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Study of a Wire-driven Leg Rehabilitation System

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Abstract

We propose here a new type of leg rehabilitation system. The aim of the system is to realize multiple-degree-of-freedom (DOF) training of a leg by manipulating the patient's leg by wires. A single-DOF experimental system was built and tested, and the experimental results showed the feasibility of a wire-driven leg rehabilitation system. Next, a 2-DOF experimental system was designed, with a target motion of flexion/extension of both the hip and knee joints. Experiments of single-DOF motion on a test dummy and a male subject showed that the system generates enough accurate motion to support range of motion exercise. In addition, the results showed that the wire-driven mechanism would be a human-friendly system.

1. Introduction

In an aging society, the need for physical therapy continues to grow, as more and more people suffer from physical impairment caused by diseases or accidents. Proper physical therapy promotes the patient's recovery and return to society. However, a shortage of physical therapists makes therapists' workload too great.

In Japan, most physical therapists work in hospitals, which means patients are deprived of continuous therapy once they leave the hospital. This sometimes causes their condition to worsen, especially in the case of elderly patients. One solution to this problem is the development of mechatronic devices for rehabilitation that can be used by patients without the ongoing aid of physical therapists.

Among many therapeutic methods, CPM (Continuous Passive Motion) is a good example of a mechatronic application. The CPM concept, in which the joint is moved very slowly by an external-powered device, was first introduced in the 1970s [1]. CPM has been applied mainly to patients following joint surgery, but the scope of the application has widened to, for example, rehabilitation of the bedridden elderly.

In most cases of postoperative treatment, only limited degrees of freedom of the extremity are focused on. However, in order to avoid disuse atrophy in the case of the bedridden elderly, therapeutic devices should have multiple degrees of freedom. For example, Krebs et al. developed and have been clinically evaluating a robot-aided neurorehabilitation system called MIT-MANUS. MIT-MANUS provides multiple-degree-of-freedom (DOF) exercises of upper extremities for stroke patients [2].

For multiple-DOF joint exercise of lower extremities, a system called TEM (Therapeutic Exercise Machine) has been proposed and developed [3]. Range of motion (ROM) exercise of both the hip joint and knee joint can be carried out using TEM. TEM is designed to carry out 3-DOF motion in the sagittal plane.

The systems mentioned above support and manipulate the target extremity by rigid links. Thus a user may fear that system failure will cause injury to the extremity. Also, the use of rigid links makes it difficult to increase degrees of freedom because the system could become too large and heavy for bedside use. Therefore, a different approach is needed to increase degrees of freedom of the system. One of the prospective approaches is to use wire-driven mechanisms.

Since wire-driven mechanisms are light, flexible, and hence human-friendly, several systems that apply wire-driven mechanisms to help people in rehabilitation have been developed. Tateno et al. studied powered upper limb orthoses [4]. They proposed an upper limb orthosis that consists of a 2-dimensional SCARA manipulator and wires. Wires suspend the patient's disabled arm and locate the arm vertically, whereas the SCARA manipulator locates the arm horizontally.

Takahashi et al. proposed an upper limb motion assist robot that helps an elderly patient lift his/her arm [5]. The robot uses a 2-dimensional wire-drive system and a linear drive system to locate the patient's wrist in three dimensions. Homma et al. proposed an upper limb motion assist system for use with disabled arms [6-8]. The system uses strings arranged in parallel to support the disabled arm and move it by controlling the length of each string.

In this paper, we focus on the rehabilitation of legs, and we propose a multiple-DOF rehabilitation system that employs a wire-driven mechanism.

In section 2, the system concept is described. In section 3, the results of experiments with a single-DOF experimental system are shown. In section 4, a 2-DOF experimental system is described and the results of experiments with single-DOF motion are reported. In section 5, a summary and description of planned future work are presented.

