Am J Transl Res 2021;13(7):7654-7666
www.ajtr.org /ISSN:1943-8141/AJTR0132165

Original Article

Optimization of traditional Chinese medicine rolling manipulation and pressure attenuation

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Received February 20, 2021; Accepted June 5, 2021; Epub July 15, 2021; Published July 30, 2021

Abstract: Background: Traditional Chinese Medicine (TCM) massage utilizes mechanical force stimulation, and the amount of mechanical force influences therapeutic outcome. This amount is determined by pressure, frequency, and duration; however, there are no standard definitions for these measures. Methods: An orthogonal design was used to evaluate massage efficacy using muscle tension as an index. Pressure (2, 4, 6 kg), duration (5, 10, 15 min), frequency (60, 120, 180 repetitions/min), pain (mild, medium, severe), weight (<60, 60-75, >75 kg), and sex (male, female) were evaluated. Additionally, a porcine model of muscle tension was used to construct pressure-time curves for muscle tissues under static and dynamic pressure. Results: We identified an interaction among the six massage measures (P<0.05). Of these measures, only two were individually significant: manipulation frequency and patient pain level (P<0.05). Specifically, 120 repetitions/min improved muscle tension significantly more than 60 or 180 repetitions/min (P<0.05), and patients with severe pain had significantly improved muscle tension compared to those with medium or mild pain (P<0.05). In the porcine muscle model, both static and dynamic pressure were attenuated by approximately 12.5% per cm. This attenuation dropped to 10% per cm when the pressure sensor was placed below tissues with different thicknesses instead of being inserted into tissues at different levels. Conclusion: Manipulation frequency and patient pain level were primarily responsible for the therapeutic effects of TCM massage. Mechanistically, pressure was attenuated by nearly 75% at a depth of 2 cm from the muscle surface during TCM massage.

Keywords: Tuina, massage, traditional Chinese medicine, lumbar disc herniation, skeletal muscle, pressure attenuation

Introduction

Tuina (massage) is an important part of Traditional Chinese Medicine (TCM) and is used to treat disease, eliminate fatigue, and enhance physical fitness. Massage is increasingly accepted as an effective treatment for disease prevention and health care. Currently, the medical community recognizes massage as a treatment that relaxes tendons and activates collateral ligaments, which promotes blood circulation, regulates Qi, and relieves pain [1, 2]. Of the massage manipulation techniques, rolling manipulation relaxes tendons and collateral ligaments most effectively [3]. Rolling manipulation involves a large area and a deep force and is clinically effective in treating soft tissue fatigue and injury [4]. Although rolling manipulation has clear clinical benefits, the method is variable and has not been systematically investigated to define the optimal combination of pressure, frequency, and duration to achieve the desired therapeutic outcome.

Long-term clinical practice has identified the amount of manipulation stimulation as a key factor of massage [5]. The amount of manipulation stimulation is determined by dynamic measures: pressure, frequency, and duration. Variation of any of these measures alters the effects of the massage. Therefore, therapeutic effects vary when rolling manipulation is combined with different measures. Currently, the rolling manipulation-response relationship is not fully understood in the medical community, and there is no guidance for standardization or normalization. Moreover, uniform instruction for rolling manipulation is not administered, and the rolling manipulation standards are often adjusted according to the personal habits of the physician. To improve clinical efficacy in obese patients or patients with a high degree of pain, physicians may increase pressure and prolong the duration of rolling manipulation, which often results in subcutaneous congestion, skin damage, syncope, or other adverse reactions [6]. In addition, the literature published between 1986 and 2001, improper manipulation caused 115 accidents of fractures, dislocations, nerve damage, paraplegia, death, and other serious accidents [7]. The frequent occurrence of massage accidents has greatly reduced the academic status of the discipline and has severely restricted the promotion and clinical application of massage [8]. Therefore, optimizing the combination of dynamic measures of rolling manipulation massage in different groups of people is expected to provide guidance for its clinical application.

The incidence of lumbar disc herniation in the working population is more than 50% [9]. Lumbar disc herniation is a chronic musculoskeletal injury, often accompanied by unilateral or bilateral lower limb muscle spasm [10, 11]. Interestingly, the primary manifestation of skeletal muscle injury is also muscle spasm and pain. Since massage concentrates on skeletal muscle, it is an attractive therapy for pain relief after lumbar disc herniation or skeletal muscle injury. Most clinicians regard the relief of muscle tension as an indicator of successful massage treatment. Modern experimental studies have also shown that massage improves muscle tension, mechanical properties of muscle tissue, muscle strength, and promotes the repair of injured muscle tissue [12, 13].

Massage involves mechanical force acting on the body surface, and massage therapy is achieved through the coordinated manipulation and rhythmic stimulation of the body surface [14]. However, the relationship between the mechanical force acting on the body surface and the internal pressure applied to the muscles remains unknown. It is also unclear whether the mechanical force is attenuated before, during, or after acting on the muscles.

Here, we used an orthogonal experimental design to investigate the use of defined levels of pressure, frequency, and time of rolling manipulation massage on skeletal muscle tension in patients with lumbar disc herniation. We also evaluated the effect of patient pain level, weight, and gender in this model. After defining the optimal values in patients, we investigated the application of mechanical force and rolling manipulation in an *in vitro* model of porcine sacrospinous muscle. The combination of sensor technology and dynamic data acquisition allowed us to study muscle stimulation and attenuation of force. Our results provide a theoretical basis for the mechanism of action of massage therapy and allow for quantitative investigation of the effects of massage on skeletal muscle tension.

