A Computer Simulation Study on the Cycle-to-Cycle Control Method of Hemiplegic Gait Induced by Functional Electrical Stimulation

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論文内容要旨

Functional electrical stimulation (FES) has been utilized to restore gait in the patient with impairment of the central nervous system caused by the spinal cord injury or the stroke. Restoration of the paralyzed gait using FES needs a sophisticated control strategy. The FES systems that use the open-loop control can result in a good gait when the muscles do not fatigue and there are no external disturbances. Although the trajectory-based closed-loop control has been developed, it has not been used yet in the clinical FES gait because of difficulties to result in accurate tracking performance. The cycle-to-cycle control delivers the electrical stimulation in the form of the open-loop control in a cycle of gait. Correction of the stimulation burst duration is given to a cycle of gait based on the evaluation of the previous cycle of gait. The cycle-to-cycle regulations of the stimulation burst durations to achieve certain target joint angles seem to be easy to generate a successful gait. Considering other method of the closed-loop FES gait control, the cycle-to-cycle control method is an candidate.

In previous researches, the cycle-to-cycle control was not studied in a concrete framework of the closed-loop control. Its feasibility to control multi-joint movements has still not been explored clearly. Objective of this study was to test feasibility of the cycle-to-cycle control in controlling multi-joint movements of swing phase of FES gait. In order to realize the cycle-to-cycle control, a concrete framework of the cycle-to-cycle control was developed through gait analysis and studies of the joint movements during gait and functions of the lower limb muscles. In order to compensate the non-linearity of the musculo-skeletal system responses, the cycle-to-cycle control was implemented using fuzzy controller. Computer simulation using the electrically stimulated musculo-skeletal model was chosen as an approach to test the designed controller.

The cycle-to-cycle control regulates the stimulation burst duration of a current cycle of gait, $TB[n]$, based on the performance of the previous cycles. Obtained joint angle of the previous cycle is delivered as a feedback signal. Error is defined as difference between target joint angle and the obtained joint angle. Basic algorithm of the cycle-to-cycle control is shown in Equation (1),

$$TB[n] = TB[n-1] + \Delta TB[n] \qquad (1)$$

where $\Delta TB[n]$ is the control action generated by the controller.

A concrete framework of the cycle-to-cycle control was established through the knowledge engineering approach. The knowledge acquisition was performed by the analysis of gait data measured from the neurologically intact subjects and the literature study about muscle function of the lower limb. The framework of the cycle-to-cycle control was expressed in the target joint angles and the stimulation schedule. The target joint angles in Table 1 were determined by the average values of the joint angle parameters of the swing phase of the normal gait. Parameter $\Delta\theta$ was introduced in order to evaluate whether the target joint angle was reached or not. The $\Delta\theta$ of each controlled joint angle was set by average value of intra-subject standard deviation of each target joint angle from the gait analysis. The stimulation schedule in Figure 1 was designed based on the knowledge about the joint movements and the functions of the lower limb muscles. Stimulations of the iliopsoas, the bicep femoris short head (BFSH) and the bicep femoris long head (BFLH), the vastus muscles and the rectus femoris, the gastrocnemius medialis, and the tibialis anterior were controlled to induce the joint movements reaching the following target joint angles: maximum hip flexion angle, maximum knee flexion angle, maximum knee extension angle, maximum ankle plantarflexion angle, and maximum ankle dorsiflexion angle, respectively. After the hip joint reached the target maximum hip flexion angle, the iliopsoas was stimulated again to keep hip flexion and reach the target of hip joint angle at initial contact. The tibialis anterior and the soleus were stimulated simultaneously to reach the target of ankle joint angle at initial contact. Beginnings of the muscle stimulation were at the maximum hip extension, maximum knee extension and maximum ankle dorsiflexion angles at the end of stance phase. In our result of the gait analysis, timing of those maximum joint angles in a cycle of gait varied among subjects. In order to facilitate the computer simulation, these maximum joint angles were assumed to be occurred simultaneously.

