. Systems that measure selected vital parameters and automatically adjust the exercise intensity to track a user-defined level would substantially facilitate physical activity for individuals with limited physiological capabilities.

1.2.2 Considering Cycling Biomechanics for Customized Motor Assistance

Physiological limitations are not the only limitations that can complicate cycling for the user. Limitations of the musculoskeletal system, like limited range of motion of joints, muscular impairments or missing limbs can make physical activity in general and cycling in particular difficult or even impossible for some persons. In consequence, individuals with physical disabilities often suffer from secondary health conditions such as CVDs (Bakalim, 1969;

Yekutiel, Brooks, Ohry, Yarom, & Carel, 1989), because they perceive their disability as a barrier to be physically active (Jaarsma et al., 2014).

Still, physical activity would be helpful for many individuals with physical disabilities. For instance, in persons with arthritis it can decrease the symptoms of the disease. However, joint pain and decreased range of motion require proper fitting of the bicycle (Deanna Westby, 2001). Also, inappropriate loads and joint moments have to be avoided to prevent negative effects.

Individuals with cerebral palsy (CP) would also benefit from cycling as a regular physical activity (Fowler et al., 2010), because it can increase their mobility, endurance and coordination (Damiano, 2006). The symptoms of CP (such as decreased muscle strength, muscle spasticity and decreased range of motion) complicate cycling on a bicycle, because kinematics and muscle activation differs from individuals without CP and the efficiency of the cycling movement is lower (Johnston, 2007; Johnston, Barr, & Lee, 2007; Kaplan, 1995; Lauer, Johnston, Smith, & Lee, 2008).

For stroke patients with hemiplegia or hemiparesis, ergometer cycling is a feasible method for rehabilitation (Brown, Nagpal, & Chi, 2005), because it allows exercising without exacerbating abnormal muscle activity. Nevertheless, cycling outdoors can be challenging for stroke patients, because of weakened muscles, spasticity and poor balance (Chen, Chen, Chen, Fu, & Wang, 2005; Fujiwara, Liu, & Chino, 2003). Also, the asymmetric recruitment of muscles complicate smooth pedaling movements which would cause changing cycling speeds in outdoor cycling. In patients with poststroke hemiplegia the nonplegic leg has to compensate the lower net work of the plegic leg (Brown & Kautz, 1998). Similarly, in patients with hemiparesis, the sound leg exerts higher forces than the paretic side. With higher loads, the force output of the paretic side increases and hence also the training effect (Chen et al., 2005). Unilateral movements might in consequence result in less impairment of the paretic leg than bilateral movements (Kautz & Patten, 2005). Therefore, the load for the affected leg needs to be adjusted accordingly to achieve the desired amount of rehabilitation effect, smooth pedaling and relief of the opposite leg.

After an amputation, many individuals are still able to use a bicycle (Narang, Mathur, Singh, & Jape, 1984). Although the force effectiveness is not significantly affected by transtibial amputation (Childers & Gregor, 2011), work and force asymmetry between both legs are significantly different to individuals without amputation (Childers, Kistenberg, & Gregor, 2011). The resulting higher moments in the joints on the intact side can lead to other diseases like osteoarthritis (Royer & Wasilewski, 2006). The muscle activity patterns in the affected limb also changes due to the amputation (Childers, Prilutsky, & Gregor, 2014).

These examples illustrate that cycling can be a difficult task for individuals with certain conditions. Facilitating or enabling outdoor cycling for those individuals could increase their independence and motivate them to be more physically active. In order to achieve this, the individual biomechanical limitations have to be considered and the motor assistance needs to be adjusted to biomechanical parameters such as the muscle activity pattern or the force output.

1.2.3 An Energy Management System With Biometrical Assistance

Innovative energy management systems are necessary that determine the right split between the two power sources—human and motor power—available for propulsion. In order to provide safe transportation and to maximize the health improving effects for individuals with physical conditions, the system has to act on two levels (Fig. 4):

Physiological level: Considering physiological parameters helps prevent exhaustion, reduces the risk of cardiovascular events and increases the positive effects on the health of the individual.

Biomechanical level: Adjusting the motor torque to the pedaling cycle can facilitate cycling for individuals with physical impairments, reduces muscular discrepancies and increases the rehabilitation effect.

The combination of assistance on a physiological and biomechanical level shall be referred to as “Biometrical Assistance” in this thesis.

