Wearable robot for simulating knee disorders in the training of manual examination techniques

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Abstract. This study addresses a haptic simulator of diseased knee joints that is intended for use in the training of manual examination techniques used in physical therapy. These techniques involve clinicians moving the impaired joint of a patient to test the dynamic joint resistance caused by a condition. Our exoskeleton robot simulates five types of common knee problems. The simulated symptoms were checked in terms of subjective similarity to actual symptoms that physical therapists experience in their work. Three of the five symptoms could be correctly identified whereas the other two were found to require further tuning. The proposed patient simulator could improve the training of manual examination techniques by being able to simulate a variety of symptoms.

Keywords: Patient simulator, Physical therapy, Manual examination

1 Introduction

Physical therapists manually examine the biomechanical and neural responses of the limbs of their patients to understand the nature of their disorders. In these examinations, the therapists test the dynamic joint resistance, as well as the range of joint motion, when the impaired limbs are moved passively. Although a therapist requires clinical experience to master these manual examination techniques, educational facilities rarely have the means of giving trainee therapists experience with real patients. To solve this issue, we have been developing patient simulators, which will allow trainee therapists to experience the haptic characteristics of diseased joints [2, 3]. A unique aspect of our approach is that we use an exoskeleton robot to simulate joint impairment, rather than taking the robotic patient approach of earlier schemes [4, 6]. In our approach, a healthy person wears the exoskeleton, which simulates the abnormal behavior of a patient's limb. Since the simulator incorporates part of an actual human body, a high level of realism can be achieved, including the complexity of human joint motion, as well as the bone and skin features of the human body.

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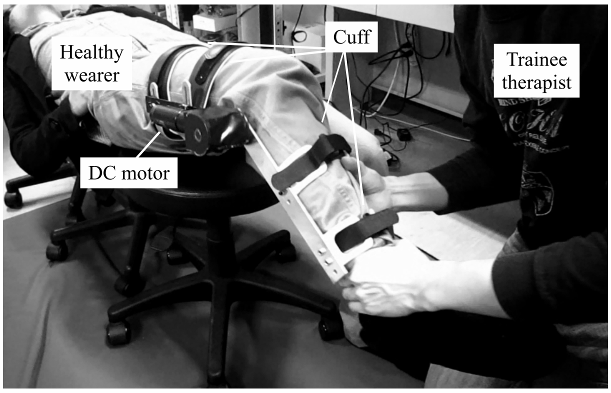

Fig. 1. Exoskeleton-type knee patient simulator. The healthy wearer (on the left) plays the role of patient. The trainee (on the right) practices the examination techniques.

The objective of this study is to demonstrate and validate the authenticity of a variety of simulated knee symptoms using a knee exoskeleton robot, building on our previous work whereas we simulated a spastic knee joint and crepitus [2, 3]. In this study, we also set out to simulate the symptoms of contracture, lead-pipe rigidity, cog-wheel rigidity, velocity-dependent resistance, and bony ankylosis, which are common symptoms that physical therapists are likely to treat in a clinical setting, and which are described in the following section. To test the authenticity of the simulated symptoms, we invited practicing physical therapists to participate in a symptom-classification experiment.

2 Wearable knee impairment simulator

Fig. 1 shows a mock patient, wearing the knee exoskeleton, and a trainee therapist whose task is to specify the knee joint impairment. The wearer relaxes and does not invoke any voluntary motions, while the trainee flexes or stretches the wearer's leg to test the dynamic force feedback. This is undertaken in an educational facility, where the trainees take turns in playing the role of patient when learning these manual techniques.

The knee robot consists of two links, fastened to the wearer's femoral and lower thighs, and one DC motor (RE35, Maxon, stalling torque = 949 mN·m, 1/86 gearing) which exerts a torque around the knee joint through a pair of bevel gears. The DC motor is controlled by a microcomputer operating at 5 kHz through a voltage-current converter (4-Q-DC ADS 50/5, Maxon). This system, which was developed as part of another study, was able to measure the joint angle and one-dimensional force applied to the tibia link.

3 Simulated symptoms

We simulated five different symptoms. Three of these, namely, contracture, lead-pipe rigidity, and velocity-dependent resistance, were also simulated in some earlier studies using robotic patient simulators. We focused on the authenticity and feasibility of the five types of simulated symptoms produced by the wearable joint simulator, rather than on developing sophisticated algorithms. Here, we briefly describe each symptom and how they were simulated. Each symptom involves gain parameters, which determine the severity of a symptom or its characteristics. In a latter experiment, these parameters were moderately set by the coauthors of this article, both of whom are physical therapists, such that each symptom was barely discernible.

Lead-pipe rigidity: Lead-pipe rigidity, which typically accompanies Parkinson's disease, is characterized by a constant stiffness of the joint. This stiffened joint can be simulated by providing a constant resistance against passive joint motion. We set the joint resistance torque of the lead-pipe rigidity to 0.5 N·m.

