A Study of Viscoelasticity Index for Evaluating Muscle Hypotonicity during Static Stretching

Naomi Okamura, Mariko Tsukune, Yo Kobayashi, *Member*, *IEEE,*
and Masakatsu G. Fujie, *Fellow*, *IEEE*

Abstract— **Static stretching is widely used as a preventative treatment for musculoskeletal disabilities by providing muscle hypotonicity, which results from changes in muscle tissue structure. However, the quantitative evaluation of hypotonicity during stretching has had limited success owing to the confounding factor of mechanical stress relaxation. To resolve this problem, we propose a new evaluation method for hypotonicity based on a viscoelastic muscle model using fractional calculus, which is known to be effective for biomaterials. We made continuous measurements of rectus skin indentation during static stretching as an indicator of reaction force in the rectus femoris muscle. The viscoelastic ratio and modulus were computed from the indentation trace. Both viscoelastic parameters decreased significantly between the early and final phases of stretching. The results suggest that our method is useful for quantitative evaluation of muscle hypotonicity during stretching.**

I. INTRODUCTION

Muscle conditioning is essential to maintain motor function. As a method of adjusting the muscle tone, stretching is widely practiced. Static stretching is effective in relaxing the hypertonic muscle after strenuous exercise. However, the duration of stretching required to bring about muscle hypotonicity is unclear. In general, 15–30 seconds is recommended, but theories abound, spanning 6–60 seconds [1]. The difficulty lies in the continuous evaluation of stretching while the task is being performed.

Traditionally, assessment of muscle tone has been made by measurement of static torque. In studies by Magnusson et al. [2] and McNair et al. [3], static torque decreased gradually during static stretching but the electromyograph (EMG) was unchanged. The main cause of the decrease in the static torque was thought to be a mechanical stress relaxation. However, static torque is also influenced by changes in muscle structure, which depend on physiological muscle reflex. The duration of stretching required to bring about muscle hypotonicity hinges on physiological muscle reflex of a target muscle. It is necessary to detect a change in a target muscle, but the change in static torque includes many other muscles around the joint. Therefore, it is difficult to detect hypotonicity of the target muscle from the static torque.

In recent years, a method for the evaluation of muscle tone has been developed using skin surface indentation. The muscle reaction force, indicated by the degree of indentation, reflects the change in muscular tension (Fig. 1). It is considered to be well suited for measuring tone change within a single muscle. Nashimoto et al. [4] and Kimura et al. [5] have suggested, though, that muscle reaction force reduces after static stretching. Uchiyama et al. [6] showed that for isometric contraction of the biceps, the muscle reaction force increases in proportion to muscle contraction. In addition, it was found that the reaction force correlated more strongly with elasticity than viscosity when modeled as a spring-damper. The same group reported that reaction force of the rectus femoris muscle increases proportionally to its contraction when measured by a contact-type muscle hardness meter [7]. Kinoshita et al. [8] and Murayama et al. [9] recorded a linear increase in muscle reaction force with muscle elongation.

The above findings make use of the proportional relationship between reaction force and elastic modulus to determine hypotonicity. However, there remains the confounding influence of stress relaxation cause by viscoelastic properties of muscle. It is difficult to express these properties by spring- damper. Our previous experiments on bending and stretching of the arm suggest that a "spring-pot", based on fractional calculus, can accurately represent the viscoelastic properties of biomaterials, including muscle [10]. Furthermore, Grahovac et al. [11] generated stress relaxation curves from a spring-pot model that agreed with the sample data from [2].

In this paper we present a new method to evaluate muscle hypotonicity during static stretching using a spring-pot viscoelastic model to account for the effect of muscle structure

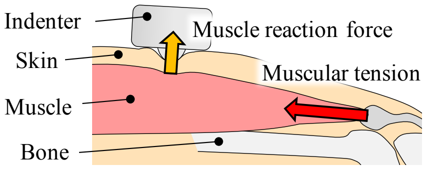


Figure 1. Muscle reaction force measured in an skin surface indentation.

Manuscript received March 17, 2014. This work was supported in part by Grants for Excellent Graduate Schools, Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, a Scientific Research Grant (S) (No. 25220005) from the MEXT of Japan, and the "Institute of Advanced Active Aging Research", Organization for University Research Initiatives, Waseda University, Tokyo, Japan.