2. Concept of a proposed system

The aim of this study is to develop a leg rehabilitation system for multiple-DOF motion exercise of the hip, knee, and ankle joints. To make the system suitable for bedside use, we propose a system using a mechanism with parallel wires, as shown in Figure 1. The system consists of a bed, frames, wires, pulleys, actuators, and a controller. A patient lies on the bed, with his/her impaired leg suspended from frames around his/her body by wires. The length of each wire is controlled so that the suspended leg is moved along the determined trajectory.

Advantages of the proposed system are as follows:

(1) Multiple-DOF motion can be achieved using relatively low powered actuators compared with those used in mechanisms that use conventional rigid links.

(2) Since the leg is not fixed to rigid links, the patient's posture can be easily changed. Thus, this system is applicable to patients suffering from bedsores, for example.

(3) A problem with CPM devices composed of rigid links is that an axis of links does not correspond to the axis of a knee joint. This sometimes causes damage to the wounded part. The proposed system does not have rigid links attached to the patient, which eliminates this problem.

(4) A patient using the proposed system feels less unpleasant because his/her leg is not fixed to the system by rigid links.

We decided to use a step-by-step approach for realizing the proposed system. Target joints and the type of motion of the proposed system were as follows:

(1) Flexion/extension of a knee joint
(2) Flexion/extension of a hip joint
(3) Abduction/adduction of a hip joint
(4) External/internal rotation of a hip joint

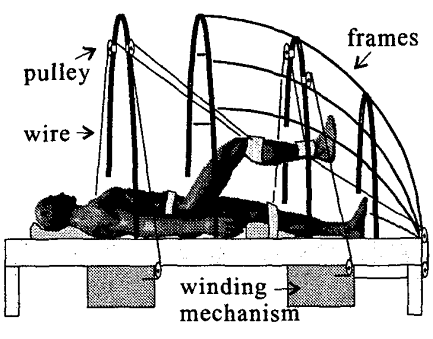


Figure 1: *Concept of a wire-driven leg rehabilitation system*

(5) Dorsi-/plantar-flexion of an ankle joint
(6) Abduction/adduction of an ankle joint

Our study is proceeding as follows. In the first stage of development, our target is just a single-DOF motion providing flexion and extension of a knee joint. Next, the target degrees of freedom will be increased, along with other improvements to the system. Ultimately, we aim to build a 6-DOF leg rehabilitation system.

3. A single-DOF experimental system

3.1 Outline of the system

First, we designed and built a single-DOF experimental system, in order to examine the feasibility of a wire-driven leg rehabilitation system. Since a knee joint can be modeled as a single-DOF joint, we focused on flexion and extension of a knee joint.

With this single-DOF system, the patient is in a supine position. The upper part of his/her leg is suspended by a suspending mechanism. The ankle of the suspended leg is fixed to a foot holder attached to the bed. The foot holder moves straight. Both the suspending mechanism and the ankle holding mechanism move cooperatively to carry out the knee joint motion. The length of each wire and location of the foot holder of the ankle holding mechanism are calculated according to the desired knee joint angle.

Figure 2 shows an overview of the experimental system. The system is 0.91 m wide, 2.15 m long, and 1.86 m high.

The system consists of a suspending mechanism, an ankle holding mechanism, frames, and a control system. The suspending mechanism is composed of two wires, a belt that holds the leg of the patient, and two winding units that are fixed to the frames. Each winding unit consists of a 23-W DC servomotor, gears (gear ratio: 1/100), a drum, and a torque sensor. These units wind wires cooperatively.

