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Wearable Dummy to Simulate Equinovarus for Training of Physical Therapists

Hiroshi Okumura[1], Shogo Okamoto[1], Shun Ishikawa[1], Yasuhiro Akiyama[1], Kaoru Isogai[2], Yuji Hirano [3], and Yoji Yamada[1]

[1]Department of Mechanical Engineering and Science, Nagoya University, Nagoya, Japan
[2]Department of Physical Therapy, Tokoha University, Hamamatsu, Japan
[3]Department of Rehabilitation, Yokkaichi Municipal Hospital, Yokkaichi, Japan

Abstract: It is indispensable for physical therapists in training to experience various symptoms during their period of education; however, such chances are limited in educational institutions. We developed a prototype of a wearable dummy-robot system to simulate equinovarus, which is a typical disorder of the foot caused by stroke, to enhance the training of physical therapists (PTs). This wearable dummy system makes it possible to simulate joint disorders, while allowing the trainees to learn about the complex joint movements of humans, such as those observed in human feet. The dummy system deforms the foot of a healthy wearer using a wire mechanism so that the resultant foot posture and resistance force required for therapeutic operations resemble those of typical equinovarus patients. The resistance forces felt by the trainees can be tuned by changing the endpoint of the wire. From sensory evaluations involving PTs, it was concluded that with potential future improvements, the dummy simulator will become an effective training tool to aid physical therapy students.

Keywords: Wearable dummy, Equinovarus, Physical therapy.

1. INTRODUCTION

Physical therapists (PT) play an important role in treating patients whose motor functions are impaired as a result of disorders such as stroke and arthritis. Because patients' symptoms substantially depend on individuals and their types of impairments, physical therapy students need to experience various symptoms to master therapy techniques. However, students rarely have the chance to experience such a variety of symptoms in training institutions. Even during internship training, it is considered ethically problematic for unqualified trainees to treat patients. Therefore, some research groups have started to develop dummy robots that simulate patients' symptoms to support the education of PTs.

Masutani et al. developed a robotic leg that simulates impaired knee joints [1]. The simulated impairments included a motion-limited joint, jackknife phenomenon, and articular rigidity. They also focused on its appearance by forming bone features and covering the robot with skin-like materials. Kikuchi et al. simulated the spastic movements of a foot joint using a leg and foot robot [2]. Grow et al. compared and validated two representative spasticity models using a robotic joint [3]. In these studies, they simply modeled human joints as uniaxial joints. However, human joint movement involves multiple degrees of freedom. Takahashi et al. simulated the stretch and contraction of a forearm accompanied by the extension and flexion of an upper limb using an oval cam in a robotic joint [4]. Oki Electric Industry Co, Ltd, proposed a robot with six degrees of freedom for the trainings of PTs [5]. Physical therapy students can learn about the typical dynamic resistances and motions of impaired joints using these dummy robots.

One of the major topics in the development of such robot systems is how to make them resemble human limbs. Ishikawa et al. proposed a framework for a wearable dummy robot to simulate joint disabilities [6]. Within this framework, a healthy person wears an exoskeleton-type robot, which simulates the behaviors of joint impairment. As described in section 3.1, the strength of this approach is that it simulates symptoms as it allows the students to experience the complex trajectory of human joint motion and the characteristics of the skin and bone.

In this study, we simulated foot equinovarus using a dummy robot. Equinovarus is common and typical symptom of patients suffering from hemiplegia or spasticity as a result of stroke, and PTs often face this in the field. At most 40% of stroke patients develop spasticity [7, 8]. If the equinovarus progresses, the patient suffers from a gait disorder and a severe decline in his/her quality of life. Therefore, PTs give importance to improving in the symptoms of equinovarus. Thus far, in earlier studies, the dummy robots have simulated symptoms such as contracture, rigidity, a limited range of joint motion, and clonus. Despite its importance, there has been a hesitancy in previous studies to use dummy robots to simulate equinovarus. This may be because the behaviors of the human foot joint are overly complex and difficult to simulate using a robot, as described in section 2.1.