A computer simulation using the musculo-skeletal model can be performed in developing a control method or design and evaluating the designed controller for FES. In this study, the electrically stimulated musculo-skeletal model and the motion equation for swing phase of gait was designed to evaluate the controller implementing the cycle-to-cycle control method. The motion equation was derived from the geometric diagram of the skeletal system model using the Lagrangian method.

Table 1. Target joint angles and $\Delta\theta$ of the swing phase control.

Joint	Angle	Target	$\Delta\theta$
Hip	max. flexion	32.4°	2.0°
	initial contact	29.3°	2.8°
Knee	max. flexion	69.0°	1.9°
	max. extension	3.6°	2.7°
Ankle	max. plantarflexion	-16.4°	3.4°
	max. dorsiflexion	4.9°	1.3°
	initial contact	-0.3°	1.3°

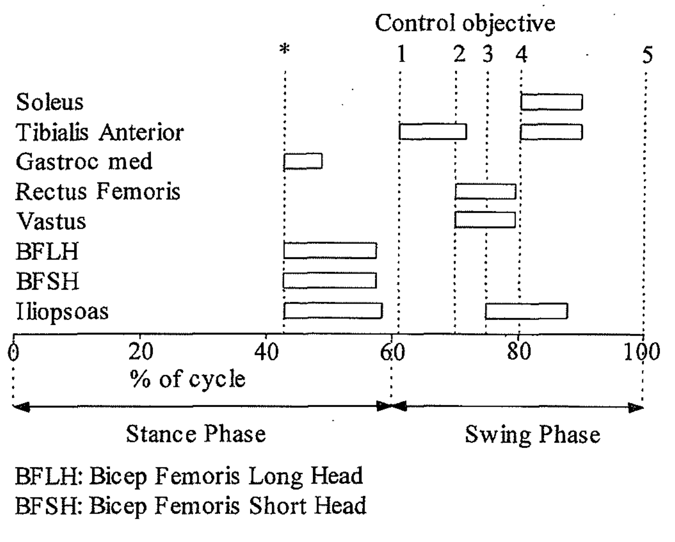

Figure 1. The stimulation schedule. *: the beginning of the stimulation (the maximum hip extension angle, the maximum knee extension angle of the end of the stance phase, and the maximum ankle dorsiflexion angle of the end of the stance phase). The control objective: 1: the maximum ankle plantarflexion angle, 2: the maximum knee flexion angle, 3: the maximum hip flexion angle, 4: the maximum ankle dorsiflexion angle, and 5: the maximum knee extension angle and the hip and the ankle angles at initial contact.

A fuzzy controller is inherently a non-linear controller. Since the characteristic of the electrically stimulatec musculo-skeletal system is known to be non-linear, the control method was realized using a fuzzy control scheme A proportional-integral-derivative (PID) controller and an adaptive PID controller were also designed in order tc test its control capability in realizing the cycle-to-cycle control method. The designed controllers were tested ir automatic generation stimulation burst duration and in compensation of muscle fatigue.

In computer simulation test of controlling of single-joint (knee) movements, the fuzzy controller was superio to the PID and the adaptive PID controllers. Since the small oscillation of the maximum knee extension was observed in the preliminary computer simulation experiment of the fuzzy controller for two-joint (knee and ankle) movements, the adaptive fuzzy controller was considered to be necessary in clinical application. An adaptive fuzzy controller based on the gradient descent method and an adaptive fuzzy controller with parameter adjustment realized in a fuzzy model were designed. Structure of the adaptive fuzzy controller with parameter adjustment realized in a fuzzy model is shown in Figure 2. The fuzzy controller with parameter adjustment realized in the fuzzy model was shown to become effective when oscillating response was caused due to inter-subject variability. Since the fuzzy controller showed to be effective in controlling the single-joint and two-joint movements, it was expanded to realize the cycle-to-cycle control for multi-joint (hip, knee, and ankle) movements. The controlled joint angles in multi-joint control were evaluated by comparing to the measured trajectories of the normal gait. The controlled joint angle trajectories were qualitatively acceptable and the controlled gait pattern in Figure 3 was not significantly different from the normal gait pattern. This result showed that the fuzzy controller would be effective in realizing the cycle-to-cycle control for multi-joint movements of FES gait.