Materials and methods

Ethical approval

All protocols followed those outlined in the Declaration of Helsinki and were approved by the Institutional Review Board of Yueyang Hospital of Integrated Traditional Chinese and Western Medicine, Shanghai University of Traditional Chinese Medicine (IRB No. 2016-037). Each patient granted informed consent for participation. The reporting guidelines adhered to those proposed by the Consolidated Standards of Reporting Trials (CONSORT) group.

The fresh porcine muscle tissue used in the study was specially purchased for the research, so there was no animal testing ethics involved.

Subjects

We recruited patients with lumbar disc herniation from Yueyang Hospital of Integrated Traditional Chinese and Western Medicine. Inclusion criteria were based on the Standard of Diagnostic Effect of TCM Syndrome as follows: (1) the diagnosis was consistent with the diagnostic criteria of TCM and western medicine; (2) acid distension, spasm, or pain in the gastrocnemius muscle of at least one lower limb; (3) 18-70 years of age; (4) stable condition and able to lie in the prone position for 30 minutes; and (5) informed consent was given. The exclu-

Table 1. L^{18} (2×3^7) orthogonal experimental design

L^{18} (2×3^7)						
Processing	A	B	C	D	E	F
1	2	2	1	2	2	1
2	1	3	3	2	2	2
3	3	1	1	2	3	1
4	3	1	3	2	1	2
5	2	1	2	3	3	2
6	1	2	1	3	3	2
7	1	1	2	1	2	1
8	2	1	3	3	2	1
9	1	2	3	3	1	1
10	3	3	2	3	1	1
11	2	3	1	1	1	2
12	2	2	2	2	1	1
13	3	2	3	1	3	1
14	3	3	1	3	2	1
15	1	1	1	1	1	1
16	3	2	2	1	2	2
17	1	3	2	2	3	1
18	2	3	3	1	3	1

sion criteria were as follows: (1) serious condition or obvious surgical indications; (2) presence of life-threatening primary disease or mental illness; (3) recent history (within 3 days) of strenuous or extreme fatigue exercise that seriously affected the lower limbs; (4) lower limb disability, scarring, muscular atrophy, lumbar fracture, tuberculosis, or space occupying disease; (5) pregnancy or lactation; and (6) participation in other clinical trials. The discontinuation and elimination criteria were (1) serious adverse events or adverse reactions; and (2) If serious adverse events, reactions, or complications were observed, treatment was discontinued, and the patient was removed from the study.

Orthogonal testing scheme

Based on the characteristics of clinical massage therapy, we opted to use an orthogonal experimental scheme to investigate different combinations of rolling manipulation approaches. The dynamic parameters of rolling manipulation were used to design an orthogonal table L^{18} (2×3^7), which is presented in **Table 1**. Pressure, frequency, duration, pain level, weight, and gender are denoted by A, B, C, D, E, and F, respectively (**Tables 1** and **2**). Each parameter was evaluated at two to three defined levels, which are denoted as levels 1, 2, and 3 in **Tables 1** and **2** as follows: pressure (1 = 2 kg, 2 = 4 kg, 3 = 6 kg), frequency (1 = 60 repetitions/min, 2 = 120 repetitions/min, 3 = 180 repetitions/min), duration (1 = 5 min, 2 = 10 min, 3 = 15 min), pain (1 = painless, 2 = mild, 3 = severe), weight (1 = less than 60 kg, 2 = 60-75 kg, 3 = greater than 75 kg), and gender (1 = male, 2 = female), pain (mild, medium, severe). In the L^{18} (2×3^7) orthogonal table, 18 experimental combinations of parameters were selected. Patients were randomly assigned to one of the 18 treatment arms after matching pain, weight, and gender combinations. The massage operator administered rolling manipulation at accurate pressure, time, and frequency to each volunteer according to the assigned parameter combination.

Sample size estimation

The six-factor multilevel orthogonal design of this study required 18 treatment combinations (**Table 1**). To enable interaction and variance analysis, each treatment combination was performed three times for a total sample size of 54.

Muscle tension detection

For massage therapy and muscle tension detection, participants were required to wear loose pants, lie prone on the massage bed, and rest for 5 to 10 minutes. After the breathing and mood of the participant stabilized, the muscle tension of the testing site (the abdominal center of the unilateral gastrocnemius where the Chengjin acupoint is located) was determined. The soft tissue tension testing probe (PEK-1, Concord Co., Ltd., Japan) was maintained in an identical position on the lower limb during the test. The intelligent manipulation technique parameter determination system (Shanghai University of Traditional Chinese Medicine Shangxin Medical Technology Co., Ltd.) was positioned vertically over the testing site. Muscle tension was detected three times, and the average value of the triplicate was considered the initial muscle tension. The muscle tension test was performed again immediately after rolling manipulation. The testing position and angle were consistent with the initial measurements. The measurement was repeat-

Table 2. TCM rolling manipulation parameter and patient factor levels

Factors	A	B	C	D	E	F
	Pressure (kg)	Frequency (rep./min)	Duration (min)	Pain*	Weight (kg)	Gender
Level 1	2	60	5	mild	<60	male
Level 2	4	120	10	medium	60-75	female
Level 3	6	180	15	severe	>75	

*Pain was assessed by the Visual Analogue Scale (VAS) from 1 to 10: 1 to 3 was mild, 4 to 6 was medium, and 7 to 10 was severe.

ed three times, and the average value of the triplicates was recorded as the final muscle tension.