The objective of this study was to verify the feasibility of using a wearable dummy system to simulate equinovarus for the training of PTs. Because the complex foot joint movements are accompanied by equinovarus, it is difficult to simulate these using robotic joints. On the other hand, the wearable dummy system is potentially able to realize such complex joint motions. The

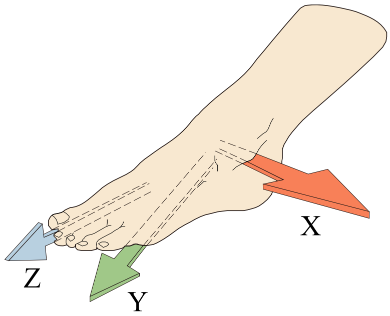


Fig. 1 Three principle axes of joint complex.

Fig. 2 Equinovarus. Left: disordered. Right: normal.

dummy system for equinovarus has some design parameters. We validated the effects of these parameters on the basis of physical models and experiments. Furthermore, we sought ways to improve the wearable dummy based on the introspective reports of PTs.

2. EQUINOVARUS TARGETED FOR SIMULATION

2.1 Foot joint regarded as joint complex

The complex foot joint movements are accompanied by equinovarus because many joints exist in the foot joint. However, if we regard them as a joint complex, we can treat the foot joint as one joint having three degrees of flexibility [9]. Fig. 1 shows how the three principle axes of this joint complex cross each other in a medial position of both malleoli. The X-axis passes through both malleoli, and corresponds to an axis of the talocrural joint. This axis conditions the plantar or dorsal flexion movement in the sagittal plane. The Y axis is along the lower leg, and conditions the adduction or abduction movement in the horizontal plane. The Z axis passes from the malleoli to the tips of the toes in the sagittal plane. This axis conditions the supination or pronation movement by directing the sole toward the inside or outside. The movements around these three principle axes are not independent of each other. Therefore, movements around two principle axes are accompanied by movement around the other principle axis. For example, a supination movement and slight plantar flexion movement are is accompanied by an adduction movement.

2.2 Pathology of equinovarus

Equinovarus is a foot deformity that affects hemiplegia patients. Fig. 2 shows both of the feet of patient suffering from equinovarus. The disordered foot takes adduction, supination, and plantar flexion positions primarily as a result of shortening or hypertonia of the triceps surae muscle, tibialis posterior muscle, flexor digitorum longus muscle, and flexor hallucis longus muscle. In the acute phase, the intensity of the foot deformity is mild, and equinovarus is accompanied by spasticity. However, in the chronic phase, the intensity of the deformity increases, and equinovarus is accompanied by contracture, where contracture means a condition where the range of joint motion is restricted. Therefore, it is difficult to restore a foot to the standard position, which is the position of the foot joint when a human assumes a standing position. Whereas PTs typically treat equinovarus by manually stretching the disordered feet, robotic rehabilitation or treatment devices for equinovarus have been studied with bright prospects [10, 11].

3. WEARABLE DUMMY TO SIMULATE EQUINOVARUS

3.1 Advantages of wearable dummy

A patient dummy for training PTs requires the following functions. First, the joint resistance force and reaction force patterns that PTs feel when they move the affected body parts of patients should be accurate. Second, it should have human-like characteristics, such as the skin, bone, and weight of a human body, to imitate a real human. Finally, it is necessary to simulate complex joint movements which have multiple degrees of freedom. Any dummy used for training should balance these functions. The foot of a patient suffering with equinovarus takes an adduction, supination, and plantar flexion position. Therefore, we anticipated that complex devices would be needed to simulate equinovarus in joint movements with multiple degrees of freedom. Thus, we proposed the development of a wearable dummy. This wearable dummy is an exoskeleton robot worn by a healthy person. It imitates the resistance forces of disabled joints or joint behaviors caused by various symptoms. The wearable dummy allows complex joint movements, such as a supination movement and slight plantar flexion movement, accompanied by adduction movement. Moreover, it has human-like characteristics, such as the feel of skin, bone, weight, and the shape of a human body. Therefore, it can produce the resistance force symptoms of equinovarus and spasticity using actuators, while maintaining human characteristics.

