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Wearable Dummy to Simulate Joint Impairment: Severity-based Assessment of Simulated Spasticity of Knee Joint

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***Abstract*— Physical therapists master manual examination techniques for testing impaired motor functions. We used a wearable robotic dummy joint that simulated disordered joint resistances to help physical therapists learn such techniques. This study developed a resistance model for a spasticity joint, and the dummy joint was used to present it. We assessed the simulated spasticity model using Modified Ashworth Scale (MAS), which is an evaluation criterion for spasticity seriousness that is widely used by physical therapists. The results of experiments involving two physical therapists showed that the model accurately expressed mild-to-severe symptoms of knee joint spasticity. It is expected that using the system in educational institutions for physical therapists will help students learn the typical levels of joint resistance caused by spasticity with different degrees of severity.**

I. INTRODUCTION

Appropriate rehabilitation not only improves a patient's quality of life but also reduces the cost of medical care by facilitating the early recovery of the patient. Physical therapists assume an important role in the rehabilitation of patients, assisting them to recover impaired motor functions caused by diseases such as stroke and arthrosis. One of their most important skills is a technique called manual examination, which is used to determine the pathology and the sites to be treated. When performing a manual examination, a physical therapist moves and palpates a patient's diseased part, and determines the level of pain and neurological symptoms. Physical therapists flex and extend the joints of patients to classify the degree of decreased ability to exercise and the patient's recovery. This process depends on the reaction force patterns, the joint's range of motion, and the patient's complaints. To learn this technique, students need to experience a variety of symptoms because the reaction force pattern generated by a disordered joint is significantly different for each symptom. However, they do not normally have enough opportunities to experience a variety of symptoms. Furthermore, using students to provide treatment is considered ethically problematic because they do not have the qualifications of a physical therapist, even during internship training.

To resolve these problems, the development of training robots that help to train physical therapists has recently been started. Masutani et al. developed a robot that simulates impaired knee joint motion. They simulated the limited motion of an impaired joint, a jackknife phenomenon, along with the rigidity of the muscles and tendons [1]. Kikuchi et al. controlled the knee joint of a patient robot using an MR clutch and DC motor to simulate the high and dynamic forces of disordered joints [2]. Grow et al. compared two types of models to simulate the spasticity of an elbow joint [3]. They attempted to prove that the robot was effective at training students to classify the spasticity.

Some researchers have attempted to realize complex human joint behaviors, which are intrinsically different from the movements made by the uniaxial joints of robots. Takahashi et al. simulated the stretching and shortening of a forearm associated with the extension and flexion of the upper limb by using an oval cam in the joint [4]. Furthermore, a training robot that presented forces in six directions was reported [5]. Morita et al. developed a knee robot that had a rotational joint as well as a joint for extension and flexion [6]. On the other hand, as described in Sec. II, the authors are developing wearable dummy joints to realize a high degree of realism while avoiding the difficulties associated with using a robot to simulate complex human joints. In this framework, an exoskeletal robotic joint is worn by a healthy human, and it simulates the joint resistances caused by motor impairment. Thus far, wearable knee [7] and ankle joint simulators [8] have been prototyped.

The objective of this study was to develop a joint resistance model for spasticity that could be used for patient simulators and to assess the simulated symptoms quantitatively. Spasticity is often caused by stroke, as described in Sec. III-A. Although prior studies have demonstrated the joint resistances associated with spasticity, they have not quantitatively assessed their simulated symptoms in relation to their similarity to those of real patients. This may be because a comparison between the simulated resistances and those obtained from real patients is not always meaningful. The joint resistances of real patients are highly individual, whereas training simulators have to present characteristic or typical joint resistances that can be used as the bases for classifying the symptoms. Such typical symptoms are more valuable for assisting trainees to learn examination techniques. To this end, we used the Modified Ashworth Scale (MAS) [9], which is widely used by medical professionals, including physicians and physical therapists to classify the severity of spasticity on the basis of generalized characteristic joint resistances. As described in Sec. III-A, the severity is evaluated in six stages by following multiple criteria. In this

