Development of An Automatic Knee Joint Control System for KAFO Using an Electromechanical Clutch

K.W. Lee, S.J. Kang, Y.H. Kim
 Dept. of Biomedical Engineering, Yonsei University, Wonju/Korea
 Research Institute for Medical Instrumentation and Rehabilitation Engineering, Wonju/Korea

Introduction
KAFO(Knee-Ankle-Foot Orthosis) is used for correcting abnormal operation and muscle weakness of knee or ankle joint, supporting one's weight. The ideal knee joint of KAFO should provide both the stability in stance and foot clearance in swing during a continuous gait cycle. To achieve these two important functions, there were a lot of researches related to the knee joint control of KAFO. Knee joint controls of the KAFO by mechanical or pneumatic devices have many problems such as increased weight or the alignment of the system (Lehmann and Stonebridge, 1978; Mauch, 1967). Electric knee joint controls using the microprocessor have been successfully applied to the KAFO (Yang, 1975; Irby, 1994). The goal of this study is to develop an automatic knee joint control system for KAFO, to evaluate the stability and the mobility of the developed system.

Methods
The developed system consists of four major parts: sensors, knee control device, control circuitry and serial data communication. Foot switch sensors and an infrared sensor were applied to detect the contact of the foot to the ground and to check knee flexion angle in situ. An electromechanical wrap spring clutch was used to control the knee joint. A microcontroller determined the knee control output from the input of sensors based on the finite state approach(Tomovic and McGhee, 1966), and the control output was also transmitted by a radio-frequency module to PC. In order to evaluate the stability of the system, the static torque of the clutch was measured using a torque transducer. The maximum knee flexion angle and its period during the gait cycle were also measured to test the mobility of the system in three gait patterns of normal subjects: normal, locked-knee, and controlled-knee. Three-dimensional gait analyses were conducted for three gait patterns of five normal subjects with Vicon 370 motion analysis system. Joint moments and powers were also calculated using an inverse dynamics.

Results and Discussion
As a result, the measured static torque of clutch was about 0.36Nm/kg, which satisfied the minimum required torque(0.20Nm/kg) for the knee flexion moment of a person with 60kg weight. As presented in Table 1, the temporal parameters and knee flexion pattern for controlled-knee gait was very similar to those in the normal gait. Maximum knee flexion angles and their timing-period during the total gait cycle of three gait patterns were 64.0±4.7° (73.2±2.1%) for the normal gait, 5.65±0.7° (55.2±6.0%) for the locked-knee gait, and 45.4±5.1° (69.8±2.6%) for the controlled-knee gait, respectively. From the three-dimensional gait analysis, the maximum knee flexion angle and moment in controlled-knee gait was 40.56±9.55° and 0.20±0.09Nm/kg respectively.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Normal gait</th>
<th>Locked-knee gait</th>
<th>Controlled-knee gait</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Non-orthotic side</td>
<td>Orthotic side</td>
</tr>
<tr>
<td>Cadence (step/min)</td>
<td>115.75 ± 0.26</td>
<td>102.25 ± 2.22</td>
<td>99.50 ± 6.14</td>
</tr>
<tr>
<td>Speed (m/sec)</td>
<td>1.29 ± 0.07</td>
<td>1.12 ± 0.05</td>
<td>1.11 ± 0.08</td>
</tr>
<tr>
<td>Stride length (m)</td>
<td>1.33 ± 0.06</td>
<td>1.30 ± 0.07</td>
<td>1.33 ± 0.07</td>
</tr>
<tr>
<td>Step length (m)</td>
<td>0.70 ± 0.04</td>
<td>0.61 ± 0.07</td>
<td>0.74 ± 0.02</td>
</tr>
<tr>
<td>Single support (%)</td>
<td>38.30 ± 0.96</td>
<td>41.50 ± 1.13</td>
<td>33.86 ± 0.97</td>
</tr>
<tr>
<td>Double support (%)</td>
<td>22.63 ± 1.91</td>
<td>23.66 ± 1.80</td>
<td>23.31 ± 1.64</td>
</tr>
<tr>
<td>Step time (sec)</td>
<td>0.52 ± 0.03</td>
<td>0.54 ± 0.02</td>
<td>0.67 ± 0.10</td>
</tr>
<tr>
<td>O.F.O (%)</td>
<td>12.02 ± 1.51</td>
<td>11.83 ± 1.61</td>
<td>11.80 ± 1.19</td>
</tr>
<tr>
<td>O.F.C (%)</td>
<td>50.32 ± 0.28</td>
<td>53.40 ± 1.63</td>
<td>45.43 ± 2.03</td>
</tr>
<tr>
<td>F.O (%)</td>
<td>61.72 ± 0.89</td>
<td>64.95 ± 1.67</td>
<td>57.05 ± 2.25</td>
</tr>
</tbody>
</table>

Table 1. Temporal gait parameters in three different gait patterns

![Knee Flexion Angle](image1.png)

(a) Fig 1. Knee flexion angle from the gait analysis

In summary, the developed control system for KAFO was lighter, simpler and more reliable than other systems, because it was designed as a unilateral system. It satisfied both the stability during stance phase and free knee flexion during swing phase at the proper period during the gait cycle. However, clinical experiments for patients are left for the future study. The developed KAFO system with the automatic knee joint control would be very useful in various lower extremity orthotic applications.

References
Mauch, Bulletin of Prosthetics Research, 143-169, 1967
Yang, Ph.D. Thesis, Ohio State University, Columbus, Ohio, 1975
Irby, M.S. Thesis, San Diego State University, San Diego, California, 1994

Acknowledgements
This study was supported by a grant (HMP-98-G-3-061C) of the HAN(Highly Advanced National) Project, Ministry of Heath & Welfare, R.O.K