N. Okamura and M. Tsukune are with the Graduate School of Science and Engineering, Waseda University, Tokyo, 1698555 Japan. 59-309, 3-4-1 Okubo, Shinjuku-ku, Tokyo, Japan (phone: +81-3-5286-3412; fax: +80-3-5291-8269; email: n-okamura@toki.waseda.jp).

Y. Kobayashi is with the Faculty of Science and Engineering, Waseda University, Tokyo, 1698555 Japan.

M. G. Fujie is with the Faculty of Science and Engineering, Waseda University, Tokyo, 1698555 Japan.

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

change as distinct from stress relaxation. To demonstrate the feasibility of our method, we performed experiments to stretching rectus femoris. The muscle was selected as the target as it is the agonist muscle in many movement patterns. The muscle reaction force was measured by indentation testing and we confirmed the change in muscle reaction force fitted the model well. Then we investigated the usefulness of the viscoelastic parameters as new evaluation indices of hypotonicity.

II. METHOD

A. Reaction Force Model during Static Stretching

The spring-pot viscoelastic model using the fractional calculus is given by

$$F = G\frac{d^r x}{dt^r}, \qquad (1)$$

where F is the muscle reaction force, G is the viscoelastic modulus, x is the muscle elongation, t is time, and r is the ratio of viscosity to elasticity of the muscle, termed the viscoelastic ratio.

Solving (1) by the mechanical stress relaxation test gives

$$F = \frac{Gx_c}{\Gamma(1-r)} t^{-r} = F_c t^{-r}, \qquad (2)$$

where x_c is the muscle elongation constant and $\Gamma(\ )$ is the gamma function, which determine the coefficient of muscle reaction force F_c. Equation (2) can be written in logarithmic form,

$$\log F = -r \log t + \log \frac{Gx_c}{\Gamma(1-r)} = -r \log t + \log F_c \qquad (3)$$

In the case of constant viscoelasticity, log(F) decreases linearly with log(t). This linear function is the stress relaxation model during static stretching. After muscle hypotonicity, the value of the viscoelastic modulus G decreases so that the log(F)-intercept of the linear model (3) decreases. Therefore, by identifying a change in the linear approximation (3) we can detect the time of hypotonicity, as shown in Fig. 2.

B. Experimental Settings

Figure 3 shows positions of sensors during static stretching. An A201 FlexiForce® sensor (TECSKAN, USA, South Boston, MA) was fixed onto the center of rectus skin with an inextensible band to measure the reaction force of the rectus femoris muscle. The reaction force sensor with indenter tip and band is shown in Fig. 4. We also measured three-dimensional position coordinates of the leg joint to confirm that the joint angle was constant during the stretching, as muscle extension is dependent on joint angle. Motion tracking was performed using the FASTRAK® electromagnetic 3D measurement system (POLHEMUS, USA, Colchester, Vermont). Optical markers were fixed onto the following four positions shown in Fig. 3: superior border of the ilium, great trochanter of the femur, lateral epicondyle of the femur, and the ankle bone.

C. Experimental design

Subjects were 10 young healthy people who engaged in regular sports activities.

Muscle hypotonicity was examined during static stretching after rest (stA) and after a squat exercise (stB). The squat exercise was intended to increase the tone of the rectus femoris muscle sufficiently to ensure that hypotonicity occurred. Subjects were asked to perform following tasks in order: (i) Static stretching (stA), (ii) 50 squat exercises, (iii) static stretching (First-stB), (iv) static stretching (Second-stB).

Duration of stretching was about 70 seconds that is enough time to bring about muscle hypotonicity. As shown in Fig. 5, subjects lay in spinal posture, and then they started and

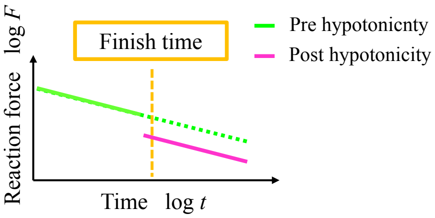


Figure 2. Model of reaction force during static stretching.