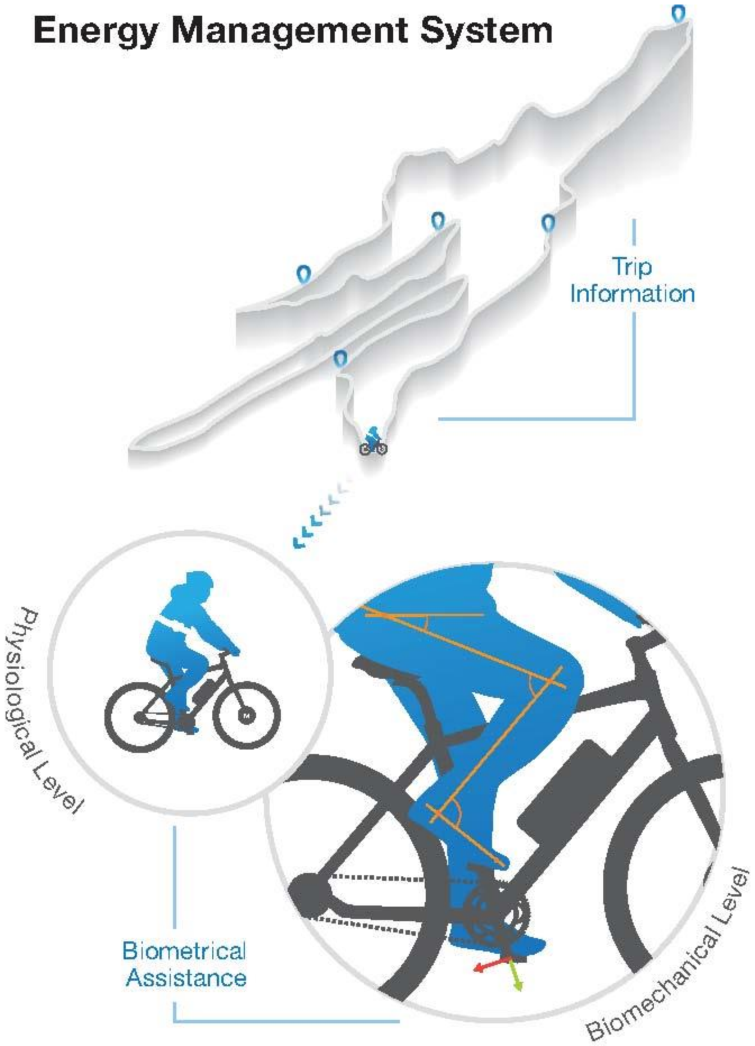

Figure 4: Energy management system for electric bicycles with biometrical assistance. The biometrical assistance acts on a physiological and biomechanical level and allows the integration of trip information for optimized energy consumption.

Since users with physical disabilities are highly dependent of the electrical assistance to be able to propel the vehicle, the risk of running out of battery has to be minimized. In consequence, an energy management system for such a vehicle also has to incorporate trip information (Fig. 4) such as environmental factors (slope, weather data, etc.) or the purpose of a trip (transportation, leisure, training, etc.) to precisely calculate the residual range of the vehicle or to distribute the available energy to ensure motor assistance during the whole cycling trip.

Together with an innovative vehicle concept, such an energy management system with biometrical assistance could facilitate and enable persons with limited physical capabilities to safely and independently engage in physical activity. Ultimately, this would have a positive effect on their health, well-being, and quality of life.

1.3 Contributions

Despite their ability to decrease the overall physical strain of the cyclist, current motor control strategies of electric bicycles lack the flexibility to adjust the assistance automatically and specifically to the individual physical capabilities of the cyclist. Especially for the aforementioned users with physical conditions, a customized assistance is essential to keep cycling a safe and healthy physical activity for them.

The aim of this thesis is to lay the basis for an energy management system with biometrical assistance that automatically adjusts the settings of the vehicle and motor to the specific physiological and biomechanical needs of the cyclist. The steps towards such a system covered in this thesis are as follows:

(1) **Limitations of Conventional Systems:** This thesis analyzes how the conventional (proportional) motor assistance strategy and different motor positions affect the cyclist's physiology and biomechanics.

(2) **Sliding Mode Control for Motor Assistance on a Physiological Level:** A sliding mode controller (SMC) was designed to adjust the motor assistance on a physiological level. The system adjusts the motor torque to maintain the heart rate of the cyclist at a user-specified level.

(3) **Evaluating Automated Electrical Motor Assistance:** A trial with 42 subjects was conducted, using a randomized block design, to validate the functionality of automated heart rate control systems compared to conventional assistance systems and to demonstrate their limitations.

