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Skin-Fat-Muscle Urethane Model for Palpation for Muscle Disorders

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Abstract— **Rehabilitation therapists are required to palpate human muscles and to correctly judge whether the hardness of tissues is abnormal or not. We developed artificial urethane models of muscles for educational purposes. Most of the earlier studies and commercial products addressed tumors caused by internal diseases. We produced several types of urethane models with different layered structures, and with fabric sheets inserted between the layers, after the measurement of the stress-strain characteristics of the skin, fat, and muscle tissues of the human gluteal region. Furthermore, 10 therapists subjectively evaluated each model concerning its similarities to the actual human gluteal region. As a result, a model that exhibited the most similar mechanical and haptic sensational properties to the actual tissue was specified. Our methods of measurement and the design of the urethane model, which includes multiple urethane layers of different hardness and fabric sheets, allowed us to create human-like muscle tissue models for palpation.**

I. INTRODUCTION

The muscles of a relaxed healthy person slightly contract, and retain their normal rigidity. However, in muscles affected by some diseases, the rigidity exceeds the range of that of a healthy muscle. For example, typically, the muscles of stroke survivors gradually harden over time. In contrast, with damages to peripheral nerves, the muscles innervated by those nerves become softer. Furthermore, palpable bands or nodules exist in the muscles of patients with myofascial pain syndrome. During physical rehabilitation, these muscular abnormalities are judged in order to determine appropriate treatment measures. Therefore, clinicians, such as physicians and physical therapists, need to accurately judge the unusual hardness of muscles to provide their patients with effective therapy.

To judge muscle hardness in the clinic, the muscles are manually palpated. To master the manual palpation technique, clinicians need long-term training during which they repeatedly practice the palpation maneuver. Unfortunately, trainees at educational institutes scarcely have opportunities to palpate the muscles of actual patients. An effective solution for the lack of such an opportunity is the use of artificial dummy muscles for training in palpation. Thus far, most of the commercially available dummies of human body tissues for the training in palpation [1], [2] and those used in studies of human palpation techniques [3], [4], [5], [6], [7] are for internal tumors such as breast and prostate cancers. Muscle and fat substitutes with well-replicated appearances are also in commercial use [8]; however, their mechanical similarities to actual human tissues are unknown. Thus far, there have been no effective muscle models for aiding the training in muscle palpation for clinical purposes.

Because of the layered structure of human tissues, the muscles are palpated through the skin and fat tissues. Fat that accounts for the large part of subcutaneous tissues is compressed by the examiner's hands or fingers when the hardness of the muscles that lie deep in the tissue is investigated. Hence, a tissue model for the training in muscle palpation should also consist of dermal and subcutaneous layers. Furthermore, clinicians use a wide range of compressive forces to palpate for abnormal hardness in the superficial and deep parts of the muscle tissue. Hence, the hardness of the tissue model should resemble that of the actual human tissue under the wide range of compressive forces that are used for clinical palpation.

In this study, we developed a skin-fat-muscle urethane model that can be used for the training in palpation for muscle hardness disorders. For this purpose, we measured the hardness of the healthy subcutaneous and muscle tissues of the human gluteal region. We then prototyped eight types of layered urethane models. Finally, practicing therapists evaluated these urethane models concerning their similarities to the hardness of actual human tissues perceived during palpation. This study was conducted with the approval of the ethical committee of Tokoha University (registration no. 2014-015H).

II. MEASUREMENT OF HARDNESS OF SUBCUTANEOUS AND MUSCLE TISSUES

Very few *in vivo* data on the relations between the pressure and deformation of skin-fat and muscle tissues are available. Then et al. presented one example of the force-displacement curves of human gluteal skin-fat and muscle tissues by using a magnetic resonance imaging device [9]. Such stress-strain curves are needed to compare the mechanical characteristics between the actual human tissues and artificial tissue models. We combined the use of a compression testing machine and an ultrasound echo to observe the thickness changes of human skin-fat and muscle tissues under pressure, and obtained their stress-strain characteristics.

A. Methods

1) Participants: Two male participants whose ages and body mass indices were 21 years and 16.0–18.2, respectively, participated in this measurement. None of them claimed any muscle disorders of the buttocks.

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Fig. 1. Ultrasonic probe installed on the loading equipment and bed setting for the measurement of the hardness of human gluteal tissues.

