Study of Wearable Knee Assistive Instruments for Walk Rehabilitation*

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Abstract
A wearable Knee Assistive Instrument for the walk rehabilitation was newly developed. Especially, this system aimed at supporting the rehabilitation for the post-TKA (Total Knee Arthroplasty) which is a popular surgery for aging people. This system consisted of an assisting mechanism for the knee joint, a hip joint support system and a foot pressure sensor system. The driving system of this robot consisted of a CPU board which generated the walking pattern, a Li-ion battery, DC motors with motor drivers, contact sensors to detect the state of foot and potentiometers to detect the hip joint angle. The control method was proposed to reproduce complex motion of knee joint as much as possible, and to increase hip or knee flexion angle. Especially, this method used the timing that heel left from the floor. This method included that the lower limb was raised to prevent a subject's fall. Also, the prototype of knee assisting system was tested. It was confirmed that the assisting system is useful.

Key words: Knee, Assist, Instrument, Walk Rehabilitation, Wearable, Non-Circular Gear, Grooved Cam, Pressure Sensor

1. Introduction
Total knee arthroplasty (TKA) has been proven to be an effective and cost-efficient intervention for end-stage knee osteoarthritis (OA). Most people who undergo TKA show marked improvements in function and reductions in pain compared with their preoperative condition (1)(2). Post-TKA improvements have been shown by the walking velocity (3)(4), the knee range of motion (5)(6) and the functional test result. A recovery of functional ability is fluctuated; nevertheless many patients experience significant improvements (7)(8). A residual limitation in patients’ functional performance has become an important focus of postoperative care. "When can I walk normally?", the surgical candidate’s greatest concern is remained before TKA surgery (9). Although patients have improved gait speed, cadence and stride length compared to their preoperative status, they cannot often match the gait characteristics of age-matched healthy individuals, even several years after surgery (10).
Adequate and intensive rehabilitation is an important requirement for successful TKA \(^{(1)}\). The primary focus of early rehabilitation is to discharge from the hospital as soon as possible after their TKA surgery. Because restricted knee range of motion (RoM) affects functional activities, knee RoM is regarded as one of the primary indicators of a successful TKA. A continuous passive motion (CPM) device is an external motorized device, which rotates a joint to move passively throughout a preset circular motion. Coutts et al. \(^{(12)}\) first initiated CPM device use immediately after TKA surgery. Their rationale is based on Salter's research and the postulate that CPM enhanced collagen tissue healing with better fiber orientation, avoiding cross-linking and thus generating better movement restoration. CPM has been widely used as an adjunct to physiotherapy (PT) after TKA for the past 25 years. Although several systematic reviews favour the use of CPM in the first rehabilitation phase after surgery \(^{(13)}\) \(^{(14)}\), there still is substantial debate about the total period of CPM application and the duration of individual sessions. Walking is the single most important functional activity performed by patients after TKA. Pre-surgery gait patterns can be retained after surgery \(^{(15)}\) \(^{(16)}\) and may have a larger effect upon post-surgery gait patterns. So, it was very difficult to recover walk status to normalize for the knee OA patients suffering from impaired walking for many years, even if they relieved severe gonalgia. For obtaining normal gait, patients need for physical training to master a proper walking pattern and correct flexion angle of knee joints.

In this report, we analyzed a gait with stride, knee and hip joints flexion angles to investigate a new process of post-TKA rehabilitation. We developed a walking CPM device named as "Knee Assistive Instruments for Rehabilitation (KAI-R)". KAI-R is a device for postoperative patients, it is necessary to confirm the safety of the patient before fitted. As a first step, we tested in healthy subjects.

2. Gait analysis

In general, visual evaluation is based on the measurement data which can evaluate the body's motion in two coordinates, during walking. As a minimum requirement the observer must evaluate stride length and step time as well as motion at pelvis, hip, knee and ankle-foot during the gait cycle \(^{(17)}\). This cycle is divided into seven periods shown in Fig.1.