(4) **Model Predictive Control for Enhanced Motor Assistance:** A model predictive controller (MPC) was designed to regulate the heart rate by adjusting motor torque and transmission ratio of the vehicle for enhanced functionality. Information about the environment, the cyclist and the vehicle were integrated into the control system to optimize the energy consumption and reduce the risk of running out of power.

1.4 Thesis Structure

Chapter 2 presents two separate exploratory outdoor studies which analyzed the effect of motor assistance strategies and motor positions of conventional electric bicycles on the physiology and biomechanics of cyclists.

Chapter 3 introduces a sliding mode controller (SMC) that regulates the heart rate of electric bicycle riders by adjusting the motor torque. The design process is explained and the control system is implemented on a conventional pedelec. Simulations as well as initial experiments with one subject are presented to validate the system.

In Chapter 4, the control system is validated in an indoor trial with 42 participants who cycled on the QuadRad on a stationary test rig. Three scenarios were compared using a randomized block design. The study design and results are presented and discussed.

Chapter 5 introduces a model predictive controller (MPC) that adjusts motor torque and transmission ratio for enhanced tracking performance of the heart rate. The MPC allows the integration of trip information to reduce range anxiety and to optimize the energy distribution during a cycling trip. Again, the design process and simulations for validation are presented.

Chapter 6 discusses the results and outlines the conclusions as well as future work.

2 Impact of Electrical Assistance on Physiological Parameters during Cycling[7]

Meyer, D., Steffan, M., & Senner, V. (2014). Impact of Electrical Assistance on Physiological Parameters During Cycling. *Procedia Engineering*, *72*, 150–155

"The bicycle is a curious vehicle. Its passenger is its engine."
~ John Howard

Summary

Electric bicycles facilitate cycling by adding power from an electric motor to the propulsion. However, there is a lack of studies that show how the conventional (proportional) electrical assistance system and different motor positions affect the cyclist's physiology. This effect was analyzed in an exploratory study with two outdoor experiments. The first experiment compared objective and subjective parameters of physical strain in three young, healthy subjects during two test rides—once with and once without electrical support—in mountainous terrain. The objective physical strain is deduced from the heart rate and blood lactate concentration, whereas subjectively perceived exertion is indicated using the Borg scale. The second experiment analyzes the muscle activity of the thighs in three young, healthy subjects during rides with two different electric bicycles (rear-wheel hub motor and mid-mounted motor). The results show that all physiological parameters are reduced by using the electrical assistance and that this reduction increases with higher loads. The amount of reduction in physical strain also depends on the physiological constitution of the cyclist and is higher for cyclists with lower cardiorespiratory fitness. The activity pattern of the muscles however does not change and the position of the motor does not affect the activation pattern. The results suggest that a control system that adapts to the individual physiological constitution of the cyclist would be beneficial in terms of energy consumption, safety, effect on health and usability.

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[7] This chapter is based on a conference paper co-authored by Moritz Steffan and Veit Senner that has been published in *Procedia Engineering* (DOI: 10.1016/j.proeng.2014.06.026). The full chapter is included in the examiners' copies of this dissertation. In order to avoid any kind of plagiarism or dual publication it is not included in the freely accessible version of this dissertation. The paper was published as part of the conference proceedings of the 2014 conference of the International Sports Engineering Association (2014), Sheffield.

3 Sliding Mode Control for Heart Rate Regulation of Electric Bicycle Riders[8]

Meyer, D., Zhang, W., & Tomizuka, M. (2015). Sliding Mode Control for Heart Rate Regulation of Electric Bicycle Riders. *ASME 2015 Dynamic Systems and Control Conference, 2*

"I have been impressed with the urgency of doing. Knowing is not enough; we must apply.
Being willing is not enough; we must do."
~ Leonardo da Vinci

Summary

The increasing demand in electric bicycles has led to the development of numerous control strategies for the motor assistance. The most common control strategy assists proportionally to the cyclist's own power output at the pedals (proportional assistance). These conventional electrical assistance systems lack the flexibility to automatically and specifically adapt to the cyclist's individual physical constitution. Therefore, a sliding mode controller (SMC) for electric bicycles is proposed. It uses a physiological parameter to customize the amount of motor assistance to the individual needs of the cyclist. The control system—consisting of feedback as well as feedforward control—maintains the heart rate of the cyclist at a user-defined level by adjusting the motor torque. The paper describes the system analysis process and experimental design of models for the human cardiovascular system, the bicycle's longitudinal dynamics and the cyclist's reaction to changing velocity. Also, the development process of the SMC and the integration of the feedforward control are shown. The controller was implemented on a conventional electric bicycle for experimental validation. Simulations as well as an outdoor experiment with one subject were conducted. The results show that the control system successfully maintains the heart rate at the specified level. Introducing the feedforward part also improved the cycling experience by reducing the maximum human torque outputs. The result also suggested that further experiments with several subjects would be necessary to proof the general validity of the control system.