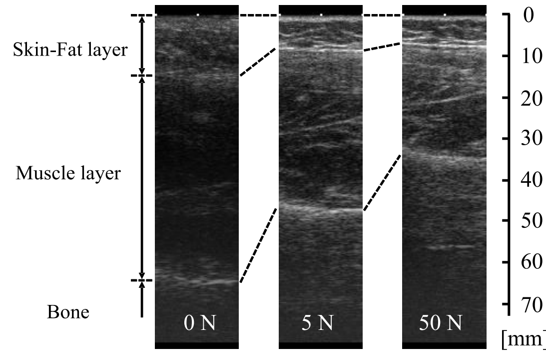

Fig. 2. Representative ultrasonic images of the skin, fat, and muscle layers of the human hip. Each image was taken when the hip surface was pressed by the probe with a compressive force value of 0, 5, or 50 N.

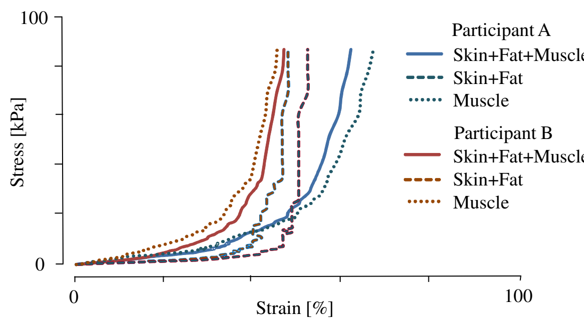

Fig. 3. Stress-strain curves of hip tissues for two participants.

2) Experimental setup: The probe of an ultrasound imaging scanner (NEMIO SSA-550A; Toshiba Medical Systems Corp., Japan) was installed on the compression testing machine (SV-52NA; Imada Seisakusho Co., Ltd., Japan) by using a mechanical fixture. The surface area, which could come in contact with the skin, of the ultrasound probe was 576 mm^2 (12 mm $\times$ 48 mm).

3) Body part to be tested and setup for positioning of subjects: The gluteal region was selected partly because it is sufficiently larger than the size of the ultrasound probe. Furthermore, this part can be easily tested because the pelvic bone supports the gluteal muscles on a flat face during an indentation test. Each subject laid face down on a bed that was inclined 50° as shown in Fig. 1. This setup allowed us to horizontally direct the outer surface of the pelvic bone of the subject.

4) Procedures of the indentation test: The probe of the ultrasound image scanner was moved to push the gluteal region of the subject on the bed. The probe was moved at 100 mm/min until the indentation force reached the target force value. The ultrasound images were then recorded. This process was repeated for each of the target force values that ranged from 0 to 50 N. The target force values were incremented by 0.2, 0.5, 1, and 5 N in the range of 0–5, 5–10, 5–20, and 20–50 N, respectively.

5) Analysis: As shown in Fig. 2, the ultrasound images provided distinguishable borderlines among the skin-fat and muscle tissues and bone. The thicknesses of the skin-fat and muscle layers were measured along the indentation axis at each loading step.

B. Results

The net deformations of the skin-fat and muscle layers were compared with the undeformed initial thickness of each layer. The initial thickness of the skin-fat and muscle layers were, respectively, 17 mm and 48 mm for participant A and 15 mm and 49 mm for participant B. By using the indentations observed through the ultrasound images, the stress-strain curves of the entire gluteal tissues and each of the skin-fat and muscle tissues were obtained as shown in Fig. 3.

The gluteal tissues exhibited significant nonlinearity. The strain rapidly increased until around the stress of 10 kPa. The maximum strain of the entire tissue was 62% and 47%, respectively, for participants A and B when the stress reached 87 kPa. The skin-fat layer exhibited higher nonlinearity than the entire tissue including skin, fat, and muscles. The strain of the skin-fat layer was 48% and 52% for each of the two participants when the stress reached 87 kPa, which indicates that these tissues are compressed to half the initial thickness under the pressing forces of manual palpation. The muscle layer exhibited more moderate non-linearity than the skin-fat layer. The strain of the muscle layer increased until the stress nearly reached 20 kPa. The maximum strain of the muscle layer was 67% and 45% for each of the two participants when the stress reached 87 kPa. The profiles of these stress-strain curves of human gluteal tissues are similar to those presented by Then et al. [9].