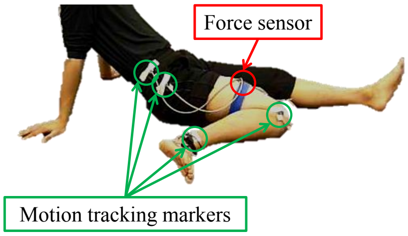
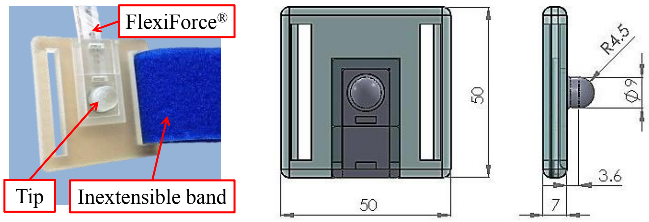


Figure 3. Positions of force sensor on rectus femoris muscle and motion tracking markers.



(a) Sensor components (b) Dimensioned drawing of the sensor case

Figure 4. Muscle reaction force sensor.

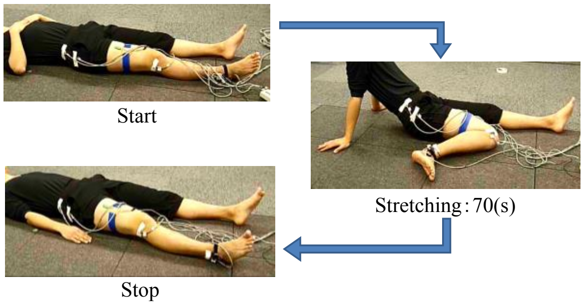


Figure 5. Model of reaction force during static stretching.

stopped stretching motion of rectus femoris muscle when they were given signals from experimenter. They were asked to keep their leg angles constant during stretching performed, but degree of muscle extension was leave to subjects' option.

D. *Analytical approach*

The viscoelastic ratio r and the viscoelastic modulus G were calculated using (3). The muscle reaction force was estimated from empirical data by the method of least squares. First, values of r and F_c were calculated as the slope and intercept of the linear regression. Next, G was calculated as

$$G = \frac{F_c \cdot \Gamma(1-r)}{x_c}. \qquad (4)$$

In this study we do not consider the effect of muscle elongation on viscoelasticity. Therefore, we simply let $x_c = 1$.

We used the data of reaction force got in a section in which leg joint angles were constant. We define the first 10 seconds of the stretching as the 'early phase' and the last 30 seconds as the 'final phase'. These two phases take into account the logarithmic nature of the viscoelastic response. Also these phases were selected not to cover the time muscle hypotonicity mainly occurs. The values of r and G in the early phase are denoted as r_1 and G_1, and those in the final phase as r_2 and G_2. After calculating these viscoelastic parameters we examine the quantities r_1–r_2 and $(G_1$–$G_2)/G_1$ to determine their dependence.

III. RESULTS

A. *The value of the viscoelastic parameters*

The change in muscle reaction force during static stretching and the early and final phase linear fits are shown in Fig. 6. The reaction force decreased linearly except at around $t \approx 25$ sec. The values of viscoelastic ratio r and viscoelastic modulus G during static stretching are plotted in Fig. 7. The mean ± standard error (SE) of r_1, r_2, G_1 and G_2 in stA are 0.097 ± 0.022, 0.062 ± 0.021, 14.1 ± 1.96, 13.6 ± 3.07, and in stB they are 0.079 ± 0.010, 0.032 ± 0.006, 12.8 ± 1.32, 10.2 ± 1.01, respectively. The results show that r decreases significantly only under the condition of static stretching after squat exercise (stB) with Wilcoxon rank sum test.

B. *Relationship between the rates of change of the viscoelastic parameters*

The rates of change of viscoelastic parameters between the early and final phases are shown in Fig. 8. The linear regression equation is given by (5). The coefficient of correlation (R^2) was 0.92, indicating a strongly linear relation.

$$r_1 - r_2 = 0.029 \cdot \frac{G_1 - G_2}{G_1} \qquad (5)$$

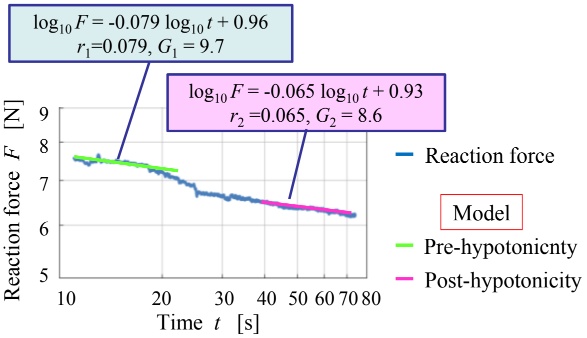


Figure 6. Viscoelastic parameters calculated from reaction force during static stretching.