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[8] This chapter is based on a conference paper co-authored by Wenlong Zhang and Masayoshi Tomizuka that has been published in *Proceedings of the ASME 2015 Dynamic Systems and Control Conference* (DOI: 10.1115/DSCC2015-9712). The full chapter is included in the examiners' copies of this dissertation. In order to avoid any kind of plagiarism or dual publication it is not included in the freely accessible version of this dissertation.

4 Evaluating a Heart Rate Regulation System for Human-Electric Hybrid Vehicles[9]

Meyer, D., & Senner, V. (2018). Evaluating a Heart Rate Regulation System for Human-Electric Hybrid Vehicles. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 232 (2), 102-111.

> *"An experiment is a question which science poses to Nature, and a measurement is the recording of Nature's answer."*
> ~ Max Planck

Summary

The rising popularity of electric bicycles has led to the development of new control strategies. In the course of this progress, a sliding mode controller (SMC) that regulates the heart rate of electric bicycle riders has been designed. Initial experiments have been conducted, but thorough experimental evaluation is necessary to show the validity of a heart rate control system in general and the SMC design in specific. For this paper, a study with 42 participants was conducted. The participants performed a 70 minute test cycle with a four-wheeled human-electric hybrid vehicle on a custom built stationary test rig. The SMC was implemented and adapted to the four-wheeled vehicle for this trial. A randomized block design with 14 blocks and 3 groups was used in the experiment. The groups compared: 1) user controlled motor assistance based on subjective perceived exertion; 2) user controlled motor assistance based on heart rate; 3) adaptive motor assistance based on heart rate. The participants were assigned to the blocks using an estimate of their fitness level assessed in a submaximal exercise test and then randomly assigned to a group. The paper describes the study design as well as the experimental procedure. Also, the analysis of the data is explained and the results are presented. The results show that the automated assistance maintains the heart rate inside the specified zones. With this system, users of human-electric hybrid vehicles can cycle at a desired intensity without having to monitor physiological parameters themselves. The limitations of the system indicate that advanced control systems are necessary to increase the usability of the heart rate control.

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[9] This chapter is based on a journal paper co-authored by Veit Senner that has been published in *Journal of Sports Engineering and Technology* (DOI: 10.1177/1754337117710069). The full chapter is included in the examiners' copies of this dissertation. In order to avoid any kind of plagiarism or dual publication it is not included in the freely accessible version of this dissertation.

5 Regulating the Heart Rate of Human-Electric Hybrid Vehicle Riders under Energy Consumption Constraints Using an Optimal Control Approach[10]

Meyer, D., Körber, M., Senner, V. & Tomizuka, M. (2018). Regulating the Heart Rate of Human-Electric Hybrid Vehicle Riders under Energy Consumption Constraints Using an Optimal Control Approach. *IEEE Transactions on Control Systems Technology*.

> *"You never change things by fighting the existing reality.*
> *To change something, build a new model that makes the existing model obsolete."*
> ~ Buckminster Fuller

Summary

New control strategies for the motor assistance of electric bicycles have been developed, to adapt the assistance to the cyclist's individual physical constitution. These control strategies are subject to mechanical limitations. Also, the state of charge of the battery is not included into the motor control which can cause range anxiety. Particularly individuals with poor health or physical limitations depend on the electrical assistance, because they are unable to propel the vehicle without motor support. This paper presents a model predictive controller (MPC) that manipulates two variables (motor torque and transmission ratio) to regulate the heart rate of riders of human-electric hybrid vehicles. The MPC minimizes a cost function to find the optimal ratio between both variables to maintain the heart rate inside user-specified limits while considering constraints. Information about the environment, the cyclist's fitness and vehicle parameters are integrated into the system to formulate constraints for the motor power and to optimize the energy consumption during the trip. The paper describes the development of the algorithm for including available trip information as well as the control system. Simulation results for different scenarios are presented to proof the validity of the control design. The results show that the system maintains the heart rate inside the desired zone more effectively when two variables are manipulated compared to manipulating each one separately. The controller also improves the distribution of the available energy when trip information is accessible. The algorithm leads to improved heart rate regulation and reduces the risk of running out of battery.

