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主　論　文　の　要　旨

論文題目　Design and evaluation of gait phase-dependent control for a robotic walker to facilitate lower limb strength training
(効果的な下肢筋力トレーニングを目的としたロボット歩行器のための歩行位相依存制御の設計と評価)

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論　文　内　容　の　要　旨

With aging, human muscle strength, cognition, and coordination gradually deteriorate, possibly leading to the loss of mobility. Physical therapists advise elderly people to stay physically active to preserve or restore mobility. Walkers are widely prescribed by clinicians to such patients to enlarge the base of support for improving walking stability. And robotic walkers, which are wheeled walkers equipped with motors and sensors, can be used to assist physical therapists in rehabilitation treatments for helping elderly people regain mobility.

Strength training for lower limb muscles is beneficial for people, who suffer from walking disorders or muscle atrophy, to maintain and improve their walking ability. However, the improvement in lower limb strength does not always transfer to better walking ability because the strength training is not task specific. The muscles that are responsible for generating propulsion force during walking are not trained in these training programs.

This study aims to propose and develop a gait phase-dependent control strategy by using a robotic walker to provide walking training to elderly people for enhancing their lower limb muscle strength during repetitive use. The proposed control strategy should be able to train the muscles, which are crucial for the walking ability of users, in a task-specific manner. This study can be divided into two parts, the first is the design of the gait phase-dependent control. The challenge in developing the gait phase-dependent control is detecting the gait phase with high accuracy and low time delay. And the second part is an evaluation of the training performance of the proposed gait phase-dependent control. The evaluation consists of two steps due to a consideration of ethics: 1) evaluate the gait phase-dependent control with young subjects by monitoring the effects of the gait phase-dependent control on their muscular activations and gait patterns; 2) conduct experiments with elderly subjects for several weeks. Evaluate the training outcome for elderly people by observing changes in their walking ability.

Chapter 1 introduces the background as well as the related research of the thesis. Besides, the motivation and the objectives of the thesis are presented.

Chapter 2 presents an accurate and robust gait phase estimation method to obtain the gait phase information in real time for achieving the gait phase-dependent control. A force sensor mounted under the handle is widely used in smart walkers to constitute a human-machine interface. The interaction force can be used to estimate gait parameters using methods such as the Kalman filter for real-time estimation. However, the estimation performance of Kalman filter-based methods decreases when the instants of peaks in the interaction force are not captured. To improve the stability and accuracy of gait parameter estimation, an adaptive oscillator-based online estimation method is proposed. A multiple model switching mechanism is introduced to improve the estimation accuracy when the gait of a user is asymmetric, and an adaptive rule is proposed to improve the estimation robustness. Simulations and experiments demonstrate the accuracy and robustness of the proposed gait parameter estimation method. Here, the average estimation error for the gait phase is 0.691 rad when the gait is symmetric and 0.722 rad when it is asymmetric.

Chapter 3 describes an experiment with eight healthy young subjects, which was conducted to examine how the gait phase-dependent control influences muscular activity and gait patterns. EMG data from the muscles of the lower and upper limbs, as well as participants' lower limb joint angles, are recorded during walking with a robotic walker under different conditions to investigate the effects of the gait phase-dependent control. It is found that gait phase-dependent control can lead to a high activation level of plantar flexors and a high angular velocity of the ankle joint. Also, the muscular activity in triceps brachii under gait phase-dependent control is lower than that with constant resistance. Therefore, the gait phase estimation method can train plantar flexors with high effectiveness and efficiency. The training efficiency is defined as the physical load on an upper limb muscle (tricep brachii), and the proposed method can reduce the muscular activity on tricep brachii by 9.2% in comparison with that with constant resistance. This experiment result shows that the gait phase-dependent control has the potential to be used for improving the walking ability of users.

In Chapter 4, the long-term effect of gait phase-dependent control on the walking ability of elderly people is investigated with an eight-week training experiment. 24 healthy, elderly subjects participated in the eight-week experiment. Four clinical measures are used to evaluate the walking ability of participants before, in the middle, and after the experiment. Moreover, EMG and kinematic data are captured to investigate the effects of gait phase-dependent control on the muscular activation and gait pattern of elderly subjects. The experiment results show that training with gait phase-dependent control can improve the preferable walking speed and walk ratio of subjects. It indicates that the proposed gait phase-dependent control can be used for improving the walking ability of elderly people by training their lower limb muscles.

Chapter 5 summarizes the thesis and demonstrates a future perspective regarding this research.

Overall, this study designed and developed a control strategy for robotic walkers to provide task-specific strength training. The proposed adaptive oscillator-based gait phase estimation method can estimate the gait phase in real time by using the interaction force between a walker and a user, and it can provide high accuracy and robustness even when the user has an asymmetric gait pattern. With the proposed gait phase estimation method, the gait phase-dependent control can be achieved by adjusting the level of resistance generated by two motors based on the estimated gait phase of a user. Experiments with both young and elderly subjects are conducted for evaluating the effects and training performance of the proposed gait phase-dependent control. The results indicate that the proposed gait phase-dependent control is suitable for improving the walking performance of users by enhancing lower limb muscle strength. Especially, it can contribute to the strengthening of the plantar flexors with both effectiveness and efficiency. The training performance for patients with different neurological impairments will be further investigated in the future.