III. Skin-fat-muscle Urethane Models of the Gluteal Region

As previously described, the stress-strain characteristics of the subcutaneous and muscle tissues are nonlinear. As shown in Fig. 4, we measured the stress-strain characteristics of cylinders made of urethane rubber by using the same equipment as described in Sec. II. Each cylinder was made of a unique material, and the height and radius of these cylinders were approximately 40 mm and 50–60 mm, respectively. Cylinders made of soft urethane rubber, such

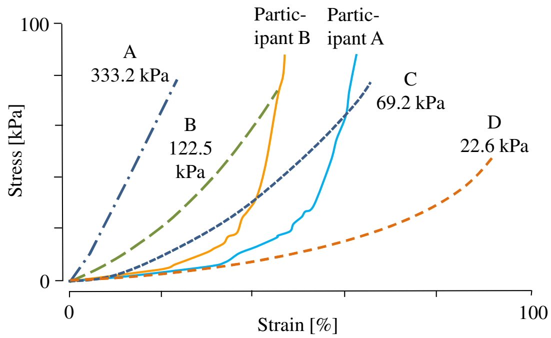

Fig. 4. Stress-strain curves of urethane cylinders and human hips. Urethane cylinders were characterized by using Young's modulus, which was calculated on the basis of the part where the stress-strain characteristics were almost linear. The curves for the two participants are the stress-strain curves of the their entire gluteal tissues.

as C and D in the figure, exhibited large initial strain and nonlinear stress-strain characteristics. In contrast, the stress-strain characteristics of the cylinders made of hard urethane rubber, such as A and B, are more linear. These measurements suggest that the solid model made of a unique material cannot represent the stress-strain characteristics of human body tissues. It is known that a layered rubber structure can realize rheological properties similar to human tissues [10]. We also tuned the stress-strain characteristics of urethane models by laying fabric sheets between layers, which prevented the deformations of the rubber compound. In this section, we prepared several types of urethane models intended to represent the skin-fat-muscle of the human hip by using layered urethane rubbers and fabric sheets, and measured their stress-strain characteristics.

A. Materials

We used urethane rubber (H00-100J; Exseal Corp., Japan), the material hardness of which can be controlled by changing the amount of hardener. As shown in Fig. 5, we laid a cotton sheet that is typically used for shirts between two urethane layers. The stretch ratio of the cotton cloth was 0.13%/N and 0.07%/N in each of the two directions. Furthermore, a sheet of stretchable knit cloth was attached on the top surface of the urethane model. Its stretch ratio was 3.1%/N and 9.9%/N in each of the two directions. This superficial sheet is intended to be the keratin layer of the human skin. The surface of urethane rubber is highly adhesive, and no bonding materials were used to attach these urethane and cloth materials.

B. Cylindrical model

The skin-fat-muscle model was cylindrical in shape, with the height and radius being approximately 65 mm and 60 mm, respectively. The radius of the model was large enough for the assessor to conduct palpation. The height of the model was comparable to the depth of the human gluteal tissue including the skin, fat, and muscle, which were measured as shown in the previous section.

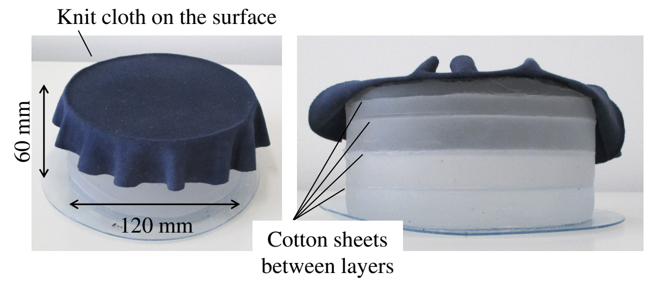

Fig. 5. Example of a cylindrical urethane model. Left: A knit cloth was located on the surface such that the surface hardness resembles the hardness of human skin. Right: A cotton sheet was placed between two urethane layers.

C. Layered structure of prototypes

As shown in Fig. 6, we formed eight types of models that differ in terms of the number of layers and fabric sheets. The top layer of each model except for model 1 corresponds to the subcutaneous layer, and its thickness was 16 mm, which is a representative thickness of the tissues above the muscle. In models 2–7, the top subcutaneous layer and the muscle layer included the hardener at 2.3% and 2.4%, respectively. Model 8 included cotton sheets equally spaced between the rubber layers with different hardener ratios. These eight models were determined on the basis of our experience.

D. Stress-strain curves of urethane models

We measured the stress-strain characteristics of the above-mentioned eight types of models, by using the equipment mentioned in Sec. II. For each model except for models 1 and 2, the stress-strain characteristics of skin-fat and muscle layers were also calculated. For model 2, the boundary of two layers was not captured by the ultrasonic echo; hence, the characteristic of each layer was not identified. As shown in Fig. 7(a), the stress-strain curves of models 4, 5, 7, and 8 were similar to those of the actual gluteal tissues. In contrast, as shown in Fig. 7(b), concerning the skin-fat tissues, models 5, 6, and 7 were similar to the actual gluteal tissues. The superficial layers of models 4 and 8 were extremely softer than the skin-fat tissues of the human hip. Furthermore, as shown in Fig. 7(c), the muscle layers of models 4, 7, and 8 were similar to the muscle of the human hip. The muscle layer of model 5 was much harder than the actual muscle. Collectively considering the similarities of stress-strain characteristics of skin-fat and muscle layers, model 7 was most similar to the human gluteal tissues. Nonetheless, a rapid increase of the stress-strain curve of human skin-fat and muscle layers around the strain of 50% were not fully reproduced even in model 7.