TCM rolling manipulation

The massage operator performed rolling manipulation using the corresponding parameters of each treatment combination. Rolling manipulation was centered on the Chengjin acupoint of the unilateral lower limb. To perform rolling manipulation, the proximal little finger of the back of the palm is positioned near the treatment site, the metacarpophalangeal joint is slightly flexed, the wrist joint is flexed and extended to the maximum extent, and the forearm is rotated synergistically. The proximal back edge of the palm continues to move back and forth on the treatment site. To maintain accurate treatment parameters during rolling manipulation, we used an intelligent manipulation technique parameter determination system and a Speeding Stopwatch (PC2000A, China). We synchronously monitored the pressure, time, and frequency parameters of rolling manipulation.

Observation index

To evaluate the effect of rolling manipulation, we calculated the degree of muscle tension improvement for each patient. The rate of muscle tension improvement was calculated by comparing muscle tension before and after rolling manipulation and was used in our statistical analyses.

Improvement rate of MT =

$$\frac{(\text{Before treatment MT} - \text{After treatment MT})}{(\text{Before treatment MT})} \times 100\%$$

Porcine sacrospinous muscle model of muscle tension

To better study the attenuation of muscle tension after massage, we used a porcine sacrospinous muscle model. We collected fresh sacrospinous muscle tissue from pigs and dissected the tissues to uniform sizes (15 cm*30 cm). Vernier calipers were used to accurately define muscle thickness in every experiment. A diaphragm pressure sensor was inserted into different thicknesses or different layers of fresh porcine sacrospinous muscle to assess muscle tension (**Figure 1A**). The diaphragm pressure sensor was paired with an intelligent manipulation technique parameter determination system to administer rolling manipulation with defined pressure, frequency, and duration parameters. An EDX-2000A dynamic data acquisition system (Concord Co., Ltd., Japan) was used to collect muscle tissue pressure information, record the pressure-time curve, and observe pressure attenuation.

Sensor static baseline calibration

After the diaphragm pressure sensor was connected to the data acquisition system, the assembly was placed horizontally on the parameter determination system, and the parameters were adjusted to zero. After the curve stabilized, a 4000 g mass was gradually deposited directly above the sensor. The data acquisition system collected data, and the parameter determination system monitored the stability of the load. Typically, a 10-s static curve was collected. These steps were repeated with metal masses of 3000 g, 2000 g, 1000 g, 500 g, 100 g, 50 g, and 20 g to obtain a static baseline calibration of the sensor.

Static pressure decay in different thicknesses and layers of skeletal muscle

The diaphragm pressure sensor was connected to the data acquisition system, the instrument parameters were adjusted to zero, and fresh pig sacrospinous muscle was placed horizontally on the parameter determination system. Static pressure-time curves were collected as described for the baseline calibration by plac-

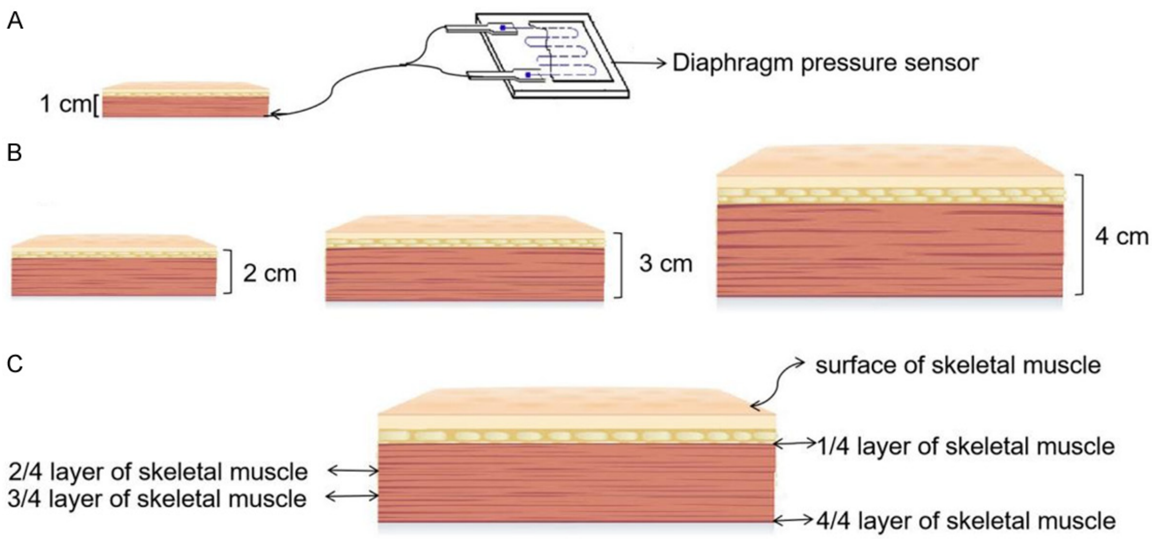

Figure 1. Schematic diagram of *in vitro* muscle pressure detection. A. The diaphragm pressure sensor to measure static pressure attenuation. Muscle tissues were placed above the diaphragm pressure sensor, and metal masses were added. To measure dynamic pressure, the diaphragm pressure sensor was positioned similarly, and rolling manipulation (4000 g, 120 repetitions/min, and duration of 10 min) was applied to the surface of the muscle tissue by the parameter determination system. B. Isolated muscles of different thicknesses were used in both static and dynamic pressure attenuation experiments. C. In 4-cm-thick muscle tissue, both static and dynamic pressure attenuation were measured at different tissue depths. The pressure sensor was inserted into the tissue at the locations indicated in the diagram.

ing the diaphragm pressure sensor at the bottom of 1-, 2-, 3-, or 4-cm-thick muscle tissue (**Figure 1A** and **1B**), adding metal masses of decreasing weights, and recording the detected pressure in the tissue. Individual single curves were obtained from eight samples of isolated sacrospinous tissue with identical masses. The mean value was calculated for statistical analysis.