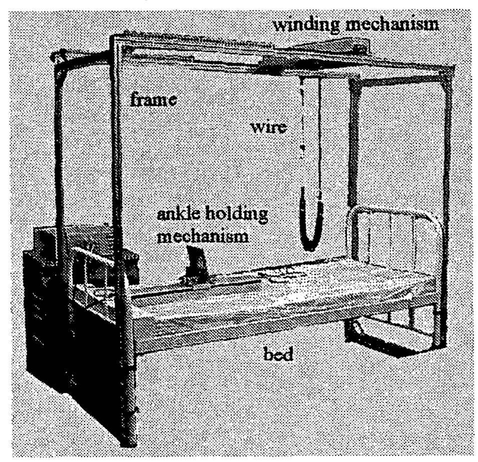


Figure 2: *A single-DOF experimental system*

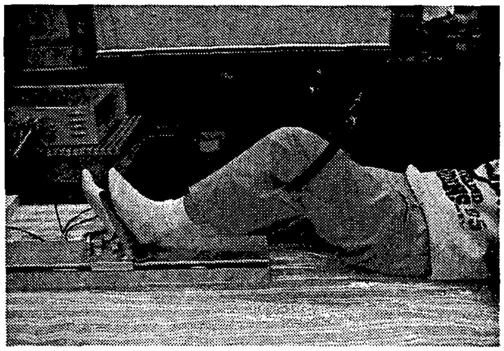


Figure 3: Close-up view of a leg wearing the experimental system

The ankle holding mechanism is composed of a foot holder, a ball screw with a pitch of 5 mm and a 40-W DC servomotor. The foot holder has a 0.5-m stroke. Frames are attached to the bed and hold the winding units. Both the winding mechanisms and the ankle holding mechanism have limit switches at both ends of the motion range. The system also has two emergency switches, one is held by the patient, the other is held by the operator, to stop the motion at any time either of them feels the leg is in danger.

Figure 3 gives a close-up view of the experimental system attached to the user's leg.

3.2 Experiment

We conducted an experiment using the single-DOF experimental system. The subject was an unimpaired male in his thirties. The target motion was flexion and extension of the knee joint between 0° and 72°. The belt of the suspending mechanism was attached to the subject's leg at about 0.1 m above the knee joint. We measured executed knee joint motion using inclinometers (FAS-E inclinometers manufactured by MicroStrain Inc.), which were attached to the upper and the lower part of the leg.

Figure 4 shows the results of our experiment. In the figure, changes of the knee joint angle are shown in time series. A gray line shows the target motion, and black lines show the measured motion of five trials.

3.3 Discussion

Figure 5 shows the relation between the calculated knee joint angle and the measured knee joint angle during a single trial. Offset of the measured knee joint angle was caused by the bend of the knee joint at the initial stage of the experiment. As shown in Figure 5, the relation between the calculated angle and the measured angle shows nonlinearity. When the direction of wire tension gets close to vertical, there is not enough force obtained to move the upper part of the leg along the desired trajectory.

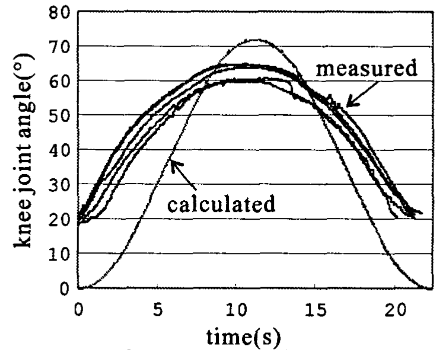


Figure 4: Result of the range of motion experiment

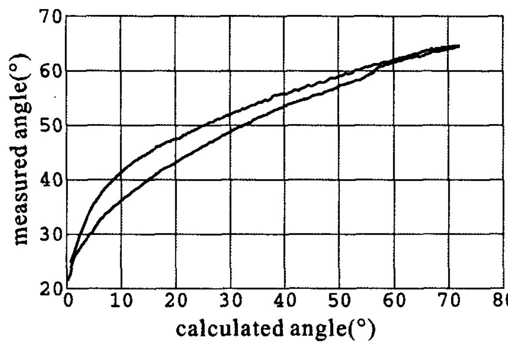


Figure 5: Relation between calculated knee joint angle and measured knee joint angle