IV. Subjective Evaluation of Similarities between Human Tissues and the Urethane Models

When clinicians palpate muscles, they also apply pressure to lateral directions with their hands and fingers. Hence, the quality of the model is not assured only on the basis of

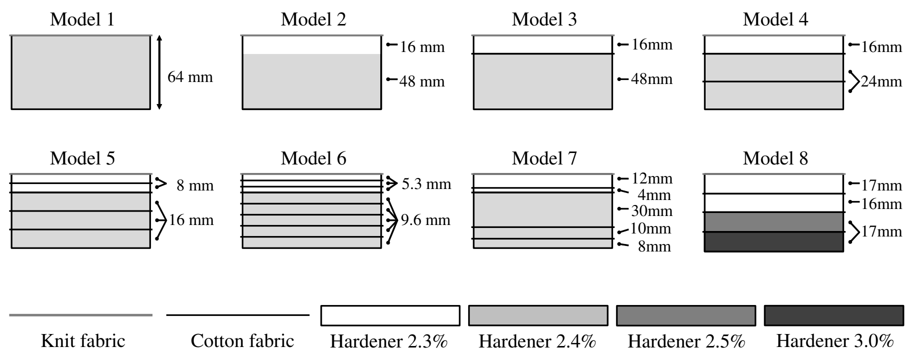

Fig. 6. Eight types of prototypes of skin-fat-muscle models of the human gluteal region.

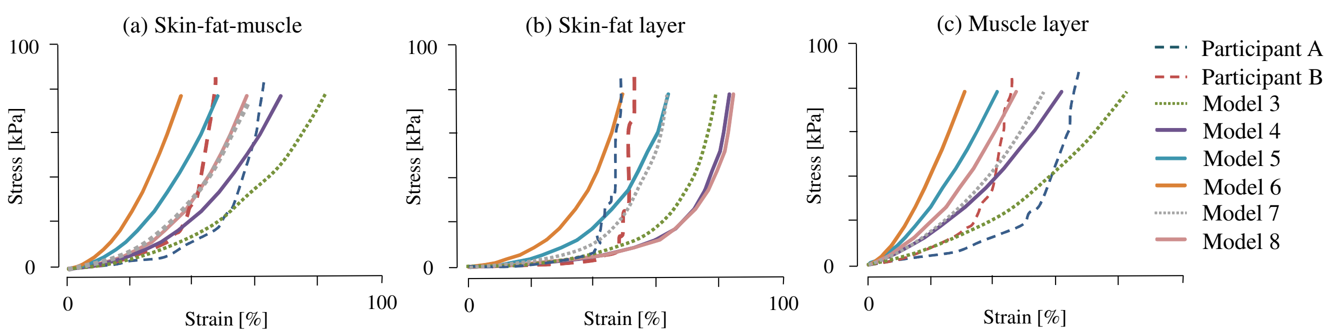

Fig. 7. Stress-strain curves of the eight types of urethane models. (a) Curves of the entire models. (b) Curves of the skin-fat or superficial layers. (c) Curves of the muscle layers.

the discussions in the previous section that focused on the stress-strain characteristics of the normal directions. Here, we invited 10 therapists to evaluate the urethane models in terms of the similarities of the haptic sensations experienced during the palpation procedures.

A. Stimuli: Urethane models

The participants tested the eight types of urethane models described in the previous section.

B. Participants

The assessors, participants of the experiment, were 10 licensed physical therapists, Judo therapists, and masseurs engaged in manual therapy and surface anatomy education (mean age: 41.5 ± 8.6 yewrs, mean experience: 19.3 ± 9.4 years).

C. Tasks

All participants were requested to manually examine each of the eight types of urethane models and sorted them in the order of the similarities with actual human gluteal tissues as they imagined or experienced in daily practice. The urethane models were randomly arranged on a table before the task, and all of them were simultaneously presented to each participant. The participants were allowed to freely touch the urethane models within 3 min. They were instructed to examine the models as if they had to palpate for muscle disorders of the human gluteal region, and to remember that the models also imitate the skin and fat tissues above muscles.