Similarly, isolated tissue with a thickness of 4 cm was horizontally placed on the parameter determination system, and the diaphragm pressure sensor was inserted into the upper 1/4, 2/4, 3/4, or 4/4 of the isolated tissue (**Figure 1C**). Static pressure-time curves were collected as described above, and individual single curves were obtained from eight samples of isolated tissue with identical masses. The mean value was calculated for statistical analysis.

Baseline calibration of TCM rolling manipulation parameters

To establish a dynamic pressure baseline for the diaphragm pressure sensor, TCM rolling manipulation (4000 g, 120 repetitions/min, 10 min) [15] was applied to the surface of freshly isolated muscle tissue. The parameter determination system monitored the quality of the manipulation, and the resulting curve was allowed to stabilize. After stabilization, the data acquisition system composed the dynamic curve. This curve served as a dynamic pressure baseline for the sensor.

Dynamic rolling manipulation pressure decay in different thicknesses and layers of skeletal muscle

As described above, the diaphragm pressure sensor was fixed to the parameter determination system, and isolated porcine sacrospinous tissues with thicknesses of 1 cm, 2 cm, 3 cm, and 4 cm were placed on the sensor. Then, TCM rolling manipulation was applied to the tissue surface with the following parameters: 4000 g, 120 repetitions/min, and 10 min duration. Similarly, fresh porcine sacrospinous muscle with a thickness of 4 cm was placed horizontally on the parameter determination system, and the diaphragm pressure sensor was inserted into different layers of the tissue at depths of 1/4, 2/4, 3/4, and 4/4. The parameter determination system monitored the quality

Table 3. Analysis of variance of rolling manipulation parameters and patient factors in the orthogonal model

Sources of variation	SS	df	MS	*F value*	*P value*
Pressure	6.252	2	3.126	1.166	P>0.05
Frequency	20.56	2	10.28	3.834	P<0.05
Duration	1.663	2	0.832	0.31	P>0.05
Pain	179.371	2	89.686	33.452	P<0.05
Weight	0.307	2	0.154	0.057	P>0.05
Gender	0.675	1	0.675	0.252	P>0.05
Pressure*Frequency*Duration*Pain*Weight*Gender	33.127	9	3.681	1.373	P<0.05
Error	40.215	15	2.681		

SS is Sum of squares of deviation; df is degree freedom; MS is Mean Square.

of the manipulation, and the data acquisition system collected the dynamic pressure-time curves. Individual single curves were obtained from eight samples of isolated sacrospinous tissue with identical masses. The mean value was calculated for statistical analysis.

Statistical analysis

SPSS 25.0 software was used for all statistical analyses. For patient studies, we analyzed the main effects and interactions of each factor by univariate analysis. Experimental results are expressed as mean ± standard error (SE).

For studies using the porcine sacrospinous tissue model, pressure-time curves were analyzed as continuous variables and were expressed as mean ± standard deviation (SD). Differences between groups were analyzed by one-way analysis of variance (ANOVA) with post hoc correction for multiple comparisons. P<0.05 was considered significant.

Results

Rolling manipulation parameters and patient factors influence muscle tension improvement after TCM rolling manipulation in patients with lumbar disc herniation

We evaluated the interaction of pressure, frequency, time, pain, weight, and gender using an orthogonal experimental design in patients with lumbar disc herniation that received TCM rolling manipulation massage therapy. We found a significant interaction between all of the factors evaluated (**Table 3**) (P<0.05). Moreover, manipulation frequency and patient pain level both individually influenced the improvement of lower limb muscle tension in patients with lumbar disc herniation (P<0.05). We then went on to study the specific levels of these factors and their contribution to muscle tension improvement.

Although rolling manipulation pressure improved muscle tension of the gastrocnemius, there was no significant difference between pressure levels of 2, 4, or 6 kg (**Figure 2A**) (P>0.05). The frequency of rolling manipulation also improved muscle tension of the gastrocnemius; however, we found that 120 repetitions/min improved muscle tension significantly more than either 60 or 180 repetitions/min (**Figure 2B**) (P<0.05). In contrast, we did not observe a significant difference between rolling manipulation durations of 5, 10, or 15 min (**Figure 2C**) (P>0.05). Interestingly, we found that rolling manipulation showed significantly more muscle tension improvement in patients with severe pain compared to those with those with mild or medium pain (**Figure 2D**) (P<0.05). Finally, we did not observe any significant differences in muscle tension improvement in patients of different body weight or gender (**Figure 2E** and **2F**) (P>0.05).