3.2 Description of wearable dummy to simulate equinovarus

The wearable dummy deforms the foot of a wearer in an equinovarus position. Moreover, it presents the reaction force pattern of equinovarus to a trainee performing an manual examination. Fig. 3 shows a manual examination of an equinovarus patient. When a PT performs a

Fig. 3 Manual examination of equinovarus patient.

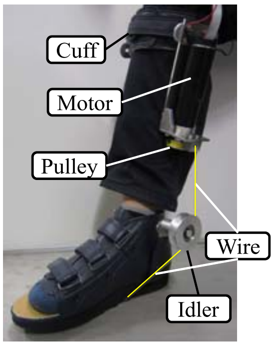


Fig. 4 Wearable dummy system for simulating equinovarus.

Fig. 5 Simulated equinovarus: Foot transformed by wearable dummy from different view points.

manual examination against the foot of a patient suffering from equinovarus, they apply force to it in the abduction, pronation, and dorsal flexion directions. The hands of the PT perceive resistance forces in the adduction, supination, and plantar flexion directions from the foot of the patient. The wearable dummy produces these resistance forces for the trainee performing the examination.

3.3 Mechanism of wearable dummy to simulate equinovarus

3.3.1 Mechanism forcing foot into posture of equinovarus position

Fig. 4 shows a prototype of the wearable dummy we developed. This wearable dummy was composed of a shoe, and a cuff attached to the lower part of the knee joint. A DC motor (Maxon motor, RE35, maximum continuous torque 97.2 mNm, torque constant 38.8 mNm/A) with a gear head (Maxon motor, GP 32 HP, gear ratio 23:1) was attached to the cuff that was designed carefully such that it would not cause any pain to the wearer. We used a servo amplifier (Maxon motor, 4-Q-DC ADS 50/5)

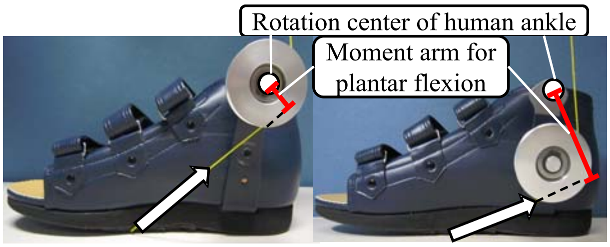
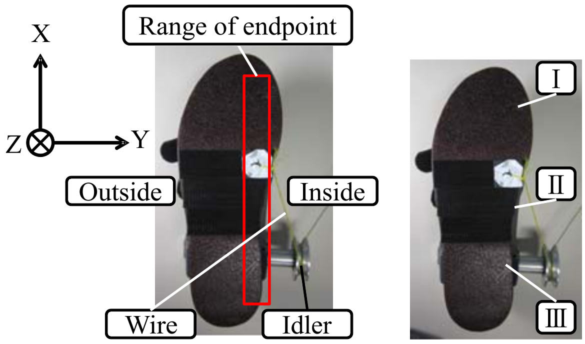


Fig. 6 Change in distance between rotation center of human ankle and idler.



(a) Range of endpoint (b) Endpoints

Fig. 7 Sole of wearable device. The end point of the wire can be adjusted within the red rectangle.

in the current control mode as the driver for the DC motor. A wire extended from the sole went through the idler, and was wound by a DC motor. We made a wire run along the tibialis posterior muscle in order to simulate equinovarus accompanied by the contracture and hypertonia of the tibialis posterior muscle. Fig. 5 shows a foot transformed into the equinovarus position by the wearable dummy.