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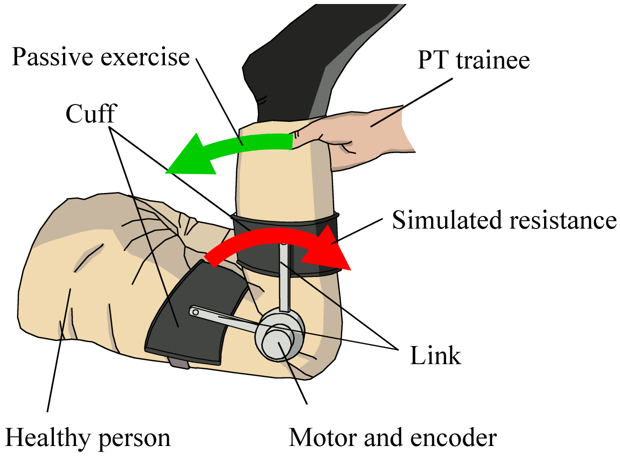

Fig. 1. Conceptual diagram of wearable dummy joint

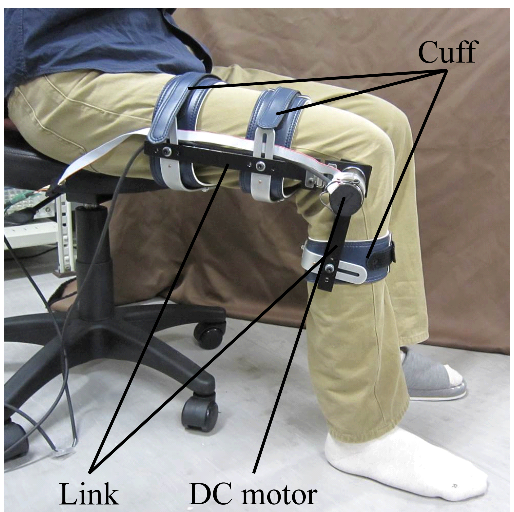

Fig. 2. Wearable dummy joint to simulate knee-related disorders

study, the developed spasticity model was assessed using the MAS to examine whether the model could present a wide variety of severity levels.

II. WEARABLE DUMMY JOINT

We use a wearable dummy robot to simulate the resistances of impaired joints. There are some technical issues to overcome when developing our training robot for rehabilitation. The first issue involves accurately simulating a variety of symptoms. For example, the robot is required to simulate a complex resistance force pattern and the large reaction force caused by contracture. The robot also needs to simulate the trajectory of complex human-joint motions. For example, a human knee joint stretches with extension. Thus, a human joint has a complex trajectory caused by various motions such as the rotation, stretching and shortening associated with flexion and extension. Finally, human-like characteristics are necessary, including the overall appearance, texture of the skin, and conversation with patients. The robot must consider all of these issues.

Fig. 1 shows a conceptual rendering of the dummy knee joint designed to be worn by a healthy student. At educational sites, students practice examination techniques in pairs. One student assumes the role of the patient, and the other practices the manual examinations. The wearable dummy joint was designed to assist in these actual practices. The student who plays the patient wears the dummy joint. Then, the other student grasps their lower thigh and flexes and extends the knee joint. At that time, the "patient" does not voluntarily move but relaxes their muscles, as in an actual manual examination. When the knee joint is moved, the actuator mounted on the dummy applies a resistance force to the lower thigh. The force depends on the simulated symptom and movement of the dummy joint. Therefore, the dummy joint mimics the behavior of a muscle tone abnormality of the knee joint and a disordered knee joint. The learner can practice the manual examination with various postures such as prone and sitting positions, as shown in Figs. 1 and 2, respectively.

Our dummy joints do not have the convolution, stretching and shortening mechanisms possessed by a human knee joint. However, these mechanical differences between a human joint and the dummy joint can be absorbed by human fat or clothes. Therefore, the dummy joint does not prevent these human joint motions. Hence, the trainee can experience the minor rotations and slides inherently possessed by human knee joints. Furthermore, unlike previous dummy robots, human-to-human communication is maintained because the trainee touches a real human leg.

Fig. 2 shows a developed dummy joint. This dummy joint attached to the thigh of a healthy human using two cuffs, with one cuff on the lower leg. As an actuator, a DC motor (RE35, Maxon, stalling torque 949 $\mathrm{mN \cdot m}$), gearhead (1/86), and motor driver (Maxon, 4-Q-DC servo amplifier ADS 50/5, current control mode) were used. The kinetic friction of the gear system was specified as 0.5 $\mathrm{N \cdot m}$, and it was compensated for during the later experiments.