In order to design concept of the stimulation schedule, five knowledge-based stimulation schedules and one EMG-based stimulation schedule were developed and tested. The stimulation schedule A was the originally designed in this study (see Figure 1). In the stimulation schedule B, the hamstrings were stimulated after the ankle joint angle reached the target of maximum plantar flexion, in order to reduce excessive knee flexion caused by simultaneous stimulation of the hamstrings and the gastrocnemius medialis as seen in movement developed by the stimulation schedule A. The co-activation of the tibialis anterior and the soleus was also omitted in order to test the significance of that. The stimulation C was aimed at testing of effect of omitting the stimulation of the gastrocnemius medialis at the beginning of control on knee flexion. Effect of the co-activation of the vastus muscles with the hamstrings in the knee flexion at the beginning of swing phase was tested in the stimulation schedule D. The stimulation schedule E was to test effect of the stimulation schedule D when the stimulation of the soules substituted for the gastrocnemius medialis in inducing the ankle plantar flexion. Possibility of using

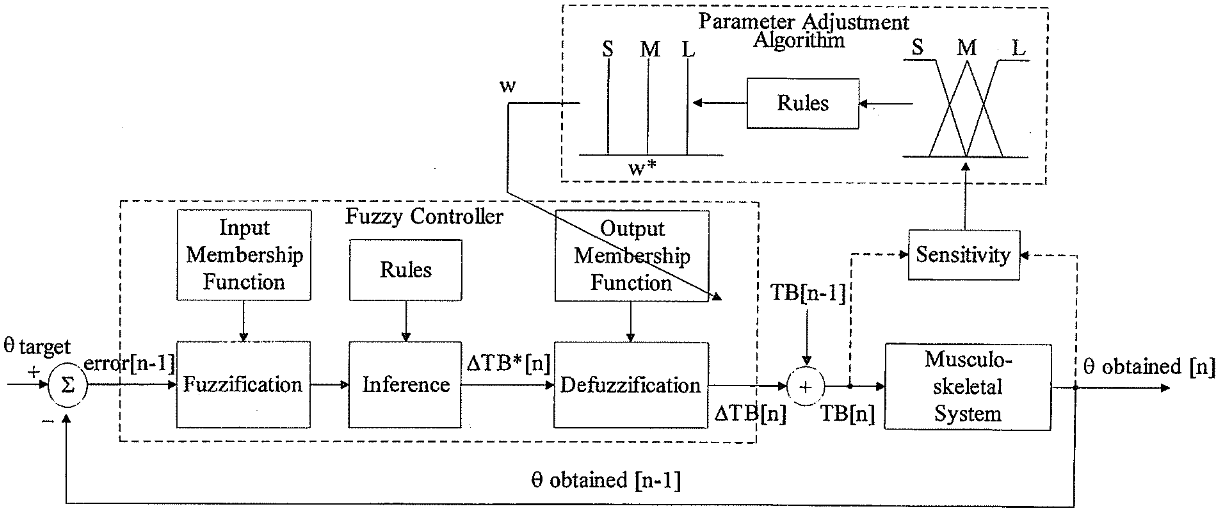

Figure 2. Adaptive fuzzy controller with parameter adjustment realized in the fuzzy model.

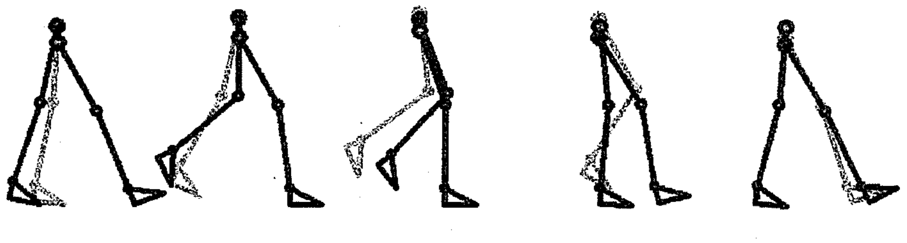

Figure 3. Stick picture of the controlled gait pattern (black) and the normal gait pattern (gray).