3.3.2 Mechanism for adjusting equinovarus

The degree of deformity and resistance forces felt by PTs are diverse and correspond to the acuteness of the equinovarus symptoms. Therefore, the wearable dummy was equipped with a mechanism for adjusting the degree of deformity and resistance force felt by trainees in order to simulate equinovarus more faithfully. There are three types of parameters that could be adjusted. These parameters were the tension by the motor, positions of the idler, and endpoints of the wire. The torque applied to the foot was changed by changing the tension of the motor, which caused a change in the magnitude of the resistance force felt by trainees in the standard position.

Fig. 6 shows the change in the moment arm between the rotation center of the plantar flexion and tension applied to a foot by changing the position of an idler. This produced a change in the magnitude of the resistance force felt by the trainees in the direction of the plantar flexion in the standard position. When the idler position was high, due to the short moment arm, the plantar flexion torque applied to the foot was small. In contrast, when the idler position was low, the long moment arm produced the large flexion torque.

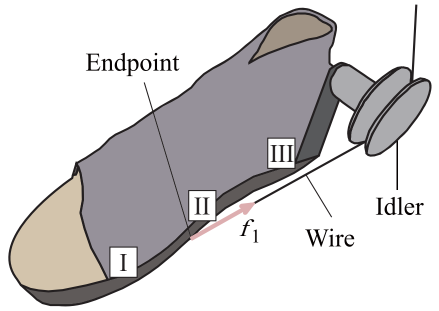
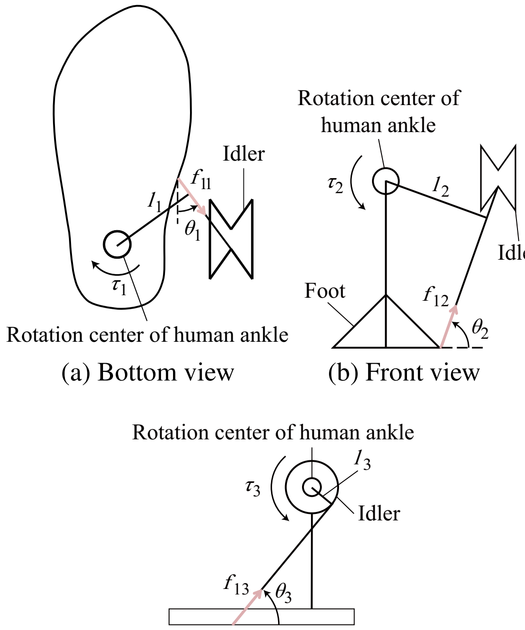


Fig. 8 Tension applied to sole (endpoints of wire).



(a) Bottom view (b) Front view

(c) Side view

Fig. 9 Trihedral figures of wearable dummy system

The position of the endpoint of the wire could be varied within the range shown as a red rectangle in Fig. 7(a). The angle between the shoe and the wire changed with the endpoint. Accordingly, the direction of tension f_1 represented in Fig. 8 changed, and the resistance force felt by the trainees in the adduction and supination direction changed.

Fig. 9 shows a physical model of the wearable dummy that explains the principle behind the changes in the resistance forces in the adduction, supination, and planter flexion directions. Fig. 9 shows the projection of f_1 from the bottom, front, and side views, where f_{11}, f_{12}, and f_{13} represent f_1 on these planes. l_1, l_2, and l_3 are the moment arms between the rotation center of the human ankle and f_{11}, f_{12}, and f_{13}, respectively. θ_1, θ_2, and θ_3 are the angles between the shoe and f_{11}, f_{12}, and f_{13}, respectively. τ_1, τ_2, and τ_3 are the adduction, supination, and plantar flexion torques and are expressed as