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[10] This chapter is based on a journal paper co-authored by Moritz Körber, Veit Senner and Masayoshi Tomizuka that has been published in *IEEE Transactions on Control Systems Technology* (DOI: 10.1109/TCST.2018.2852743). The full chapter is included in the examiners' copies of this dissertation. In order to avoid any kind of plagiarism or dual publication it is not included in the freely accessible version of this dissertation.

6 Discussion, Conclusion and Future Work

"A bicycle ride around the world begins with a single pedal stroke."
~ Scott Stoll

Physical activity is associated with many health improving effects. The bicycle combines physical activity with inexpensive, sustainable, and flexible mobility. Cycling can play an important role to prevent traffic jams, lower environmental pollution, and counteract an inactive lifestyle. Electric bicycles can encourage individuals with limited physical capabilities, such as the elderly, sedentary persons, persons with health conditions or physical disabilities, to be physically active. However, because of their sensitive physical constitutions, these persons need customized motor assistance strategies to prevent exhaustion and negative effects on their health.

This thesis analyzes the impact of proportional motor assistance of electric bicycles and different motor positions on the physiology of the rider (Chapter 2). It also presents a control system that adjusts the motor torque to regulate the heart rate of cyclists (Chapter 3) and evaluates it (Chapter 4). Finally, an optimal controller is designed that adjusts motor torque and transmission ratio of the vehicle to regulate the heart rate of the rider while considering motor power constraints. This allows to include trip information into the control system for improved energy consumption (Chapter 5).

The results of this work facilitate cycling for individuals with limited physical capabilities, because it allows to regulate the physical exertion of the cyclist. Therefore, it lays the foundation for a biometrical assistance system that acts on a physiological as well as a biomechanical level. Such a system could enable safe transportation and physical activity for persons with physical disabilities that can turn a single pedal stroke into a challenge.

6.1 Discussion

6.1.1 The Effect of Electrical Motor Assistance on the Physiology of the Cyclist

By adding the motor power to the human power, the total power to overcome the acting cycling resistances is distributed between both power sources, which directly affects the cyclist's physiology. Gojanovic et al. (2011) showed that cycling with a pedelec in a hilly terrain with the highest assistance mode can reduce the mean heart rate about 10% of the maximum heart rate (HR_{max}) in sedentary subjects. With a moderate assistance the mean reduction is about 4% of HR_{max}. However, peak heart rate during the experiments reached 85% of HR_{max} with high assistance and 90.5% of HR_{max} with a moderate assistance, which is considered a vigorous exercise intensity. Simons et al. (2009) also found a significant reduction in mean heart rate between cycling with no motor support and cycling with support in habitually active adults. Peak heart rate ranged from 81% of HR_{max} with no motor assistance to 77.9% and 74.9% of HR_{max} with moderate and high motor assistance, respectively, again exceeding levels of moderate exercise intensity. Sperlich, Zinner, Hébert-Losier, Born, and Holmberg (2012) analyzed cycling with and without electrical assistance in 8 sedentary women on a 9.5 km long track with varying terrain. Mean power output (−29%), muscular activity, heart rate (−29.1%), oxygen uptake (−33%), respiratory exchange ratio (−9%) and energy expenditure (−36.5%) were all reduced while cycling speed increased with electric assistance. In the study of Theurel, Theurel, and Lepers (2012), 10 healthy adults performed intermittent cycling exercises with an electric and a conventional bicycle. Again, a significant reduction in average oxygen uptake, average heart rate and muscular activity were lower. Louis et al. (2012) found significant reductions of mean power output, intensity and energy expenditure in 10 trained and 10 untrained subjects. Similar power outputs were found in both groups for various speed conditions, but the resulting heart rate and metabolic equivalent (MET) were higher for the untrained group. Although the physical strain of the cyclists is reduced when using an electric bicycle, the intensity is still high enough to meet health guidelines. For instance, using an electric bicycle for commute can improve fitness in untrained persons and therefore electric bicycles could be a promising tool to promote physical activity (Geus, Kempenaers, Lataire, & Meeusen, 2013).

These studies show that motor assistance reduces the physical strain in individuals of different age and fitness level. Similarly, the experiments presented in Chapter 2 corroborate these results. The first experiment shows that using a pedelec during a long cycling trip (ca. 30 km) reduces the mean heart rate, blood lactate concentration, and subjectively perceived exertion in young, healthy subjects. The effect of the electrical motor assistance was found to be higher for individuals with lower cardiorespiratory function (CRF). In consequence, a similar reduction of physiological parameters is expected in individuals with health conditions that limit their physiological capabilities. However, no study focused on these users yet. Still, the high deviations of the measured parameters already indicate that the motor assistance should consider physiological parameters to compensate influences from the environment (e.g. varying terrain) and differences in CRF between cyclists.