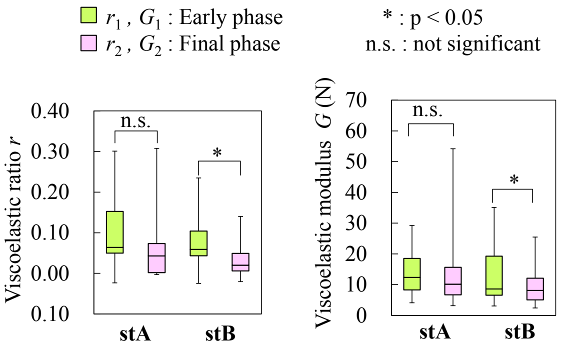


Figure 7. Viscoelastic parameters calculated from reaction force during static stretching.

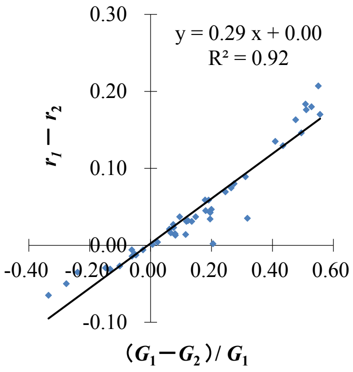


Figure 8. Relationship between the rates of change of the viscoelastic modulus G and the viscoelastic ratio r.

IV. DISCUSSION

A. *Applicability of the model*

In Fig. 6, the pair of linear trends have been fitted to two segments of (the logarithm of) a time record of indentation reaction force. In between these segments the slope is decreasing. This suggests that the spring-pot model can capture the stress relaxation behavior during static stretching, and that it is possible to detect the viscoelastic state change caused by muscle hypotonicity.

B. *The value of the viscoelastic parameters*

As shown in Fig. 7, the values of the muscle viscoelastic parameters r and G in the final phase are lower than those in the early phase. Their respective differences (final – early) are statistically significant in stB. Muscle hypertonicity is more likely to occur by stretching after squat exercises than after rest. According to this, the change in muscle viscoelastic parameters is thought to be due to muscle hypotonicity.

The maximum value of the viscoelastic ratio r was 0.308, and the mean value was 0.062. The viscoelastic contribution is therefore very minor during stretching so G is effectively a simple elastic modulus.

We calculated the rate of change of the viscoelastic modulus, $(G_1 - G_2) / G_1$ (%). The mean value in stA was 7%, and in stB was 15%. Previous study of static stretching for rectus femoris muscle [4] reported mean of muscle hardness reduced 8 % with the stretching after rest. The reduction rates of [4] and stA were closed, so the viscoelastic modulus G is a suitable evaluation index of muscle hypotonicity by static stretching.

The change of the viscoelastic ratio $r_1 - r_2$ (%) was also calculated. The mean value in stA was 3.4 %, and that in stB was 4.7%. In addition to the viscoelastic modulus G, the viscoelastic ratio r will be a new evaluation index of muscle hypotonicity by static stretching.

C. Relationship between the rate of change of the viscoelastic parameters

To realize real-time detection of muscle hypotonicity during static stretching, computational effort needs to be minimized. As per the linear model given by (3), the parameter r gives the slope but G is a function of the intercept and the value of r. This means the value of r is more suitable than the value of G for the real-time detection of muscle hypotonicity. Figure 8 and (5) show that the change of the viscoelastic ratio, $r_1 - r_2$, is proportional, though, to the change of the viscoelastic modulus $(G_1 - G_2) / G_1$. From this relationship, we can use the value of r instead of the value of G to evaluate the effect of muscle hypotonicity.