stimulation schedule based on EMG data was tested in the stimulation schedule F. Gait pattern of each stimulation schedule generated by computer simulation is shown in Figure 4. The result showed that combination of the information of timing pattern of muscle activation and the knowledge about joint movements and muscle function would be necessary in design of the stimulation schedule for FES gait. The co-activation of the iliopsoas, the hamstrings and the vastus muscles at the beginning of swing phase and that of the tibialis anterior and the soleus at the end of swing phase were found to be effective in swing phase control.

This study showed the cycle-to-cycle control to be feasible in controlling swing phase of FES-induced gait. The fuzzy controller was shown to be effective to implement the cycle-to-cycle control method. The cycle-to-cycle control realized in the fuzzy controller was expected to be tested clinically.

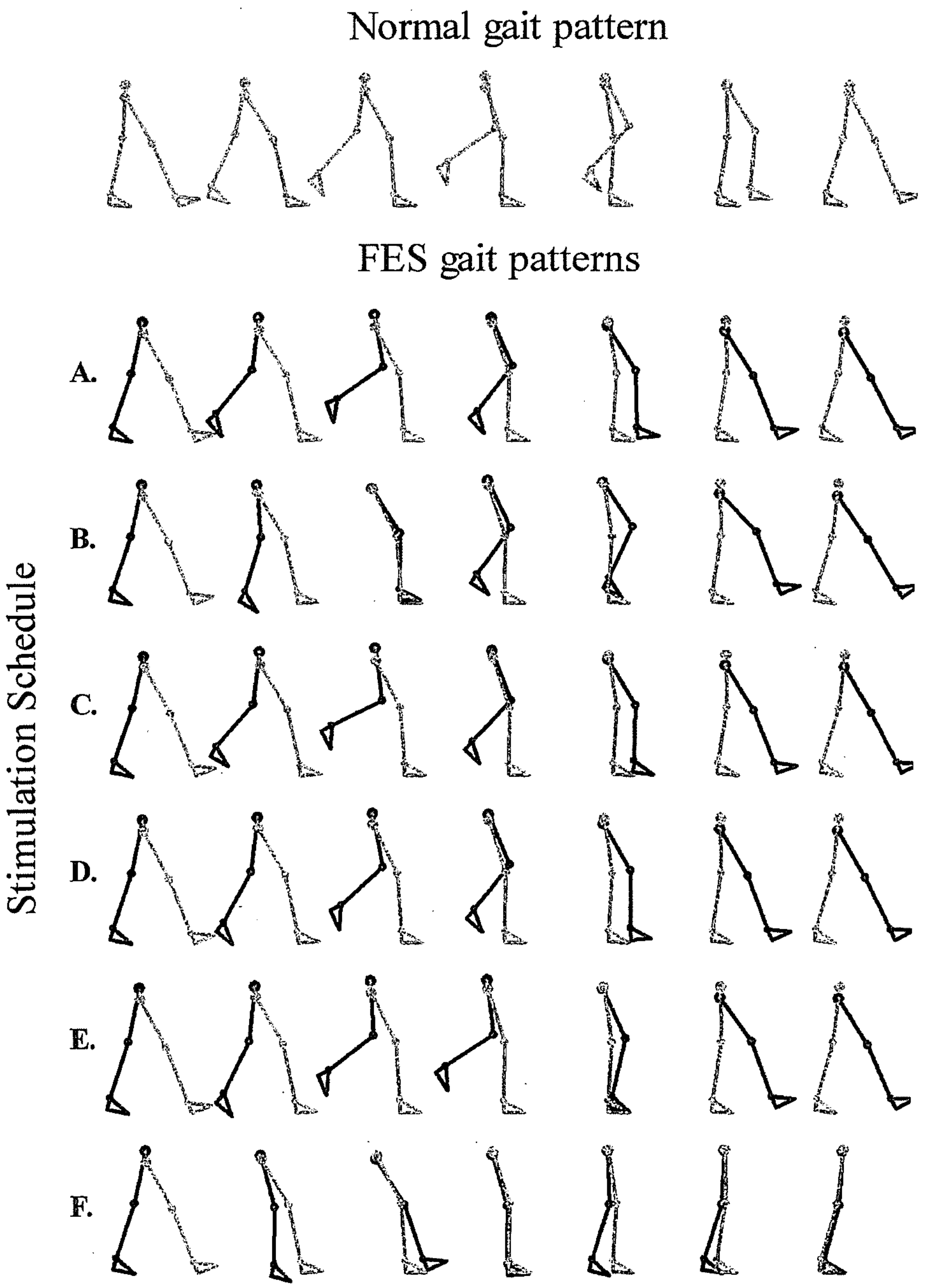

Figure 4. Gait pattern of each stimulation schedule. The black leg in the simulated FES gait is the controlled paralyzed swing leg, and the gray leg is the normal stance leg.

論文審査結果の要旨