![Gait cycle diagram](image-url)


Fig.1 Gait cycle
Quantitative methods of the kinematic parameters of gait which are time-distance measurements and joint angles have been shown to adapt to each individual difference\(^\text{(18)}\). And their diagnostic value has been emphasized by Grieve\(^\text{(19)}\) and Lamoreux\(^\text{(20)}\). Perry, Bontrager and Antonelli\(^\text{(21)}\) consider that velocity and single-support time reflect the subject’s mobility and support characteristics respectively. Andriacchi, Ogle and Galante\(^\text{(22)}\) have demonstrated the value of time-distance measurements over a range of walking speeds as an indicator of knee disability.

Based on these papers, we performed gait analyses of healthy persons. We put two markers on the lateral surface of pelvis, thigh, calve, and ankle, respectively. The subjects were measured with a high speed camera during free walking for six meters. Then we analyzed the walking parameters (Fig.2).

Based on these results, we have designed our walking assistive device.

3. Design of a Knee Assistive Instruments for Rehabilitation (KAI-R)

3.1 System structure of KAI-R

Based on the result of an analysis for cadence, stride, knee and hip joint flexion angles, an assist robot was developed. This robot consisted of a knee joint assist mechanism for knee flexion motion, a hip joint support mechanism, a shoe with foot sensor to detect walking status and braces. Especially, the driving system of this robot consisted of a CPU board which generated the walking pattern, a Li-ion battery, DC motors with motor drivers, contact sensors to detect the state of foot, potentiometers to detect the state of hip joint angle, as shown in Fig.3.

Also, a foot pressure sensor used a conductive rubber whose resistance changed with
pressure. Especially, that could detect the state of heel contacts. That contact pressure was detected as voltage. And when the detected voltage exceeded the threshold level, it was regarded that a foot left the ground. This threshold level could be set freely depending on the state of the patient's recovery or rehabilitation goals. Hip potentiometer converted the hip rotation to the voltage, as same as the foot contact sensor. When the detected voltage exceeded the threshold level, it could confirm that the hip joint rotated to the configured angle.

3.2 Assisting mechanism for Knee joint

In general, the knee joint rotates within 0 to about 130 degrees at the walking on flat and slope. And, during the 15 to 90 degrees, knee joint rotates with gliding to the back direction, at the bones contacts section, as shown in Fig.4. Also, that motion at the bone
center section is well known. So, this motion is defined as the "roll-back" motion. However, this roll-back motion length on the outside of leg is extended from that length at the bone center section, which is caused by a medial rotation. So, we proposed the design method of a knee motion assist mechanism using grooved cams and one non-circular gear. The rotation center of this gear was almost fixed, however, in the proposed mechanism, a rotation center of this gear moved along a center groove.

To approximate to an imaginary knee joint rotation center, we used a symmetrical modified trapezoid motion curves as shown in Fig.5.

![Motion velocity of the imaginary rotation](image)