Additionally, the second experiment in Chapter 2 shows a reduction of the activity in the leg muscles in young, healthy subjects, but the activation pattern during one pedal revolution is similar with and without electrical assistance. Also, the motor position (mid-mounted or rear wheel hub motor) does not affect the activation pattern, but might affect the amount of activation of certain muscles. If there is a different impact on persons with biomechanical limitations has not been analyzed yet. The motor assistance of conventional electric bicycles provides support proportionally to the cyclist’s own power output at the pedals and might therefore amplify an asymmetric pedaling movement in individuals with biomechanical limitations. Further experiments with subjects with limited physical capabilities are necessary to fully understand the impact of current motor assistance systems on these users and how the assistance should be adjusted to compensate their individual limitations.

6.1.2 Heart Rate and the Relative Exercise Intensity Concept

Heart rate is used as a control variable for the systems developed in this thesis (Chapters 3 and 5). The heart rate is a commonly used parameter to monitor the physiology during physical activity, because it reflects the exercise intensity very well (Bot & Hollander, 2000) and is easy to measure (Achten & Jeukendrup, 2003). However, it is affected by physiological (e.g. cardiovascular drift and hydration) and environmental (e.g. temperature and altitude) factors (Achten & Jeukendrup, 2003) and does not display the real physical strain of an individual in all situations. Also, the cardiorespiratory fitness (CRF) of the individual needs to be determined by an appropriate method to be able to draw accurate conclusions about the exercise intensity from heart rate measurements during physical activity.

Prescribing the exercise intensity relative to maximum CRF values[11] of the individual is a common method (Kenney, Wilmore, & Costill, 2015; Lucía, Hoyos, & Chicharro, 2001; McArdle, Katch, & Katch, 2010). The state of CRF is determined with mathematical models or in experimental tests (Jackson et al., 1990; Kenney et al., 2015; McArdle et al., 2010). For instance, maximum heart rate (HR_{max}) or maximum oxygen uptake ($VO_{2,max}$) can be estimated with regression models (Gellish et al., 2007; Jurca et al., 2005; Kenney et al., 2015; Tanaka, Monahan, & Seals, 2001). Experimental methods to determine CRF are divided into maximal and submaximal exercise tests, either performed in a laboratory or outdoors (Faria, Parker, & Faria, 2005; Kenney et al., 2015; Powers, 2014). No equipment is needed when mathematical formulas to estimate CRF are used, but they do not yield the same accuracy as experimental tests and it differs between individuals (Mann, Lamberts, & Lambert, 2013; Whaley, Kaminsky, Dwyer, Getchell, & Norton, 1992).

Furthermore, exercise intensity prescriptions based on maximum CRF values do not yield the same precision as threshold concepts (lactate or ventilatory thresholds) (Davis & Convertino, 1974; Katch, Weltman, Sady, & Freedson, 1978; Meyer, Gabriel, & Kindermann, 1999; Swain, Abernathy, Smith, Lee, & Bunn, 1994). Graded incremental exercise tests (GXTs) to exhaustion using laboratory equipment to measure gas exchange and/or blood lactate concentration to analyze ventilatory and/or lactate thresholds yield more accurate results (Kenney et al., 2015). Consequently, these tests allow reliable recommendations for exercise intensity (Hills & Byrne, 1998). However, these methods are time consuming, require special equipment and have to be evaluated by professionals (McArdle et al., 2010). Submaximal tests are a reasonable compromise of cost, time and accuracy. Several submaximal tests have been developed in the past to simplify the estimation of maximum values as well as threshold values of sportsmen (Astrand & Ryhming, 1954; Conconi, Ferrari, Ziglio, Droghetti, & Codeca, 1982; Grazzi et al., 1999).

In summary, the accuracy of the relationship between heart rate and exercise intensity strongly depends on the method that is used to determine cardiorespiratory values. For healthy subjects, submaximal tests and mathematical models are an appropriate method, because even if estimated and real CRF do not match the risk and the negative effects of exhaustion are reasonably low. In Chapter 4, a study with 42 healthy, (almost exclusively) young subjects was carried out. Their CRF was assessed with a submaximal exercise test and the maximum heart rate was determined using a regression model. The test and model yielded mostly appropriate results, but several outliers indicated that even for this homogeneous subject group the accuracy differs amongst individuals.