III. SIMULATED SPASTICITY

A. SPASTICITY & MODIFIED ASHWORTH SCALE

Spasticity is a well-known syndrome, most commonly arising after stroke, multiple sclerosis, spinal cord injury, some traumatic brain injuries, and other central nervous system lesions [10]. It is a motor disorder characterized by a velocity-dependent increase in the tonic stretch reflex with exaggerated tendon jerks; the disorder results from hyperexcitability of the stretch reflex, and it is one component of the upper motor neuron syndrome [11], [12]. A study showed that approximately 40% of patients with initial central paresis developed spasticity within six months of suffering a stroke [13]. Disability due to spasticity is a significant health issue for stroke patients. Physical therapists need to precisely understand the severity of spasticity to treat the disability.

TABLE I

MODIFIED ASHWORTH SCALES AS DESCRIBED IN SOURCE ARTICLE [9]

Score	Modified Ashworth Scale
0	No increase in muscle tone
1	Slight increase in muscle tone, manifested by a catch and release or by minimal resistance at the end of the range of motion when the affected part(s) is moved in flexion or extension
1+	Slight increase in muscle tone, manifested by a catch, followed by minimal resistance throughout the remainder (less than half) of the range of movement (ROM)
2	More marked increase in muscle tone through most of the ROM, but affected part(s) easily moved
3	Considerable increase in muscle tone, passive movement difficult
4	Affected part(s) rigid in flexion or extension

As listed in Table I, the Modified Ashworth Scale (MAS) classifies the severity of spasticity into six levels according to the presented symptoms [9]. The MAS provides evaluation criteria for use in clinical settings. These are based on the resistances that physical therapists experience when they passively move patients' joints. At level 1, there is mild muscle tone and the presence of a catch and release if the diseased part is moved passively. Additionally, a slight resistance manifests at the end of the range of motion. When the severity increases to level 2, there is a marked increase in muscle tone through most of the range of motion. However, the affected part can be easily moved. At level 4, the joint is rigid, and the affected part cannot be moved. Medical professionals are in good agreement about these MAS judgments [14].

As described in Table I, it is not only the tonic reflexes but also the limited range of joint motion and the rigidity of the muscles and tendons that provide information about the degree of spasticity. For practical purposes, limits for the range of motion and the rigidity of the muscles and tendons are significant criteria when evaluating the extent of the symptoms. Our dummy joint needed to collectively simulate these criteria.

B. SIMULATED SPASTICITY

Using the MAS, physical therapists classify spasticity on the basis of the degree of muscle tone and the resistance at the end of the range of motion. In addition to joint tonic reflex, our model of spasticity includes resistance due to muscle tone and resistance at the end of the range of motion. Physical therapists commonly apply the MAS on the basis of these symptoms. The following model is based on a uniaxial joint, however, as we stated before, this does not restrict a human joint's motion with multiple degrees of freedom. Subtle rotation or stretching of the human knee accompanied with its flexion are mostly realized because the compliance of the skin or clothes beneath the cuff absorbs minor differences in mechanical structures between the dummy and human limb. We also assume that the knee joint of relaxed healthy wearer is of little friction and its biomechanical factors yield little resistance with the exception being at the end of the motion range where natural impedance of human body is significant. The following impairment model imitates joint resistances mostly at the range where the healthy knee smoothly moves.

Typically, tonic reflexes are defined as resistances characterized by a velocity-dependent increase [11], [12]. Thus, they are expressed as viscosity resistances against joint angular velocity. The resistance torque due to the tonic reflex is constant until an angular velocity ω_0. When the angular velocity of the knee joint reaches ω_0, the torque increases in proportion to the angular velocity. Denoting the joint angle by $\theta(t)$ and using a constant torque τ_0 and coefficient of viscosity c, the angular velocity-dependent resistance torque $\tau_c(t)$ is expressed as

$$\tau_c(t) = \begin{cases} \tau_0 + c(|\dot{\theta}(t)| - \omega_0) & (|\dot{\theta}(t)| > \omega_0) \\ \tau_0 & (|\dot{\theta}(t)| \leq \omega_0). \end{cases} \tag{1}$$

Here, τ_0 indicates the constant resistance present throughout the range of motion, i.e., rigidity.

According to the MAS, a limit for the range of motion manifests from level 1. At level 1+, there is a resistance over nearly half of the range of motion. When the knee joint's range of motion is $0 < \theta(t) < \theta_{max}$ (extension position is 0), using modulus of elasticity k, the resistance torque at the end of the range of motion $\tau_e(t)$ is expressed as

$$\tau_e(t) = \begin{cases} -k(\theta(t) - \theta_e) & (0 \leq \theta(t) < \theta_e) \\ 0 & (\theta_e \leq \theta(t) < \theta_{max} - \theta_e) \\ k(\theta(t) - \theta_{max} + \theta_e) & (\theta_{max} - \theta_e \leq \theta(t) \leq \theta_{max}). \end{cases} \tag{2}$$

Here, θ_e denotes the angle at which the joint motion starts being limited and depends on the severity of spasticity.