In this report, using this design method, knee motion assist mechanism was designed. Each terminology was defined as Table.1. A curve of a knee joint center motion was defined in Equation 1-8 using non-dimensional time and displacements.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Terminology</th>
<th>Symbol</th>
<th>Terminology</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_x$</td>
<td>Displacement to x-axis direction</td>
<td>$h_y$</td>
<td>Displacement to y-axis direction</td>
</tr>
<tr>
<td>$h_{xmax}$</td>
<td>Maximum displacement to x-axis direction</td>
<td>$h_{ymax}$</td>
<td>Maximum displacement to y-axis direction</td>
</tr>
<tr>
<td>$S$</td>
<td>Non dimensional displacement</td>
<td>$T$</td>
<td>Non dimensional time</td>
</tr>
<tr>
<td>$V$</td>
<td>Non dimensional velocity</td>
<td>$A$</td>
<td>Non dimensional acceleration</td>
</tr>
<tr>
<td>$A_{rpm}$</td>
<td>Maximum non dimensional acceleration</td>
<td>$T_0$</td>
<td>Initial non dimensional time</td>
</tr>
<tr>
<td>$T_1, T_2$</td>
<td>Intermediate value of $T$</td>
<td>$T_3$</td>
<td>Terminal value of $T$</td>
</tr>
<tr>
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<td>Initial non dimensional velocity</td>
<td>$V_1, V_2$</td>
<td>Intermediate value of $V$</td>
</tr>
<tr>
<td>$V_3$</td>
<td>Intermediate value of $V$</td>
<td>$S_0$</td>
<td>Initial non dimensional displacement</td>
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<td>Intermediate value of $S$</td>
<td>$S_3$</td>
<td>Intermediate value of $S$</td>
</tr>
<tr>
<td>$r_c$</td>
<td>Radius of a cam follower assignment</td>
<td>$r_e$</td>
<td>Equivalent length of the imaginary rotational center</td>
</tr>
<tr>
<td>$r_p$</td>
<td>Radius of a pinion assignment</td>
<td>$\theta_e$</td>
<td>End angle of the roll-back motion</td>
</tr>
<tr>
<td>$\theta_k$</td>
<td>Equivalent angle of the imaginary rotational center</td>
<td>$\theta_s$</td>
<td>Start angle of the roll-back motion</td>
</tr>
<tr>
<td>$\theta_{pf}$</td>
<td>Offset angle of a pinion</td>
<td>$\theta_{cf}$</td>
<td>Offset angle of a cam follower</td>
</tr>
<tr>
<td>$\theta_{max}$</td>
<td>Maximum knee rotating angle</td>
<td>$\theta_{min}$</td>
<td>Initial knee rotating angle</td>
</tr>
</tbody>
</table>
\[ h_x = h_{x\text{ max}} \cdot S, \quad h_y = h_{y\text{ max}} \cdot S \]  \hspace{1cm} (1)

\[ T = \frac{\theta - \theta_s}{\theta_e - \theta_s}, \quad (\theta \geq \theta_s) \]  \hspace{1cm} (2)

Where, at the acceleration section:

\[ S = S_0, \quad V = V_0, \quad A = 0 \]  \hspace{1cm} (3)

\[ V = \frac{dS}{dT} \]  \hspace{1cm} (4)

\[ A = \frac{d^2S}{dT^2} \]  \hspace{1cm} (5)

\[ (T_0 \leq T < T_1) \]

\[ A = A_{mp} \sin \left[ \frac{\pi (T - T_0)}{2(T_1 - T_0)} \right] = A_{mp} \sin \frac{p}{C_1} \]

\[ C_1 = \frac{2(T_1 - T_0)}{\pi}, \quad p = \frac{T - T_0}{C_1} \]

\[ V = C_1 A_{mp} (1 - \cos p) + V_0 \]

\[ = V_1 - C_1 A_{mp} \cos p \]

\[ V_1 = C_1 A_{mp} + V_0 \]

\[ S = -C_1^2 A_{mp} \sin p + V_1 (T - T_0) + S_0 \]

\[ S_1 = -C_1^2 A_{mp} + V_1 (T_1 - T_0) + S_0 \]

\[ (T_1 \leq T \leq T_2) \]

\[ A = A_{mp} \]

\[ V = A_{mp} (T - T_1) + V_1 = A_{mp} \cdot p + V_1 \]

\[ p = T - T_1 \]

\[ V_2 = A_{mp} (T_2 - T_1) + V_1 = C_2 A_{mp} + V_1 \]

\[ C_2 = T_2 - T_1 \]

\[ S = \frac{A_{mp}}{2} p^2 + V_1 p + S_1 \]

\[ S_2 = \frac{A_{mp}}{2} C_2^2 + V_1 C_2 + S_1 \]  \hspace{1cm} (7)
The deceleration section had a different time interval but that was similar shape of the acceleration section.

They had different time interval ratio. At the x-axis, the time interval ratio of an increment and decrement was 2:3. Also, at the y-axis, the time interval ratio of an increment to decrement was 3:2.