Static pressure attenuation in skeletal muscle

To further investigate the mechanism by which rolling manipulation improves muscle tension, we modeled pressure attenuation using freshly isolated porcine sacrospinous muscle tissue. Since we were interested in how pressure is transferred from the surface of the tissue to the muscle layers below, we evaluated pressure attenuation in muscle tissues of increasing thickness as well as in different layers of

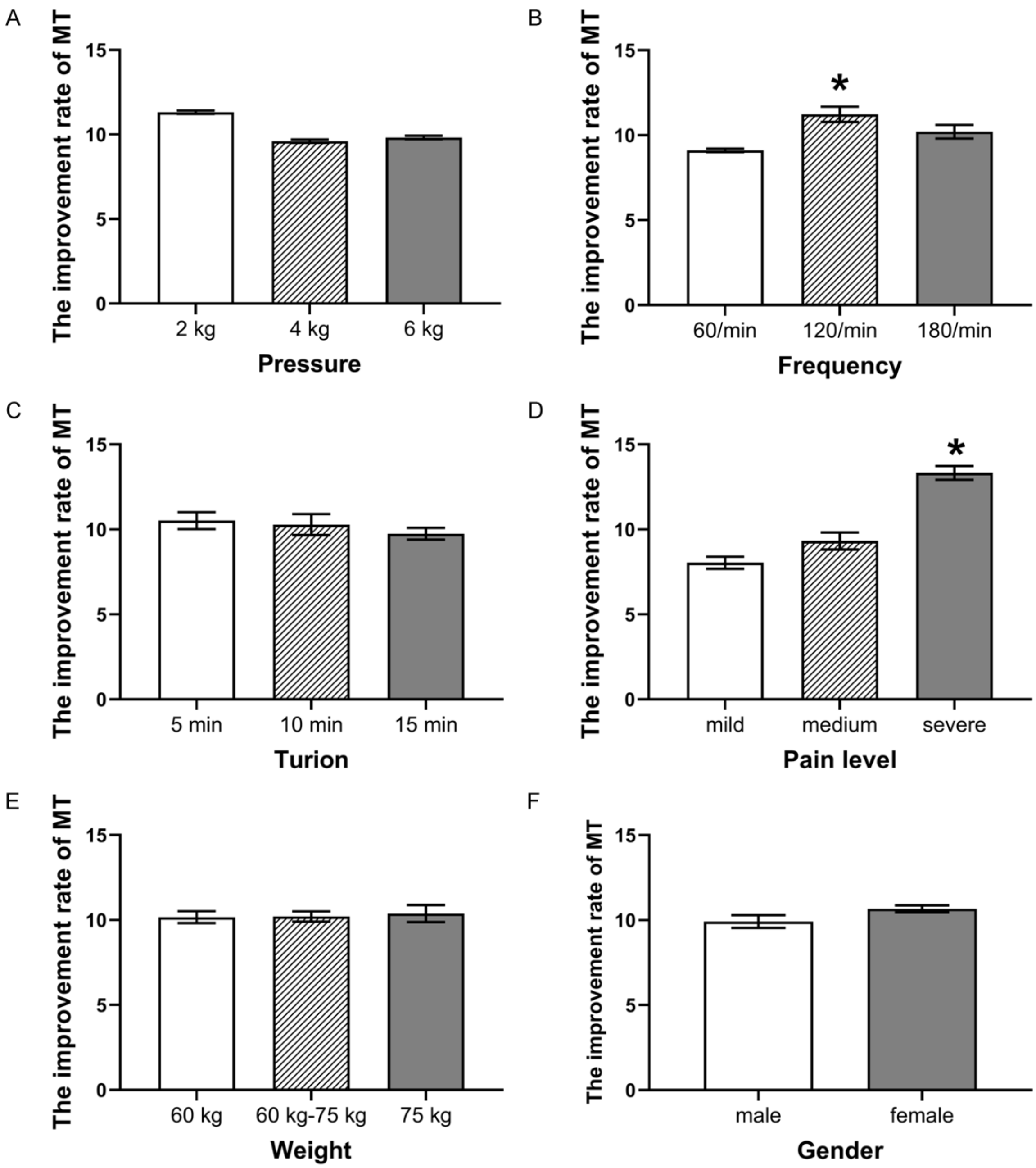

Figure 2. The benefits of TCM massage are affected by rolling manipulation parameters and patient factors. TCM rolling manipulation was applied in patients with lower limb tension, and the rate of gastrocnemius muscle tone improvement (%) was quantified. Muscle tone improvement was stratified and compared by factors: pressure (A), frequency (B), duration (C), pain level (D), body weight (E), and gender (F). Columns indicate independent levels per factor, and error bars indicate the SD (n=3). $^{*}P<0.05$.

muscle tissue of the same thickness (4 cm). We began by applying a static force and analyzing the resulting pressure-time curves. By comparing pressure values at the same time point on each static curve (**Figure 3A**), we found that static pressure was attenuated in skeletal muscle of each thickness compared to the static calibration baseline (**Table 4**). We also compared each thickness to the previous thickness and found that more pressure was attenuated in thicker tissues. Indeed, pressure attenuation showed a linear relationship with an approximate slope of 0.314 in consecutive muscle tissue thicknesses.