機能的電気刺激（FES）は，麻痺した運動機能の再建に対して有効な方法であり，上肢の動作を中心に臨床的に検討されてきた。一方，歩行などの下肢の動作については，まだ研究段階であり，適切な下肢FES制御方法の実現が必要とされている。本論文は，FESによる歩行再建の効果が大きい片麻痺者を対象として，臨床的実用性の高い制御方法を実現するため，cycle-to-cycle制御手法を応用して歩行の遊脚期の多チャネルFES制御器を構築し，筋骨格モデルを用いた計算機シミュレーションにより評価した研究についてまとめたもので，全編6章よりなる。

第1章は序論であり，本研究の背景及び目的を述べている。

第2章では，健常者の歩行の解析結果，ならびに，cycle-to-cycle制御による歩行の遊脚期制御のための目標角度の決定と刺激スケジュールの作成について述べている。これらは，FESによる歩行制御の実現と再建動作の評価において必要な知見を提供可能にし，cycle-to-cycle制御を下肢の多関節運動のFES制御に適用するための枠組みを確立したもので，有用な成果である。

第3章では，本論文で提案する制御器を評価するために作成した片麻痺者の歩行を表現する筋骨格モデルと，cycle-to-cycle制御による歩行の遊脚期のFES制御器の設計について述べている。本論文では，電気刺激による筋骨格系の非線形な応答に対応するためにファジィ制御を採用し，遊脚期を制御する多チャネルFES制御器を提案している。また，ファジィ制御器の有効性を検討するためにcycle-to-cycle制御でのPID制御器や適応PID制御器も設計している。

第4章では，設計した制御器の制御能力について，基本的な膝関節制御，膝関節及び足関節制御の計算機シミュレーションで評価した結果について述べている。ファジィ制御器の方が優れた性能を有することを示し，また，患者の応答の差異に対応するためにファジィ制御器パラメータの適応的調節法を提案して，その有効性も示している。これらは，歩行の遊脚期の多チャネルFES制御を，臨床で様々な患者に適用可能にする重要な成果である。

第5章では，本論文で提案された制御法を，臨床応用を想定した股関節，膝関節，足関節の3関節制御に適用し，計算機シミュレーションで検討した結果について述べている。最初に，ファジィ制御器による3関節制御で再建された歩行と健常者の歩行との比較を行い，歩行パターンの類似性を確認して，臨床適用に際して問題が無いことを示している。また，本論文での多関節制御のための刺激スケジュールの作成方法の有効性と実用性を確認している。これらは，本論文で提案する歩行の遊脚期の多チャネルFES制御法が実現可能であり，かつ，有効であることを示す重要な成果である。

第6章は結論である。

以上要するに本論文は，cycle-to-cycle制御手法を応用した歩行の遊脚期の多関節運動の多チャネルFES制御の枠組みを確立し，それを実現するファジィ制御器を提案し設計して，その実現可能性と有効性を計算機シミュレーションで明らかにしたもので，医用電子工学と福祉工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。