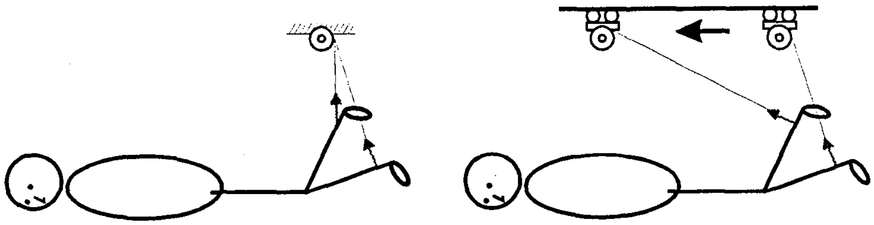
Variations of knee joint angle among five trials were within 10 degrees. The result shows the feasibility of the basic idea. However, configuration of the system should be revised, because the ankle holding mechanism fixed to the bed stops the suspended leg from lifting so that degrees of freedom of the system cannot be increased.

4. A 2-DOF experimental system

4.1 Outline of the system

Based on the results of testing a single-DOF system, we designed a 2-DOF experimental system. The target motions of the system were flexion and extension of both the hip and knee joints.

One of the characteristics of a 2-DOF experimental system is to use a moving winding mechanism. In therapeutic application, the direction of external forces should be controlled carefully in order to avoid damage to the human body. However, most of the existing wire-driven mechanisms employ fixed hanging equipment, so the direction of each wire tension changes according to the relative position between the hanging equipment and the suspended position of the object (Figure 6(a)). To keep the direction of wire tension in relation to the major axis of the leg constant, we employed a winding mechanism moving along a rail (Figure 6(b)). We used rails that were a combination of



(a) (b)

Figure 6: Conceptual sketch of (a) a fixed winding mechanism, (b) a moving winding mechanism

straight lines and arcs, in order to keep the direction of wire tension constant when the joint angle of the leg changes drastically.

Target motion is expressed as 2-DOF motion on the sagittal plane. In general, an n-DOF wire parallel positioning mechanism requires at least $n+1$ wires [9]. Therefore, our 2-DOF experimental system requires at least three wires if it is regarded as a planar system. Considering that the actual positioning is carried out not in a plane but in space, tension should be given symmetrically to the sagittal plane so that the suspended leg is kept on the sagittal plane. Therefore, we decided to use five wires in total, with one of the wires located on the sagittal plane.

The length of each wire and the location of the winding mechanism on the rail were calculated according to the desired joint angles.

The system can manipulate hip and knee joints at the same time. In the preliminary experiments, motion patterns were limited to two types of single-DOF motion, that is, to flexion/extension of the knee joint and the hip joint.

Figure 7 shows an overview of the experimental system, which is 1.7 m wide, 2.5 m long, and 2.0 m high. The experimental system consists of five rails, five winding units, a bed with frames, drivers, and a controller. Figure 8(a) and (b) show the configuration of the rails. As shown in Figure 8(b), rail A stands along the long axis of the bed, and a pair of rails B and a pair of rails C stand symmetrically in relation to rail A. Each winding unit is moved along the rail using a timing belt and a 40-W AC servomotor. The B rails share one motor for a timing belt, and the same applies to the C rails. Every winding unit has a 10-W DC motor to wind a wire. Wires are attached to the leg of the patient through belts around the leg. Wire A (wound by a winding mechanism attached to rail A) attaches to the lower part of the leg at the ankle. Wire B attaches to the upper part of the leg at the knee. Wire C pulls the lower part of the leg downward by the knee.