Cog-wheel rigidity: Cogwheel rigidity is similar to lead-pipe rigidity, however, it is characterized by a non-uniform resistance. We modeled this symptom by

$$\tau_{cog} = \begin{cases} 1.0 \text{ N} \cdot \text{m} \\ 0.5 \text{ N} \cdot \text{m} \ \ (\frac{\pi}{9} < \theta < \frac{5\pi}{36}, \frac{\pi}{6} < \theta < \frac{7\pi}{36}, \frac{2\pi}{9} < \theta < \frac{\pi}{4}) \end{cases} \tag{1}$$

where the fully extended angle was 0 rad. As a result, intermittent joint stiffness is experienced by the trainee as s/he manipulates the knee.

Contracture: Contraction involves chronically stiffened tendons or muscles constraining the joint movement. This limitation of the range of motion is typically modeled by using a spring coefficient. We also simulated contracture as an elastic resistance (5.7 N·m/rad) that acted only during knee flexion. In addition, to provide a resistance-free range, the elastic resistance was not exerted until the joint angle reached $\pi/18$ rad.

Bony ankylosis: An abnormal bony deformation or an artificial joint also limits the range of motion of the joint. The therapist can sense the contact between the non-elastic bones at the end of the range of motion. We simulated the resistance of this symptom by using a large spring constant of 28.5 N·m/rad. The free motion range was set to 0 to $2\pi/3$ rad.

Velocity-dependent resistance: A velocity-dependent joint resistance is caused by an abnormal stretch reflex of a joint, and is also referred to as spasticity. This type of resistance was simulated as a viscosity relative to an angular velocity in some earlier studies [1, 5]. We also followed their approach and determined the resistance torque from

$$\tau_{vel} = \begin{cases} c\dot{\theta}(t) \ \ (\dot{\theta}(t) \geq 0) \\ 0 \ \ (\text{otherwise}) \end{cases} \tag{2}$$

where the viscosity coefficient was set to 1.5 Nm·s/rad.

4 Classification experiment to check the authenticity of the simulated symptoms and the knee patient simulator

4.1 Methods and Tasks

We conducted a classification experiment in which physical therapists experienced and classified the simulated symptoms so as to validate the authenticity of our simulator. All of the procedures were approved by the IRB of the Engineering School of Nagoya University.

A healthy person wore the exoskeleton knee robot on the right leg and lay on a bed in a relaxed posture as shown in Fig. 1. Nine physical therapists, each with more than five years of clinical experience, took part in the experiment after providing their written informed consent. None of them had any experience of robotic joint impairment simulators. Before the main task, each was shown a list of the symptoms to be simulated and then actually experienced all of them. At this point, they were not provided with any feedback on the presented symptoms. In the main task, each participant was allowed to freely test each symptom for a maximum of one minute, before providing the name of the symptom that s/he believed was being simulated. The experiment thus involved a five-alternative forced-choice task. The simulated symptoms were presented in random order with each being experienced five times in total. Hence, each participant performed twenty-five trials.

4.2 Results - Positive answer ratios

Fig. 2 shows the averages and standard deviations of the answer ratios at which the presented and classified symptoms matched. Lead-pipe rigidity, cog-wheel rigidity, and bony ankylosis were classified as expected with statistically significant probabilities. Especially, ankylosis was always classified correctly. However, the positive answer ratios for the simulated contracture and velocity-dependent resistance were almost the chance. Velocity-dependent resistance was often confused with lead-pipe rigidity (0.31 on average) and contracture (0.33 on average). According to introspective reports provided by the participants after the main task, the velocity-dependent resistance was too small to differentiate from the other two symptoms. Moreover, contracture was often wrongly classified as velocity-dependent resistance (0.40 on average). The participants could not differentiate between these two types of symptoms possibly because the force feedback gains were set to low values.

5 Conclusion

In this study, we simulated several types of common knee disorders using an exoskeleton robot for providing training in manual examination techniques used by physical therapists. Because the wearable simulator for joint impairment is well balanced in terms of realism and cost, its practical use would allow the simulation of a greater number of symptoms. The five symptoms, namely, contracture,

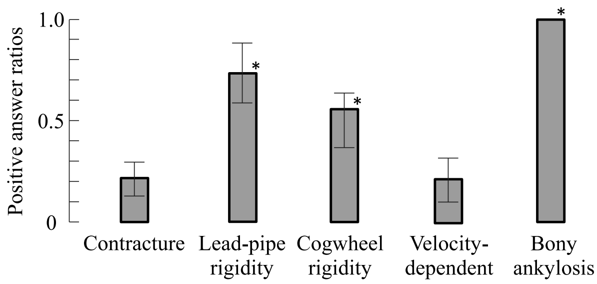

Fig. 2. Average positive classification ratios of simulated symptoms and standard deviations among the participants. Here, * indicates a statistically significant difference from the chance (0.2) with $p < 0.05$ of two-tailed t-test.

lead-pipe rigidity, cog-wheel rigidity, bony ankylosis, and velocity-dependent resistance, were simulated and evaluated. Although the gain that determines the prominence of the joint resistance has bet to be tuned to allow the device's use in an educational facilities, however, the simulated symptoms could be correctly classified in a test involving nine physical therapists.

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