The resistance torque around the knee joint due to spasticity $\tau(t)$ is expressed as

$$\tau(t) = \tau_c(t) + \tau_e(t). \tag{3}$$

In this model, the parameters characterized by the severity are τ_0, ω_0, c, θ_e, and k. We specified these parameters with the assistance of a physical therapist on the basis of a characteristic resistance for each level and the joint angle at which the resistance began to increase.

IV. EXPERIMENT

Two experienced physical therapists were invited to manually assess the severity of simulated spasticity using the MAS. The objective of this experiment was to determine whether the developed model and wearable dummy joint could present the six graded severity levels of the MAS.

One goal of our research is to develop a patient dummy that can be used to assist a physical therapy student to learn

Fig. 3. Example of experimental setup

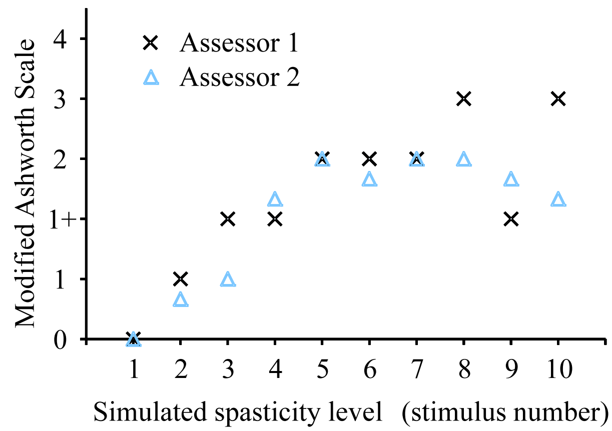

Fig. 4. Modified Ashworth Scale assigned to simulated knee spasticity

manual examination techniques, including the judgment of the severity of spasticity. Such an ability to accurately assess the spasticity in joints is of crucial importance not only in the practice of providing proper care but also for communication among therapists. This experiment was part of a pilot study to establish patient simulators for the accurate classification of spasticity.

A. TASK

A single healthy person wore the dummy knee joint on his right leg and lay down in a relaxed manner. The assessor held and moved the wearer's leg and experienced joint resistance torques caused by the passive extension of the knee joint (Fig. 3). The assessor was allowed to freely test the joint torques within the limited time, i.e. 1 min/trial. The assessor was told that the dummy joint simulated the knee joint of a spasticity patient with disordered flexor or extensor muscles. The judgment was made on the basis of the six MAS levels listed in Table I.

B. PARAMETER SETS OF SIMULATED SPASTICITY

As previously described, the simulated spasticity was characterized by multiple parameters. For a simulated symptom with the highest severity, τ_0, ω_0, c, θ_e, and k were set to 3.0 $\mathrm{N \cdot m}$, 0 rad/s, $9/\pi$ $\mathrm{Nm \cdot s/rad}$, $16\pi/45$ rad, and $54/5\pi$ $\mathrm{N \cdot m/rad}$, respectively. For a simulated symptom with the lowest severity, i.e., a healthy knee, these parameters were 0 $\mathrm{N \cdot m}$, $\pi/2$ rad/s, 0 $\mathrm{Nm \cdot s/rad}$, 0 rad, and 0 $\mathrm{N \cdot m/rad}$, respectively. We used 10 stimulus levels whose individual parameters were linearly changed between the above maximum and minimum values, as listed in Table II. The stimuli with the lowest and highest parameter sets were referred to as stimuli 1 and 10, respectively. The assessor was presented with 10 stimuli in a random order, with each being presented only once.

C. RESULTS

Fig. 4 shows the MAS levels assigned to each simulated symptom in the experiment. The simulated symptoms were classified as MAS levels 0–3 in the results of assessor 1. Only stimulus 1 (no simulated resistances) was classified as level 0, whereas the other stimuli were judged to be impaired. Stimuli 2, 3, and 4 were classified as level 1 or 1+, indicating moderate severity. Stimuli 5–7 were judged to be level 2, and level 3 was assigned to stimuli 8 and 10. As a general trend, the MAS levels increased as the severity of the simulated symptoms rose, with the exception of stimulus 9. It is speculated that this exception was observed because of the aftereffects of the previous stimulus.