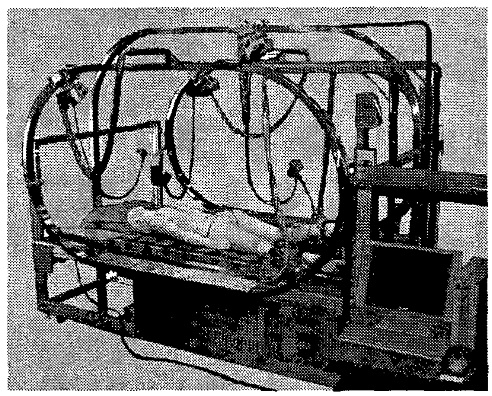
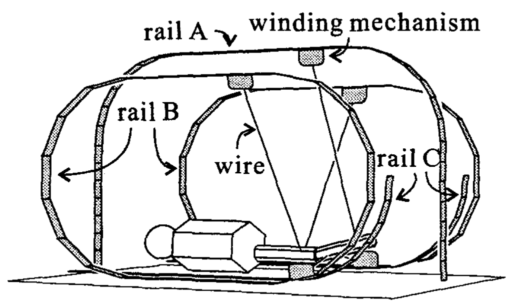
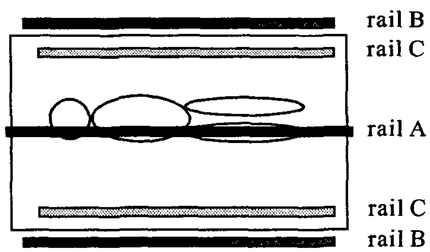


Figure 7: Overview of a 2-DOF experimental system



(a)



(b)

Figure 8: Configuration of rails: (a) perspective view, (b) plan view

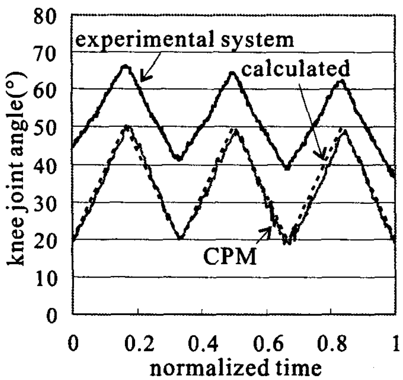


Figure 9: *Knee flexion/extension of test dummy*

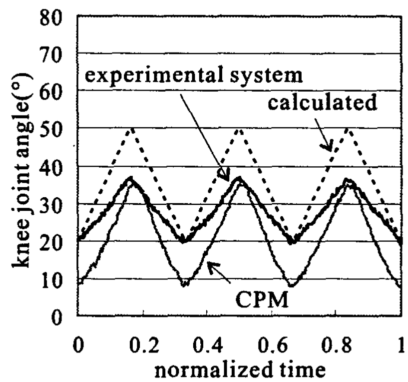


Figure 10: *Knee flexion/extension of human subject*

To make the system fail-safe, the system will stop when (1) any of the limit switches on any of the rails or the winding units is activated, (2) the magnitude of tension of any of the wires exceeds the determined threshold, (3) the patient pushes an emergency switch in his/her hand, (4) the operator pushes an emergency switch in front of the control box, (5) the operator hits any key on the computer while the system is running.

4.2 Single-DOF experiment with a test dummy

An experiment using a test dummy was carried out to examine the basic performance of the system. The target motion was flexion/extension of the knee joint of the right leg. The test dummy was set in the prone position. The trunk, the left leg, and the upper part of the right leg of the dummy rested on the bed, and the lower part of the right leg was moved. In this experiment, only wire A was used to move the leg.

The test dummy used in the experiment was developed by the Digital Human Laboratory, National Institute of Advanced Industrial Science and Technology. The height and mass of the test dummy are 1.649 m and 48.2 kg, respectively.

A wire was attached to the leg of the test dummy with a belt. The hanging position was set about 0.1 m above the right ankle. The target motion was flexion and extension of the knee joint between 20° and 50°. The target angle velocity of the joint was 1°/s.

During the motion the knee joint angle was measured using the inclinometers used in the experiment described in section 3.2.