D. Variation in the data

In Fig. 7, variances of r_2 and G_2 are smaller than those of r_1 and G_1. This is because the muscle structure in the early phase is more affected by the elongation and rate of elongation than in the final phase in which there is a greater degree of muscle tone. To establish a quantitative threshold for automatically detecting muscle hypotonicity, further experiments are needed in which the degree of stretching depended on muscle elongation is controlled.

E. Limitation

In this study, we selected the method for measuring muscle tone using skin surface indentation because it is thought to be well suited for measuring tone change within a single muscle. However, the muscle reaction force can reflect tone of surface muscles in the case of our experiment. The results are influenced by deepness and thickness of each subjects' muscles. We have to consider indenter specifications that adapted to these individual properties. Furthermore, to deal with deeper muscles, we have to try other indentation patterns in which sizes of indenter and indent positions are varied, and also compare with other method for measuring muscle tone. Through these processes, best suited measurement for our spring-pod method should be chosen.

V. CONCLUSION

For detecting muscle hypotonicity during static stretching, continuous evaluation of muscle tone is needed. In this study we proposed such a technique using a fractional calculus model of muscle viscoelasticity. Based on the experimental results, we found that the values of the muscle viscoelastic parameters r and G in the final stretching phase are lower than those in the early phase. We also showed that the viscoelastic modulus G is proportional to the viscoelastic ratio r. It would be feasible to use only r to in a real-time system for the detection of hypotonicity during static stretching.

In future work, we will examine the short-term changes of the muscle viscoelastic properties to identify the time of hypotonicity occurrence. We will also compare the transient values of, e.g., joint torque or ultrasound elasticity, with muscle elongation under control, to develop a more complete characterization of the muscle mechanics of static stretching.

REFERENCES

[1] M. J. Alter, *Science of Flexibility*, 3rd ed., Champaign, IL: Human Kinetics, 2004.

[2] S. P. Magnusson, E. B. Simonsen, P. Dyhre-Poulsen, P. Aagaard, T. Mohr and M. Kjaer, "Viscoelastic stress relaxation during static stretch in human skeletal muscle in the absence of EMG activity", *Scand. J. Med. Sci. Sports*, vol. 6, pp. 323–328, 1996.

[3] P. J. McNair, E. W. Dombroski and D. J. Hewson, "Stretching at the ankle joint: viscoelastic responses to holds and continuous passive motion", *Med. Sci. Sports Exerc.*, vol. 33, pp. 354–358, 2001.

[4] S. Nashimoto et al., "Investigation of Static Stretching Duration and the Effect using the Muscle Hardness Meter" (in Japanese), *J. Sports Injury*, vol. 17, pp. 37–39, 2012.

[5] A. Kimura, K. Matsumoto, and T. Ikeuchi, "Effects of Stretching after Exercise in Muscle Hardness" (in Japanese), Meiji Shinkyu Igaku, vol. 40, pp. 29–37, 2007.

[6] T. Uchiyama, K. Ohsugi and M. Murayama, "Relationship between Muscle Hardness Estimated by the Indentation Method and MUSCLE Contractile Level", in *Proc. 26th Annual International Conference of the IEEE EMBS*, San Francisco, CA, USA, September 2004.

[7] M. Murayama, et al., "Further Study of the Relation between Muscle Hardness and Mechanomyogram Findings during Voluntary Isometric Contractions", in *Proc. 16th Annual congress of the European College of Sport Science*, July 2011.

[8] H. Kinoshita et al., "Measurement of Tissue Hardness for Evaluating Flexibility of the Knee Extensor Mechanism", *Football Science*, vol. 3, pp. 15–20, 2006.

[9] M. Murayama et al., "Association of muscle hardness with muscle tension dynamics: a physiological property", *Eur. J. Appl. Physiol.*, vol. 112, Issue 1, pp. 105–112, 2012.

[10] Y. Kobayashi, T. Ando, M. Seki, T. Watanabe and M. G. Fujie, "Fractional Impedance Control for Reproducing the Material Properties of Muscle", in *Proc. 2010 IEEE/IROS International Conference on Intelligent Robots and Systems*, pp. 5498–5504, 2010.

[11] N. M. Grahovac, "Modelling of the hamstring muscle group by use of fractional derivatives", *Comput. Math. Appl.*, vol. 59, pp. 1695–1700, 2010.