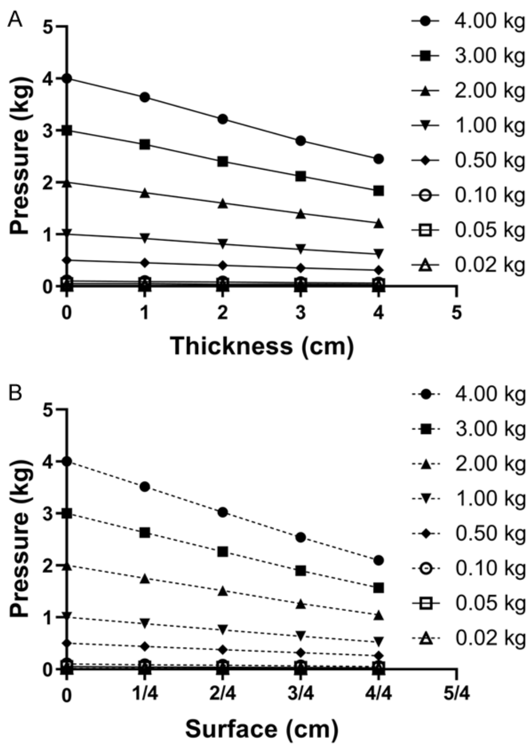

Figure 3. Static pressure attenuation in skeletal muscle. A. Static pressure decay in skeletal muscle of different thicknesses. B. Static pressure decay in different skeletal muscle layers. Data indicate the mean ± SD (n=8).

Similarly, we found that static pressure was attenuated in descending layers of skeletal muscle (**Figure 3B**). We again compared each layer to the previous layer and found that more static pressure was attenuated from one layer to the next, creating a linear relationship (**Table 5**). Specifically, insertion of the diaphragm pressure sensor into the 1/4, 2/4, 3/4, and 4/4 layers of porcine sacrospinous muscle attenuated static pressure by approximately 12.5% with each layer (1 cm). Compared to the pressure attenuation observed in skeletal muscle of different thicknesses, the attenuation rate of static pressure at increasing depths of skeletal muscle was higher.

Dynamic pressure attenuation in skeletal muscle

After establishing a baseline for static pressure attenuation in different thicknesses and layers of skeletal muscle, we went on to evaluate the effect of dynamic pressure in these systems using defined rolling manipulation parameters: 4000 g, 120 repetitions/min, and 10 min duration. We compared pressure values at the same time point for each dynamic rolling pressure calibration curve (**Figure 4A**) to the baseline and found that dynamic rolling manipulation pressure was attenuated in skeletal muscles of different thicknesses. Similar to our results with static pressure, dynamic pressure was also attenuated in each muscle layer compared to the previous layer (**Table 6**).

Finally, we compared the dynamic rolling manipulation pressure curves in descending layers of muscle tissue to the dynamic pressure baseline (**Figure 4B**). We found that dynamic pressure was attenuated at each skeletal muscle level. We also determined that each layer had more attenuated pressure when compared to the previous layer (**Table 7**). As the maximum of the curve is 4 kg, and at the depth of 2 cm from the muscle surface it is 3 kg, we concluded that skeletal muscle pressure was attenuated by nearly 75% after TCM rolling manipulation. The attenuation rate of dynamic rolling manipulation pressure was higher in increasing depths of skeletal muscle tissue compared with the attenuation rate in skeletal muscle of different thicknesses.

Discussion

Optimization of TCM rolling manipulation parameters

Clinically, lumbar disc herniation is accompanied by unilateral gastrocnemius distension, spasm, and pain, but the degree of pain varies between patients. Muscle swelling, twitching, and pain are caused by excessive muscle tension, which may be due to viscoelastic muscle tension, physiological contracture, voluntary contraction, or muscle spasm [16]. Although massage therapy can alleviate these clinical symptoms, there is no standardized method for performing rolling manipulation. To optimize the parameters used for rolling manipulation, we sought to define quantitatively the effect of different combinations of parameters on muscle tension in patients with lumbar disc herniation. The use of muscle hardness to accurately measure muscle tension has been robustly reported [17]. Therefore, we used muscle tension as an index to define the effect of rolling manipulation massage on tendons and collateral ligaments. Here, we evaluated muscle ten-

Table 4. Static pressure attenuation in skeletal muscle of different thicknesses

Thickness: (cm)	0	1	2	3	4
N	8	8	8	8	8
4 kg	4.000±0.000	3.636±0.005*	3.217±0.008*,▲	2.804±0.030*,▲	2.445±0.016*,▲
3 kg	3.000±0.000	2.730±0.004*	2.403±0.024*,▲	2.118±0.021*,▲	1.843±0.018*,▲
2 kg	2.000±0.000	1.800±0.016*	1.600±0.020*,▲	1.401±0.003*,▲	1.219±0.019*,▲
1 kg	1.000±0.000	0.916±0.001*	0.809±0.018*,▲	0.705±0.026*,▲	0.618±0.004*,▲
0.5 kg	0.500±0.000	0.446±0.002*	0.396±0.001*,▲	0.350±0.013*,▲	0.305±0.002*,▲
0.1 kg	0.100±0.000*	0.089±0.003*	0.078±0.003*,▲	0.069±0.002*,▲	0.060±0.002*,▲
0.05 kg	0.050±0.000	0.047±0.002*	0.042±0.002*,▲	0.037±0.002*,▲	0.032±0.002*,▲
0.02 kg	0.020±0.000	0.017±0.001*	0.016±0.002*,▲	0.014±0.002*,▲	0.012±0.002*,▲

*Comparison with the surface pressure, $P<0.05$. ▲Comparison with the previous thickness, $P<0.05$.