Mathematical models and submaximal tests usually are based on experimental data of healthy subjects. Therefore, these methods do not return accurate results for individuals with limited or reduced cardiovascular function. Experimental testing in a laboratory is an appropriate method to determine CRF for these individuals (Fletcher et al., 2001). Still, heart rate as the only measure for exercise intensity might not be enough, because their condition can affect the heart rate. Medication (like beta-blockers) can also alter the relationship of power output and heart

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[11] For example as a percentage of HR_{max} or $VO_{2,max}$ (Garber et al., 2011)

rate, limiting the accuracy of the relative heart rate concept (Wonisch et al., 2003). Including additional physiological parameters into the control of pedelecs would therefore be beneficial.

For instance, blood lactate concentration reflects the exercise intensity more accurately than heart rate (Goodwin, Harris, Hernández, & Gladden, 2007). By analyzing the blood lactate concentration, the aerobic threshold (AT_{LT})[12] and the maximum lactate steady state (MLSS)[13] are determined. Exercise intensities below AT_{LT} are considered low intensities and can be maintained for long time periods. Intensities in the aerobic-anaerobic transition (between AT_{LT} and MLSS) are considered moderate to high intensities (Faude et al., 2009).

Similarly, by measuring the gas exchange, the aerobic ($AerT_{GE}$)[14] and anaerobic (AnT_{GE})[15] gas exchange thresholds can be determined. Again, intensities below the $AerT_{GE}$ are considered as low and between $AerT_{GE}$ and AnT_{GE} as moderate to high (Meyer, Lucia, Earnest, & Kindermann, 2005).

An increase in core body temperature is also closely related to the metabolic intensity during exercise, even without heat stress (Sawka & Wenger, 1988). Deviations from the normal body core temperature range (36.5–38.5°C) lead to impaired functioning of the body. Detecting changes in body core temperature can therefore be used to determine physical strain and prevent injuries during physical activity (Moran & Mendal, 2002).

Compared to the heart rate, it is far more complicated to measure these parameters. Blood lactate concentration and core body temperature need to be measured invasively to achieve the most accurate results. Respiratory gas exchange measurements require expensive equipment and a special mask placed on mouth and nose of the subject. Heart rate measurements with a chest strap therefore remain the best compromise between accurate determination of exercise intensity, comfort and costs for a multitude of individuals. Further advances in measuring devices are necessary, before the parameters mentioned above can be included into the control without compromising the usability of the system.

6.2 Conclusions

In this thesis, two control systems were developed to automatically adjust the settings of pedelecs to the individual physical capabilities of the cyclist. The systems enable cyclists to specify a heart rate zone, which the control systems maintain by adjusting the motor torque (and the transmission ratio) of the pedelec. The systems are part of a so called biometrical assistance system, which acts on a physiological as well as a biomechanical level to facilitate cycling for individuals with limited physical capabilities.

In Chapter 2, two outdoor experiments were conducted to analyze the impact of proportional electric motor assistance and different motor positions of conventional electric bicycles on the physiology of young, healthy subjects. The results show significantly reduced physical strain

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[12] First significant increase of blood lactate concentration and beginning of anaerobic metabolism (Kindermann, Simon, & Keul, 1979)

[13] Highest constant power output at which lactate production and elimination are at an equilibrium (Faude, Kindermann, & Meyer, 2009)

[14] Nonlinear increase in ventilation and in the ratio of CO_2 production and O_2 consumption (Wasserman, Whipp, Koyl, & Beaver, 1973)

[15] Respiratory compensation point; overproportional increase in ventilation compared to CO_2 production (Beaver, Wasserman, & Whipp, 1986)

and muscular activity with motor assistance and higher reduction for subjects with lower CRF. In the literature, several studies with healthy, sedentary, trained and untrained individuals have been carried out, but no study focused on individuals with limited physical capabilities.

Conclusion 1: *Proportional electric motor assistance reduces the physical strain of cyclists and still maintains a health improving exercise intensity. The impact of the assistance on the individual depends on one's individual physical constitution. Motor control systems of pedelecs should consider physiological parameters of the cyclist for improved assistance. The impact on individuals with limited physical capabilities still has to be analyzed.*

In Chapter 3 and 4 a sliding mode controller (SMC) that adjusts the motor torque of pedelecs to maintain a user-specified heart rate level was designed and validated. Additionally, the controller reduces the maximum torque output of the cyclist for improved cycling comfort. The controller successfully maintains the heart rate at the user-specified level or in a user-specified zone for constant reference heart rates. For changing reference heart rate profiles the control parameters might have to be adjusted for better performance (Meyer, Zhang, Tomizuka, & Senner, 2015). Compared to cyclists changing the motor assistance manually, the controller yields similar results when the cyclists use measurements of the heart rate as control parameter and improved results when the cyclists use their subjectively perceived exertion as control variable.