In our study, the wire-cut electrical discharge machining was used to generate the non-circular gear profile. Based on a proposed method, the prototype knee motion assist mechanism was made as shown in Fig.6. The specifications of the prototype were shown as Table 2 and 3.

\[
\begin{align*}
(T_2 \leq T < T_3) \\
A &= A_{mp} \cos \frac{\pi(T - T_2)}{2(T_3 - T_2)} = A_{mp} \cos p \\
C_3 &= \frac{2(T_3 - T_2)}{\pi}, \quad p = \frac{T - T_2}{C_3} \\
V &= C_3 A_{mp} \sin p + V_2 \\
V_3 &= C_3 A_{mp} + V_2 \\
S &= -C_3^2 A_{mp} (\cos p - 1) + V_2 (T - T_2) + S_2 \\
S_3 &= C_3^2 A_{mp} + V_2 (T_3 - T_2) + S_2
\end{align*}
\]

(8)

Fig.6 The prototype knee motion assist mechanism
Table.2 Specifications of the prototype assist mechanism

<table>
<thead>
<tr>
<th>Items</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving gear module</td>
<td>0.8</td>
</tr>
<tr>
<td>Teeth number of a driving gear</td>
<td>12.0</td>
</tr>
<tr>
<td>Each roller follower diameter</td>
<td>10.0 mm</td>
</tr>
<tr>
<td>Maximum displacement to x-axis direction</td>
<td>7.5 mm</td>
</tr>
<tr>
<td>Maximum displacement to y-axis direction</td>
<td>18.4 mm</td>
</tr>
<tr>
<td>Radius of a cam follower assignment</td>
<td>35.0 mm</td>
</tr>
<tr>
<td>Radius of a driving gear assignment</td>
<td>43.2 mm</td>
</tr>
<tr>
<td>Equivalent length of the imaginary rotational center</td>
<td>19.9 mm</td>
</tr>
<tr>
<td>Equivalent angle of the imaginary rotational center</td>
<td>67.8 degree</td>
</tr>
<tr>
<td>Start angle of the roll-back motion</td>
<td>0.0 degree</td>
</tr>
<tr>
<td>End angle of the roll-back motion</td>
<td>125.0 degree</td>
</tr>
<tr>
<td>Offset angle of a driving gear assignment</td>
<td>1.2 degree</td>
</tr>
<tr>
<td>Offset angle of a cam follower assignment</td>
<td>181.2 degree</td>
</tr>
<tr>
<td>Initial knee rotating angle</td>
<td>0.0 degree</td>
</tr>
<tr>
<td>Maximum knee rotating angle</td>
<td>125.0 degree</td>
</tr>
</tbody>
</table>

Table.3 Specifications of a symmetrical trapezoid curve

<table>
<thead>
<tr>
<th>Parameters</th>
<th>X-axis direction</th>
<th>Y-axis direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{mp}$</td>
<td>6.11</td>
<td>6.11</td>
</tr>
<tr>
<td>$T_0$</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>$T_1$</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$T_2$</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>$T_3$</td>
<td>0.4</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Fig.7 Imaginary rotation center loci of a knee joint
For the normal person, attached on the knee joint, we tested about the usefulness. It was confirmed that the proposed mechanism could assist the knee motion smoothly to the maximum rotating angle as shown in Fig.7.

3.3 Hip joint support mechanism

To eliminate influence of mechanism weight, we developed the hip joint support mechanism. A suspension brace linked up with the waist belt and a hip central coordination mechanism corresponding to the hip joint center. To be fitted smoothly, we used magnet ball joint which could be detached and suspended in the joint mechanism. Femoral length adjustment mechanism accorded to the height of subjects or patients to regulate the length. In addition, the spherical structure of that joint could adapt flexion, extension, internal rotation, external rotation, adduction, abduction of the six directions of movement in human hip joint. This joint flexion or extension angle of hip joint was detected using potentiometer with special mechanism which eliminated other direction rotations as shown in Fig.8.

3.4 A foot sensor system to detect walking status

Fig.8 Hip joint structure mechanism

Fig.9 Shoe with foot sensor to detect walking status
Shoe with foot sensor system for detecting walking status was proposed, as shown in Fig.9. This system included an electrode sheet, a conductive rubber sole and shoes. These electrodes were attached on the heel section. And that contact pressure was detected as voltage. That relation between voltages $v_1$ to pressure $W$ was shown in Fig.10 and approximate as equation 9.

$$W = \frac{V + 1.0395}{0.5946}$$  \hspace{1cm} (9)$$

When the detected voltage exceeded the threshold level, it was regarded that a foot left the ground. In other words, when a threshold level was detected, the assist of a knee motion would start.