$$\begin{aligned}\tau_1 &= f_{11}l_1 \\ &= \frac{\cos\theta_2}{\sqrt{1-\cos^2\theta_1\sin^2\theta_2}}f_1 l_1 \qquad (1)\\ \tau_2 &= f_{12}l_2 \\ &= \frac{\sin\theta_1}{\sqrt{1-\cos^2\theta_1\sin^2\theta_2}}f_1 l_2 \qquad (2)\\ \tau_3 &= f_{13}l_3 \\ &= \frac{\sin\theta_1}{\sqrt{1-\cos^2\theta_1\cos^2\theta_3}}f_1 l_3, \qquad (3)\end{aligned}$$

respectively. We measured θ_1–θ_3 and l_1–l_3 when the endpoints of the wire were at I–III, and calculated τ_1–τ_3 by (1) to (3). These values are summarized in Table 1. The torques were calculated with f_1 being 8.3 N. τ_1 becomes larger as the endpoint shifts from III to I. In other words, the adduction torque applied to the foot increases as the endpoint shifts from III to I. By contrast, τ_2 becomes smaller as the endpoint shifts from III to I. Hence, the supination torque is highest when the endpoint is at III, and exhibits smaller values for II and I. Planter flexion torque τ_3 is small under each condition because l_3 is small. To increase τ_3, the position of the idler is lowered.

Table 1 Physical parameters for each endpoint. Angles, link lengths, forces, and torques at basic foot position.

	Endpoint of wire		
	I	II	III
θ_1 [rad]	0.25	0.55	1.13
θ_2 [rad]	1.11	1.05	1.03
θ_3 [rad]	0.47	0.81	1.30
l_1 [mm]	93	68	23
l_2 [mm]	89.4	87.8	87.5
l_3 [mm]	16		
f_1 [N]	8.3		
τ_1 [Nm]	0.69	0.42	0.11
τ_2 [Nm]	0.37	0.56	0.71
τ_3 [Nm]	0.065	0.09	0.12

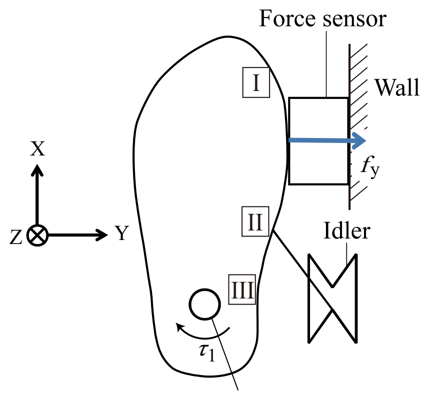


Fig. 10 Measurement of adduction torque or force.

3.4 Measurement of adduction torque using force sensor

We measured the adduction torques or forces caused by the dummy system using different endpoints. Measuring the torques applied to the foot on each principle axis is difficult, partly because the three axial motions of the foot are not independent of each other. As a beginning point, we focused on the adduction force under the basic ankle

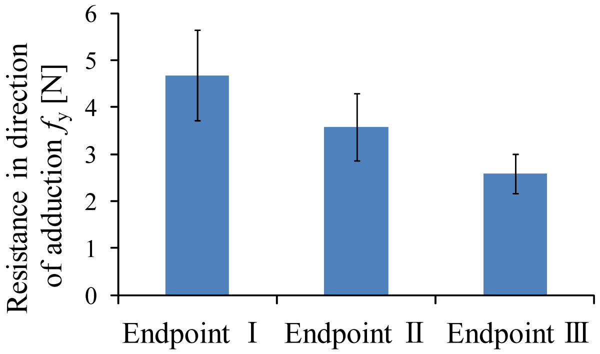


Fig. 11 Averages and standard deviations of resistance forces in direction of adduction. Adduction forces can be varied by adjusting the wire endpoint.

Table 2 Comparison of τ_1 (adduction torque) values between physical model and measurements.

