A Test of Fuzzy Controller for Cycle-to-Cycle Control of FES-induced Hemiplegic Gait: Computer Simulation in Single-joint Control

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1. Introduction
This paper presents a test of fuzzy controller to implement cycle-to-cycle control for controlling knee movement during swing phase. The fuzzy controller regulates burst duration of electrical stimulation to maintain maximum angles of knee flexion and knee extension at every swing of gait cycle. In this paper, two fuzzy controllers for the hamstrings and the quadriceps were tested in generating standard burst duration by computer simulation using musculo-skeletal model of lower leg [1] comparing with PID controllers. Using the standard burst durations as initial burst durations for different subjects were also tested.

2. Methods
Input of the hamstrings controller was the error of maximum knee flexion angle of previous cycle. Inputs of the quadriceps controller were error of maximum knee extension angle of previous cycle and desired knee extension angle range. The desired range of knee extension angle was defined as difference between obtained maximum knee flexion angle of current cycle and reference of maximum knee extension angle. Output of fuzzy inference engine was $\Delta TB^*$ corresponding to $\Delta TB$ of burst duration regulation algorithm in eq. (1),

$$TB[n] = TB[n-1] + \Delta TB$$  \hspace{1cm} (1)

where $TB[n]$ is stimulation burst duration for current cycle, $TB[n-1]$ is stimulation burst duration of previous cycle, and $\Delta TB$ is defuzzification output. The Mamdani implication was chosen as inference method. The center of gravity was used for converting the output fuzzy $\Delta TB^*$ into a crisp value of $\Delta TB$.

Standard burst durations were determined by computer simulation in a stimulation of 200 cycles using original values of parameters of musculo-skeletal model [2] with very short initial burst duration. The standard burst durations were obtained by averaging burst durations of five cycles in steady state. The standard burst durations were applied as initial burst durations for different subject models that had different values of maximum muscle force, mass of the shank, or length of the shank of musculo-skeletal model.

3. Results and Discussion
In order to evaluate control performance, settling time was defined as the number of cycles that were required to reach reference maximum knee angle with error that was less than or equal to 5%.

In all subjects the fuzzy controller had shorter settling time. One example shown in Table 1 was obtained from the reference subject model in generating standard stimulation burst duration. After third cycle, error of maximum knee extension angle increased to the maximum value then decreased until steady state. The fuzzy controller had smaller maximum error of maximum knee extension angle than the PID controller.

Using the standard burst durations as initial burst durations for different subjects resulted in inappropriate maximum knee angles at the beginning of stimulation. The fuzzy controllers could recover this condition faster than the PID controllers, although in few cases the fuzzy controllers had small oscillations.

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References

Table 1. Settling time of controllers (in cycles)

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<tr>
<th></th>
<th>Fuzzy</th>
<th>PID</th>
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<tr>
<td>max knee flex angle</td>
<td>16</td>
<td>39</td>
</tr>
<tr>
<td>max knee ext angle</td>
<td>18</td>
<td>74</td>
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