別紙1－1

論文審査の結果の要旨および担当者

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氏　　　名　　李　鵬程

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）

論文審査担当者

主査	名古屋大学	未来社会創造機構	教授	長谷川　泰久
委員	九州大学	工学研究院	准教授	中島　康貴
委員	名古屋大学	工学研究科	教授	原　進
委員	名古屋大学	工学研究科	客員教授	山田　陽滋

別紙１－２　　　　　　　　　　論文審査の結果の要旨

With aging, human muscle strength, cognition, and coordination gradually deteriorate, possibly leading to their loss of mobility. Physical therapists advise elderly people to stay physically active to preserve or restore mobility. It is prevalent for robots to carry on the physical maintenance for elderlies and patients. Walkers are widely prescribed by clinicians to such patients to enlarge the base of support for improved walking stability. Moreover, robotic walkers are wheeled ones equipped with motors and sensors that can be used to assist physical therapists in rehabilitation treatment to help 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 of lower limb strength does not always transfer to improvement in walking ability because the strength training is not task-specific, and the muscles that are responsible for generating propulsion force during walking are not trained.

This research aims to propose and develop a gait phase-dependent control strategy to provide walking training to elderly people by enhancing their lower limb muscle strength during repetitive use. It should be able to train the muscles which are crucial for the walking ability of users in a task-specific manner. This research can be divided into two parts, the first is the design of the gait phase-dependent control. The challenge for gait phase-dependent control is detecting the gait phase with high accuracy and small 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 performance.

Chapter 1 introduces the background as well as the related researches 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 as a human-machine interface. The interaction force can be used to control the walker and estimate gait parameters using methods such as the Kalman filter for real-time estimation. However, the estimation performance decreases when the peaks of the interaction force are not captured. To improve the stability and accuracy of gait parameter estimation, we propose an online estimation method to continuously estimate the gait phase and cadence. A multiple model switching mechanism is introduced to improve the estimation performance when gait is asymmetric, and an adaptive rule is proposed to improve the estimation robustness and accuracy. Simulations and experiments demonstrate the effectiveness and accuracy 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 are recorded during walking with a robotic walker under different conditions, as well as participants’ lower limb joint angles, to investigate the effects of the gait phase-dependent control. I found that gait phase-dependent control can lead to a high activation level of plantar flexors and a high angular velocity during the pre-swing phase and that the activity in triceps brachii is lower than that with constant resistance. Therefore, I conclude that the gait phase estimation method can train plantar flexors with high effectiveness and efficiency. The plantar flexors are the main contributor to generating propulsion force during walking. The strength of plantar flexors is crucial for walking ability and balance, while few rehabilitation robots can contribute to enhancing plantar flexors.

In Chapter 4, the long-term effects of gait phase-dependent control on improving the walking ability of elderly people are investigated with an eight-week training experiment. 24 healthy, elderly subjects participated in our 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 also captured to

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investigate the effects of gait phase-dependent control on the muscular activation and gait pattern of users. 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 has the potential to be used for improving the walking ability of the elderly by training their lower limb muscles.

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

Overall, the work designed a control strategy for robotic walkers to provide task-specific strength training. The proposed method can estimate the gait phase in real-time by monitoring 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. The level of resistance generated by two motors is adjusted based on the estimated gait phase of a user so that the mechanical resistance can stimulate higher muscular activity in lower limb muscles in a task-specific manner. 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 muscles 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 furtherly investigated in the future.
以上のように本論文では高齢者による歩行トレーニングを支援する目的で提案した歩行位相依存制御の方法と底屈筋を対象としたトレーニング効果の評価結果を明らかにしている。これらの制御方法並びに得られた評価実験結果は、高齢者向け歩行支援機器に対しロボティクスを応用展開するひとまとまりの技術として重要であり、工学の発展に寄与するところが大きいと判断できる。よって、本論文の提出者である李 鵬程君は博士（工学）の学位を受けるに十分な資格があると判断した。