Conclusion 2: *The torque output of the electric motor of pedelecs can be adjusted automatically to maintain the heart rate of the cyclist inside a self-chosen zone. Heart rate control can be used as a tool to adjust the motor assistance to the individual physical capabilities of the cyclist. Heart rate is a suitable parameter to determine exercise intensity for healthy individuals or individuals with reduced CRF. For individuals with health conditions, further parameters have to be considered.*

Chapter 5 presents a model predictive controller (MPC) that manipulates both motor torque and transmission ratio to regulate the heart rate of the cyclist. The MPC minimizes a cost function to find the optimal control input for torque and transmission ratio in order to maintain the desired heart rate level while considering constraints. Simulation results show superior performance of the combined control compared to manipulating both variables separately.

Conclusion 3: *Automatically adjusting the transmission ratio in combination with the motor torque improves the tracking performance of the control system when compared to manipulating only one variable.*

In Chapter 5, information about the environment, the cyclist's fitness level and bicycle parameters are used to estimate the riding resistances during the trip and to optimize the energy consumption of the available energy. Hence, energy is saved for trip sections with high riding resistances, which results in improved tracking performance of the desired heart rate.

Conclusion 4: *Including trip information in the control of the motor assistance of pedelecs improves the distribution of the available energy and prevents running out of battery.*

6.3 Future Work

Further work is necessary to eventually design an energy management system with biometrical assistance that facilitates cycling for a variety of users with different health conditions and physical disabilities. The work should target the following areas:

1) **Customized Assistance on a Physiological Level:** Using the heart rate as a physiological parameter to determine exercise intensity is applicable for many users, but the accuracy might be limited (Chapter 6.1.2). Individuals with health conditions depend on accurate parameters to ensure safe physical activity. Monitoring different or additional parameters would therefore increase the reliability of the system. With the development of new wearable sensors and technological advances in computing, more parameters can be integrated to monitor the condition of the cyclist without decreasing the comfort (Bandodkar & Wang, 2014; Pandian et al., 2008; Raskovic, Martin, & Jovanov, 2004). For instance, zero heat flux sensors can be used to monitor the body core temperature on the skin (Fox, Solman, Isaacs, Fry, & MacDonald, 1973). Biochemical sensors could measure the lactate concentration from saliva (Kim et al., 2014) or sweat (Abrar, Dong, Lee, & Kim, 2016).

2) **Customized Assistance on a Biomechanical Level:** The cyclist's biomechanics have to be considered to facilitate safe cycling for persons with physical disabilities (Chapter 1.2.2). Additional research is necessary to analyze how the electrical motor assistance has to intervene into the pedaling cycle to improve efficiency and rehabilitation effects. Musculoskeletal models are a tool to model and predict the muscle activation during cycling movement (Höchtl, Böhm, & Senner, 2010) and can be used to customize the motor assistance to different biomechanical limitations of cyclists. Also, with the improvement in wearable sensors, measurements of body kinematics could be integrated into the control system. For instance, the electrical stimulation of muscles can be determined by textile-based electrodes manufactured into fabrics (Diamond, Coyle, Scarmagnani, & Hayes, 2008).

3) **Improved Trip Information:** Including a priori known trip information into the control reduces the risk of running out of battery (Chapter 5). Still, the information might be inaccurate and is subject to changes. Direct measurements of the acting riding resistances can improve the energy consumption during the trip and further reduce the risk of running out of battery. For example, the sensors inside the motor or the smartphone respectively can be used to determine the current road surface and automatically measure the current rolling resistance (Meyer, Kloss, & Senner, 2016).

4) **Adaptable Vehicle Designs:** Individuals with disabilities not only suffer from impaired cardiac capabilities, but also from impaired balance and posture. In addition to adapting the assistance to compensate the physical limitations, the vehicle design has to be adapted to make cycling safe for the user. Specialized vehicles and integrated sensors can help users to maintain balance and be more aware of their surroundings (Blumenstein, Zeitlmann, Alves-Pinto, Turova, & Lampe, 2014).

5) **Shared Control:** With increasing severity of a physical limitation or disability, additional sensors and assistance for tasks such as steering, guidance, and obstacle avoidance can be necessary. However, to prevent overreliance and loss of situation awareness, an appropriate level of control should remain with the user (Abbink, Mulder, & Boer, 2012). Future work should also consider shared control, which has been successfully applied in assistive devices such as mobility aids (Yu, Spenko, & Dubowsky, 2003) and wheelchairs (Cooper et al., 2002).

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