After the sorting task, the participants were requested to freely describe their impressions on the urethane models. Especially, in terms of the model that was ranked first, each participant was required to describe its similarities to or differences from the actual human gluteal tissues.

D. Analysis

We applied the Steel-Dwass test on the ranks assigned to the eight types of models by using all samples from all the participants. Hence, the number of tested samples was 80.

E. Results

Fig. 8 shows the mean ranks of the eight types of the urethane models and the results of the statistical test.

Models 4, 7, and 8 were judged to be more similar to the actual gluteal tissues than the other models. In the introspective reports from the participants, models 4, 5, and 7 were referred as having well-modeled muscle layers. Model 7 was considered to be the most similar to the actual skin-fat and muscle layers among all the urethane models. Some participants criticized that they should have been able to feel the bundles of muscle fibers in the models.

In contrast, models 1, 2, and 6 were judged to be less similar to the actual gluteal tissues than the other models. Models 1 and 2 were softer than the actual tissue. Model 6 was harder than the actual tissue.

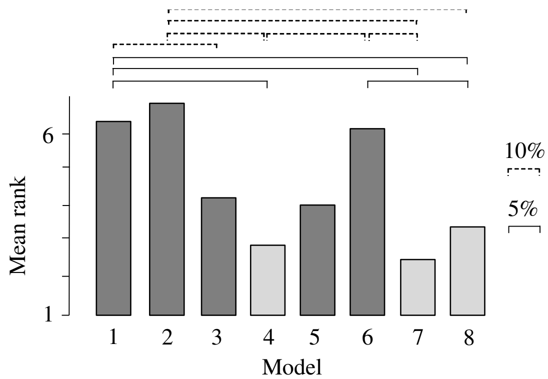

Fig. 8. Mean ranks of the urethane models. A lower rank indicates that the model was perceived to be more similar to the actual human gluteal region. The significance levels are shown at two levels: 5% and 10%. The ranks of the models represented by light boxes are statistically smaller than those of the other models.

V. Discussion: Guidance in Creating Palpation Dummies for Muscle Tissues

It is difficult to realize the stress-strain characteristics of the human gluteal region including skin, fat, and muscle tissues solely by using a solid compound of urethane rubber. One possible approach is to control the hardness characteristics through the structure of the rubber model [11], which are, for example, small air gaps in the rubber compound. However, such a structure delivers the sense of particles that do not exist in actual human tissues. For the purpose of creating a human-like urethane model, we focused on the myofascia, a membrane tissue covering muscle, and placed fabric sheets in the urethane model, which resulted in larger hardness of the model while retaining the nonlinearity of the stress-strain curves of the urethane models. Furthermore, it was found that the stress-strain characteristics of skin-fat and muscle layers can be tuned by varying the hardness of the urethane rubber of each layer, and the locations and number of fabric sheets. Hence, it is speculated that the urethane dummy models of various body parts can be manufactured on the basis of our approach.

In the subjective experiment, 10 therapists judged the models to be similar to the actual human gluteal tissues when the stress-strain characteristics of their muscle layers were similar to that of the actual human muscle layer. Especially, they preferred model 7, the superficial and deep layers of which were similar to the skin-fat and muscle layers of the human hip in terms of the stress-strain curves. These results suggest that it is effective to imitate the stress-strain characteristics of human skin-fat and muscle layers in creating urethane models that are perceived similar to the actual human gluteal region.

VI. Conclusion

Therapists manually examine the hardness of muscles affected by various disorders. To master this examination skill, satisfactory experiences are needed; however, trainees at educational instititutions have limited opportunities to touch actual patients. For the purpose of aiding the training in palpation, we developed an artificial dummy of muscles and the skin-fat tissues above muscles. Thus far, the many of human tissue models for the training in palpation have targeted the tumors related to internal diseases, and muscle disorders have yet to be addressed. First, we measured the hardness of the human gluteal tissues by using an ultrasonic echo and loading equipment. The use of an ultrasonic echo allowed us to decouple the hardness properties of the skin-fat and muscle layers. On the basis of these results, we manufactured eight types of urethane dummy models that differed in the number of rubber layers and the included fabric sheets. Accordingly, the models exhibited different stress-strain characteristics. Ten practicing therapists palpated these models and judged their similarities with the actual human gluteal region. As a result, they preferentially selected a few models whose stress-strain characteristics were close to those of the human gluteal tissues. Furthermore, their introspective reports indicated that one of these models most resembled the human tissue. As mentioned above, our method of tuning the hardness property of the models was effective in forming a urethane dummy that presents the haptic sensations experienced from palpating the actual human gluteal tissue. The method is considered to be applicable for other body parts, and is expected to contribute to the development of models for training purposes.

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