	Endpoint		
	I	II	III
Model [Nm]	0.69	0.42	0.11
Measurement [Nm]	0.63	0.48	0.35

posture. The adduction force is mainly produced by τ_1. As shown in Fig. 10, a force sensor (MINI, BL-Autotech Inc., Kobe, Japan) was fixed to the inner side of the foot and used to measure the Y-axial forces (f_y) caused by the wire tension. The force was measured twenty times, with each measurement period being approximately 1 s. The final values were computed as the averages of all the trials. During the measurement, the DC motor generated a tension of 8.3 N, and the wearer of the dummy system stayed relaxed.

The average forces were 4.68 ± 0.96, 3.58 ± 0.72, and 2.58 ± 0.42 N for the endpoints of I, II, and III, respectively. The average adduction forces were then transformed into the torques around the rotation center of the ankle for comparison with the values computed from the model in the previous section. As shown in Fig. 11, the average adduction torques were 0.62, 0.48, and 0.35 Nm for the endpoints of I, II, and III, respectively. Table 2 shows a comparison of these torques between the measurements and physical model. These values did not exactly match, possibly because of the differences in the conditions. In particular, the positional relationships between the rotation center of the human ankle and the idler might be the major source of the error. In the physical model, their X and Z coordinates were supposed to be equal; however, they were not equal during the measurement. Nonetheless, the ordinal relationships among the three conditions matched between the model and measurements. The measured forces decreased as the endpoint moved from the toe (I) to the heel (III).

4. FREE DESCRIPTION BY PHYSICAL THERAPISTS

Five PTs experienced the resistance forces presented by the wearable dummy and freely gave comments. Here, we aimed to acquire subjective and descriptive opinions, which tend to be missed in objective evaluation tasks. They performed manual examinations, as shown in Fig. 3, against a healthy person wearing the dummy. The wearer sat in a chair. The endpoint and motor's torque were varied among I–III and 3.4–11 N, respectively. The following opinions were highlighted.

Two PTs appreciated that the resistance forces simulated by the current dummy system were similar to those of a typical equinovarus patient. The other PTs pointed out that larger resistance forces were required to simulate equinovarus in the chronic phase with muscle contracture. Such large forces can be simply realized by using a motor with larger outputs. Furthermore, two of the five PTs stated that the individual differences between equinovarus patients were well represented by changing the endpoints of the wire.

The resistance forces felt by the PTs were approximately constant regardless of the foot joint angle because the DC motor installed on the wearable dummy generated constant torques. However, the resistance forces that the PTs feel from the patients are naturally proportional to the degree of dorsal flexion in the foot. They suggested that the implementation of these proportional changes in the resistance forces would lead to a more realistic simulation. It should be noted that such control of the motor torque according to the joint angle should be introduced in the future. Furthermore, the effects of spasticity will be realized. When spasticity is combined with equinovarus, the resistance forces perceived by PTs depend on the joint velocity [12]. Three PTs commented that the simulation of spasticity would be beneficial for the education of trainees.

In the acute and recovery phases of equinovarus, as a PT treats the foot of a patient with equinovarus, its range of joint motion is extended. Such changes in equinovarus over time were called for by two PTs.

5. CONCLUSION

In this article, we reported a prototype wearable dummy system that simulates equinovarus. Earlier studies hesitated to use a dummy robot to simulate such symptoms, mainly because of the complex behaviors of the human foot joint. A wearable-type dummy allowed us to simulate equinovarus in feet while maintaining the intrinsic movements of human foot joints. The simulator worn by a healthy person used a DC-motor driven string attached to his/her foot to transform it. Consequently, the foot was constrained in an equinovarus position. A few of the parameters of the dummy system were adjustable, which allowed the simulated foot to represent various levels of severity or individual differences between equinovarus patients. For example, the adduction torque could be varied as much as two fold by changing the wire's endpoint in the sole. For the assessment of the system, physical therapists experienced and evaluated the simulated equinovarus using several combinations for the endpoint of the wire and its tension. They felt that the dynamic control of the string tension would provide a better simulation. We expect that such an improvement will realize a more effective dummy system in the future.

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