3.5 Control system of KAI-R

A control system of KAI-R was designed as shown in Fig.11. Especially, to adjust the sensitivity and the foot height easily, we input a heel contact level and a hip joint rotation angle using potentiometers.
In this control system, we used foot sensor to detect the walking status and control the operation. During one gait cycle as shown in Fig.2, when heel contacted the floor at the section IC, a foot sensor started to monitor the status of heel. When a heel left from the ground, the motor started to flex the knee joint immediately. And when the section ES terminated, a hip joint motion helping knee joint moved up to the required height. Then the motor drove the knee joint to extend until the section LS terminates. This action flow chart of KAI-R for right foot was shown in Fig.12. At first, the motor speed was changed to the maximum limit value D_{0p} which held position in knee flexion direction. This limit value meant the motor speed which reduced the influences of friction loss in this actuator. This limit value was measured by forward or reverse direction. When knee was flexed to the required angle, a motor speed was changed to the maximum speed D_{1} with constant velocity increment. Then the maximum speed D_{1} was held during a required time, and that value was changed to zero with constant velocity decrement. The magnitude and duration of D_{1} affected the maximum knee flexion angle and gait cycle; an increment and decrement of the speeds affected on the knee flexion velocity. To guide the patients to a regular walking, the flexion of the patient's hip joint was detected using an encoder. An extension motion would be started after the knee joint moved up to the required height. Therefore, a hip joint angle was detected which flex until the required angle to stop the knee extension motion.

4. Verification of the usefulness using prototype system

In addition, an extension motion was similar to the flexion motion except a direction of rotation. When the knee joint was extended to the required angle, the motor speed was changed to the maximum speed D_{2}. Also, the concept of velocity increment or decrement was the same as flexion motion.
KAI-R. Especially, for physically normal person, we compared the assist walk with the non-assist walk. Knee motion of post-TKA patients has been tied to the design of TKA components\(^{(26)}\), and implant designs have also been created to conform to healthy walking. In this report, KAI-R’s gait pattern is created based on static walking normal healthy individuals. In this report, the walk state was measured using high-speed camera and image processing unit. We calculated the motion of the two markers which were attached on the lateral surface of pelvis, thigh, calf, and ankle, respectively. Then, using motion data, we compared stride, the flexion angle of knee and height of foot\(^{(27)}\). So, using this walk assist system, the flexion angle of knee was raised on swing phase, and the height of foot was increased as shown in Fig.13. We found that the flexion angle of knee and the foot height could be increased by using this walk assist system and this was very important to prevent the fall of patients. In the elder, fall was always caused by a low foot height during walking. KAI-R was probably useful to prevent falls. On the other hand, we considered that walking stride which became smaller due to reaction delay and non-conformity of physical balance adjusted by wearing the walk assist system as shown in Table. 4.

![Comparison of walking](image)

**Fig.13 Comparison of walking**

<table>
<thead>
<tr>
<th>Performances</th>
<th>Without KAI-R</th>
<th>With KAI-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stride (m)</td>
<td>1.17</td>
<td>1.01</td>
</tr>
<tr>
<td>Foot height (m)</td>
<td>0.17</td>
<td>0.39</td>
</tr>
<tr>
<td>Maximum knee flexion angle (degree)</td>
<td>73</td>
<td>103</td>
</tr>
</tbody>
</table>

### 5. Conclusions

In this report, the knee assistive instruments for rehabilitation (KAI-R) was proposed. This system included an assisting mechanism and a measuring mechanism of knee-joint, the motion planning approach of the knee-supporting. The assisting mechanism was based on the knee motion measured for each patient. Furthermore, we developed the hip joint and foot sensor system to control the action of KAI-R. Also, the prototype of knee assisting system was tested. It was confirmed that the assisting system was useful. In future work, we will test the action of healthy volunteers and do clinical trials.
References