Table 5. Static pressure attenuation in different layers of skeletal muscle

Muscle layer	Surface	1/4	2/4	3/4	4/4
N	8	8	8	8	8
4 kg	4.000±0.000	3.51±0.002*	3.022±0.002*,▲	2.540±0.023*,▲	2.096±0.002*,▲
3 kg	3.000±0.000	2.63±0.002*	2.264±0.017*,▲	1.899±0.003*,▲	1.567±0.003*,▲
2 kg	2.000±0.000	1.75±0.002*	1.514±0.023*,▲	1.264±0.014*,▲	1.049±0.003*,▲
1 kg	1.000±0.000	0.916±0.001*	0.755±0.002*,▲	0.634±0.002*,▲	0.522±0.002*,▲
0.5 kg	0.500±0.000	0.43±0.002*	0.378±0.003*,▲	0.318±0.002*,▲	0.262±0.002*,▲
0.1 kg	0.100±0.000*	0.08±0.002*	0.077±0.002*,▲	0.065±0.002*,▲	0.053±0.002*,▲
0.05 kg	0.050±0.000	0.04±0.001*	0.038±0.001*,▲	0.034±0.003*,▲	0.026±0.002*,▲
0.02 kg	0.020±0.000	0.01±0.002*	0.015±0.002*,▲	0.012±0.002*,▲	0.011±0.002*,▲

*Comparison with the surface pressure, $P<0.05$. ▲Comparison with the previous layer, $P<0.05$.

sion in both clinical and experimental studies. Since gastrocnemius muscle quality varied among the study participants, we calculated the muscle tension improvement rate of each participant using muscle tension measurements collected before and after rolling manipulation massage.

In our clinical study, we found that a moderate rolling manipulation frequency of 120 repetitions/min was most effective in relieving muscle tension in patients with lumbar disc herniation. The frequency of manipulation, or the speed of the swing of manipulation, is the periodic movement formed by the alternating contraction of the targeted muscle and the antagonist muscle [18]. When the frequency of manipulation is too fast, this alternating contraction produces interference, which affects the accuracy of the manipulation and may also injure the operator [19]. This may explain why 120 repetitions/min was superior to 180 repetitions/min under fixed pressure in our study.

Interestingly, we observed that patients with severe pain benefited significantly more from rolling manipulation in terms of muscle tension relief compared to patients with mild pain or no pain. This finding is consistent studies reporting that massage relieves Jin, activates collaterals, regulates Qi, activates blood circulation, and relieves pain [20]. We suggest that this finding can be interpreted from two perspectives. From the TCM perspective, swelling, twitching, and pain in the gastrocnemius muscle is primarily caused by muscle spasm, known as tendon injury [21]. In TCM, tendon injury is treated by locating the pain point. In this study, we selected the Chengjin acupoint as the treatment location, because this acupoint is thought to be the site of gastrocnemius muscle spasm [22, 23]. From another perspective, rolling manipulation is reported to strengthen microcirculation [24], increase the local temperature, improve the local pain threshold, and fully elongate the tension or spasm of the muscle [25, 26]. The combination of these effects relieves

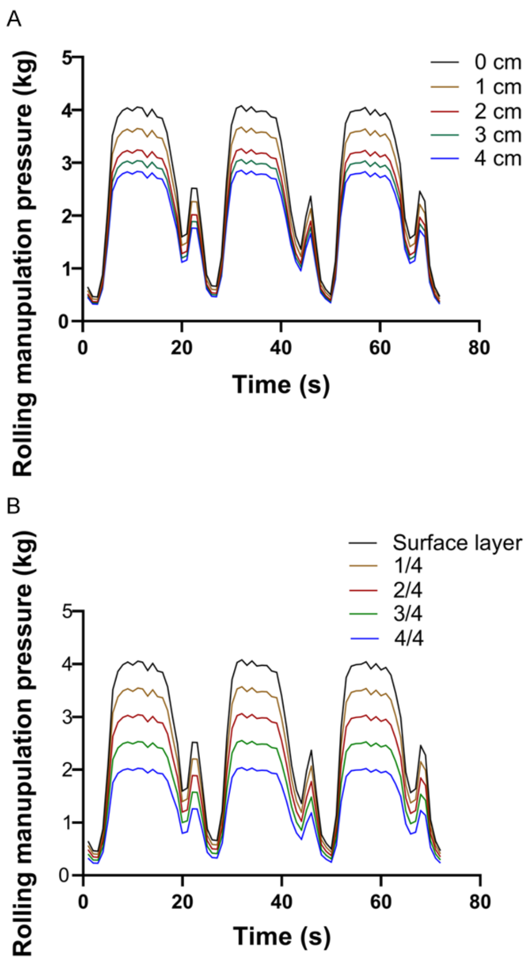

Figure 4. Dynamic rolling manipulation pressure attenuation in skeletal muscle. A. Dynamic pressure curves acquired with skeletal muscle of different thicknesses. B. Dynamic pressure curves acquired in different layers of skeletal muscle. Data are shown as mean ± SD (n=8).

the tension and spasm of the muscle, eliminating pain. From either perspective, our finding suggests that rolling manipulation massage may be particularly beneficial for patients with lumbar disc herniationwho are suffering for severe lower extremity pain.

Pressure is a key factor that affects the amount of stimulation achieved by rolling manipulation massage. Appropriate manual stimulation can promote metabolism and maintenance of muscle function, but excessive or prolonged mechanical stimulation can cause damage, especially in patients with skin damage, subcutaneous congestion, syncope, and other adverse reactions [27]. If the time and frequency of the rolling manipulation remain unchanged, the amount of stimulation will be directly proportional to the amount of pressure applied during the rolling manipulation [28]. Although pressure improved the muscle tension of the gastrocnemius in our study, we did not find a significant difference between the three levels of pressure applied (2, 4, and 6 kg). In contrast, we have previously shown that a manipulative pressure of 4 kg is optimal to promote Qi and activate blood flow when performing rolling manipulation.