For comparison, the same target motion was carried out using a commercial CPM device (Legasus CPM manufactured by Toronto Medical Inc.) with the dummy in the supine position.

Figure 9 shows the knee joint angle motion executed by the experimental system, the motion executed by the CPM device, and the target motion. The black line shows the result of our experimental system, the gray line shows the result of the CPM device, and the dashed line shows the target motion. The time scale is normalized, since the velocity of the CPM device did not correspond to the velocity of the experimental system.

4.3 Subjective evaluation by an unimpaired person

The same experiment described in section 4.2 was carried out on an unimpaired male subject in his thirties. Figure 10 shows the experimental results and the target motion.

After the tests with our experimental system and with the CPM device, the subject made a subjective evaluation, the results of which are shown in Table 1.

Table 1: *Subjective evaluation of 2-DOF experimental system*
(G: good, B: bad, N: neutral)

	Experimental system	CPM device
feeling of pressure	G	B
feeling of restraint	G	B
pain	G	N
uneasiness of posture	G	G
sense of anxiety	N	N
feeling of stiffness	B	G
feeling of being driven	B	G
smoothness of motion	G	G
noise	G	G

4.4 Discussion

Figure 11 (a), (b), (c), and (d) show the relation between the calculated angle and the measured angle under the four sets of conditions described in sections 4.2 and 4.3. Comparing two experimental results using a test dummy, our experimental system demonstrates a similar motion

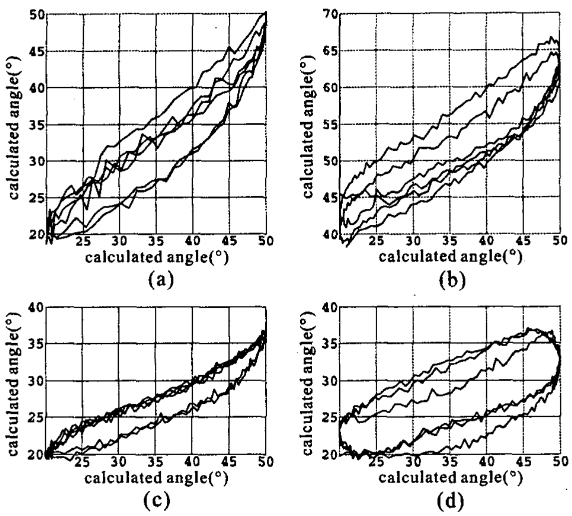


Figure 11: *Relation between calculated and measured knee joint angle: (a) dummy/CPM device, (b) dummy/experimental system, (c) human/CPM device, (d) human/experimental system*

pattern to CPM. In the case of the experiments using a human subject, the realized joint angle was smaller than the calculated angle in both cases. This is because the thickness of cloth affected the motion. In a comparison of the two cases, the experimental system shows larger hysteresis. Also, the repeatability of motion carried out by the experimental system is somewhat lower than the repeatability of motion carried out by the CPM device. Subjective evaluation shows that our proposed system will make the patient feel less restricted. The result shows that the system will be comfortable for impaired elderly people.

5. Summary and Future Work

We proposed here a new concept for a leg rehabilitation system. The aim of the system is to realize multiple-DOF training of a leg by manipulating the patient's leg by wires. A single-DOF experimental system was built and tested, and the results showed the feasibility of a wire-driven leg rehabilitation system. Next, we designed a 2-DOF experimental system. The target motions of the experimental system were flexion/extension of both the hip and knee joints. A characteristic of the system was to use winding units that move along rails to keep the direction of wire tension constant. Experiments of single-DOF motion on a test dummy and a male subject were carried out. The result showed that the system generated enough accurate motion to make it suitable for range of motion exercise. Also the result showed that the wire-driven mechanism would be a human-friendly system.

In future work, an improved system with additional degrees of freedom will be built. We are also searching for physiological signals that can be obtained noninvasively and that will be indicators of rehabilitative progress.

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