Level 4 was not assigned to any simulated symptoms. Level 4 is the most severe class, at which the knee joint can hardly be moved. Thus, to simulate this level, the simulator simply needs to exert torques greater than those used in the experiment.

In the results of assessor 2, the simulated symptoms were classified as MAS levels 0–2. Though, the trend of their results was similar to that for assessor 1.

According to the introspective reports of the assessors, the limitations of the range of knee motion played an effective role in their ratings for the symptoms. Such information was especially used of as a judgment criterion between levels 2 and 3. The simulated spasticity stimuli with significant perceived joint motion limitations were classified as level 3. In contrast, the velocity-dependent resistances might become a cue to judge moderate classes. The effects of other parameters of the simulated spasticity on the MAS assessments were intriguing and should be clarified. Nonetheless, from these results, it is highly likely that tuning the parameters of our spasticity model will make it possible to represent knee spasticity with various degrees of severity. Although just two assessors were invited to participate in this experiment, if similar results are reported from multiple assessors, the consistency between the simulated symptoms and their clinical experiences would be confirmed.

V. DISCUSSION

The universal goal of a spasticity simulator is to present resistive torques caused by general spasticity joints. Whereas our method is model-based, some may consider that an

TABLE II

PARAMETER SETS OF SIMULATED SPASTICITY

	Stimulus number									
	1	2	3	4	5	6	7	8	9	10
τ_0	0	0.3	0.7	1.0	1.3	1.7	2.0	2.3	2.7	3.0
ω_0	$\pi/2$	$4\pi/9$	$7\pi/18$	$\pi/3$	$5\pi/18$	$2\pi/9$	$\pi/6$	$\pi/9$	$\pi/18$	0
c	0	$1/\pi$	$2/\pi$	$3/\pi$	$4/\pi$	$5/\pi$	$6/\pi$	$7/\pi$	$8/\pi$	$9/\pi$
θ_e	0	$16\pi/405$	$32\pi/405$	$16\pi/135$	$64\pi/405$	$16\pi/81$	$32\pi/135$	$112\pi/405$	$128\pi/405$	$16\pi/45$
k	0	$6/5\pi$	$12/5\pi$	$18/5\pi$	$24/5\pi$	$6/\pi$	$36/5\pi$	$42/5\pi$	$48/5\pi$	$54/5\pi$

approach based on recording and precisely reproducing actual values might be more appropriate for presenting the joint resistances of patients. In the latter approach, the joint resistance torques of real patients are recorded and presented as precisely as possible. However, for training purposes, such an approach involves several flaws.

First, the data from actual patients encompass substantial individual differences. The representation of such differences with high fidelity is not valuable for patient simulators, through which trainees are expected to experience general symptoms.

Second, patients rarely develop single symptoms. Those with motor impairments suffer from multiple symptoms. Hence, the resistance torques recorded from patients are collectively caused by co-occurring or mixed symptoms. In the educational environment, trainees need to study how to discriminate or specify symptoms. The patient dummies are required to simulate individual symptoms independently. Our spasticity model tunes the severity of respective symptoms. This allows the trainers to synthesize simulated symptoms according to the educational stage. For example, they can exaggerate the influences of certain symptoms and mix or separate the resistance torques caused by multiple symptoms.

For these reasons, in the case of patient dummies for training purposes, model-based simulations are more effective than the precise representation of recorded data.

VI. CONCLUSION

This article developed a simulated spasticity model for the robotic patient dummies that are used for training physical therapists. The model produced representative joint resistance torques observed when the therapist manually tested knee joints with spasticity. In addition to the resistances caused by the tonic reflex, which is considered to be a typical symptom of spasticity, those from constant muscle tone and a limit of joint motion range were also simulated. Although these symptoms are collaterally developed with spasticity, early studies on simulated spasticity did not focus on the combination of these symptoms. Thus far, some early studies have simulated the tonic reflex using robotic dummies [2], [3]. However, the simulated symptoms or resistance torques have yet to be assessed in terms of their similarity to those of real patients. The MAS, which is a severity scale for spasticity based on the haptic sensations perceived by physicians or therapists, allowed us to validate the spasticity model in accordance with the experience of medical professionals.

We implemented the spasticity model using a wearable dummy joint that enabled us to simulate the behavior of impaired joints while maintaining good human likelihood. Two physical therapists assessed our simulated spasticity levels, and the results indicated that the simulated model was capable of presenting symptoms covering levels 0 to 3 of the MAS. In the wake of this feasibility study, we will continue to improve the spasticity model on the basis of assessments from additional therapists.

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