We also found that varying the treatment duration (5, 10, or 15 min) did not significantly affect gastrocnemius muscle tone in patients with lumbar disc herniation. As additional treatment time did not offer additional benefit, blindly prolonging rolling manipulation is a waste of energy for operators. Based on our previous research, we infer that optimal effects can be achieved when rolling manipulation is performed for approximately 10 min.

Patient weight and gender had no significant effect in our study, indicating that rolling manipulation massage may be equally beneficial to patients of any weight or gender. This suggests that gender and weight are of low reference significance to the prescription of rolling manipulation massage by physicians.

Varying rolling manipulation parameters are commonly used in clinical practice and include pressure ranging from 2 to 6 kg, frequency ranging from 60 to 180 repetitions/min, and durations ranging from 5 to 15 min. In this study, every combination of these parameters improved the muscle tone of the gastrocnemius, suggesting that random parameter matching may still improve muscle tension. This further suggests that rolling manipulation without standardized training provides therapeutic benefit but may not reach the optimal therapeutic potential. To reach this optimal therapeutic potential, each combination of rolling manipulation parameters must be robustly tested and matched.

Attenuation of TCM rolling manipulation pressure

Porcine sacrospinous muscle tissue was used as a surrogate for human tissue to generate a translational experimental response to mechanical pressure in the tissue. The porcine sacrospinous muscle is similar to that of the human sacrospinous muscle in terms of mus-

Table 6. Dynamic rolling manipulation pressure attenuation in skeletal muscle of different thicknesses

Thickness: (cm)	0	1	2	3	4
N	8	8	8	8	8
0.1 s	0.470±0.019	0.422±0.002*	0.375±0.002*,▲	0.327±0.002*,▲	0.283±0.002*,▲
0.15 s	2.217±0.021	1.999±0.019*	1.776±0.002*,▲	1.536±0.002*,▲	1.322±0.002*,▲
0.2 s	3.963±0.023	3.575±0.002*	3.175±0.002*,▲	2.745±0.002*,▲	2.361±0.000*,▲
0.25 s	4.029±0.022	3.623±0.002*	3.246±0.002*,▲	2.795±0.002*,▲	2.418±0.001*,▲
0.3 s	4.070±0.023	3.671±0.002*	3.246±0.025*,▲	2.844±0.002*,▲	2.474±0.002*,▲
0.35 s	3.923±0.018	3.547±0.001*	3.130±0.023*,▲	2.748±0.001*,▲	2.360±0.013*,▲
0.4 s	3.785±0.016	3.422±0.002*	3.013±0.003*,▲	2.651±0.003*,▲	2.246±0.021*,▲
0.45 s	3.250±0.015	2.883±0.011*	2.541±0.003*,▲	2.233±0.023*,▲	1.899±0.018*,▲
0.5 s	2.625±0.021	2.344±0.018*	2.068±0.003*,▲	1.814±0.002*,▲	1.552±0.002*,▲
0.55 s	0.471±0.019	0.421±0.002*	0.377±0.002*,▲	0.328±0.002*,▲	0.284±0.002*,▲

*Comparison with the surface pressure, P<0.05. ▲Comparison with the previous thickness, P<0.05.

Table 7. Dynamic rolling manipulation pressure attenuation in different layers of skeletal muscle

Muscle layer	Surface	1/4	2/4	3/4	4/4
N	8	8	8	8	8
0.1 s	0.489±0.012	0.445±0.016*	0.387±0.001*,▲	0.332±0.003*,▲	0.276±0.002*,▲
0.15 s	2.207±0.013	1.979±0.003*	1.739±0.001*,▲	1.495±0.003*,▲	1.241±0.002*,▲
0.2 s	3.925±0.016	3.512±0.002*	3.091±0.001*,▲	2.658±0.002*,▲	2.206±0.001*,▲
0.25 s	3.988±0.015	3.569±0.002*	3.123±0.002*,▲	2.692±0.001*,▲	2.230±0.001*,▲
0.3 s	4.051±0.012	3.625±0.001*	3.155±0.002*,▲	2.725±0.001*,▲	2.254±0.001*,▲
0.35 s	3.913±0.015	3.493±0.003*	3.056±0.002*,▲	2.637±0.002*,▲	2.188±0.002*,▲
0.4 s	3.775±0.016	3.360±0.013*	2.956±0.001*,▲	2.549±0.002*,▲	2.122±0.003*,▲
0.45 s	3.172±0.014	2.828±0.013*	2.485±0.003*,▲	2.139±0.001*,▲	1.782±0.017*,▲
0.5 s	2.569±0.012	2.296±0.006*	2.014±0.024*,▲	1.729±0.002*,▲	1.441±0.020*,▲
0.55 s	0.489±0.011	0.446±0.015*	0.388±0.001*,▲	0.331±0.003*,▲	0.275±0.002*,▲

*Comparison with the surface pressure, P<0.05. ▲Comparison with the previous layer, P<0.05.

cle thickness, subcutaneous fat thickness, and muscle characteristics [29]. Therefore, we used porcine sacrospinous muscle to establish an experimental skeletal muscle model and to simulate the *in vivo* pressure response of skeletal muscle.

The greatest difficulty of establishing skeletal muscle models lies in the appropriate description of the behavior of the different muscle textures (e.g., muscle fibers or tendons). From a kinematic perspective, each skeletal muscle is composed of two parts: muscle belly and tendon [30, 31]. Skeletal muscles can also be broadly divided into two categories: long muscles (muscles with fibers parallel to the long axis) and latissimus muscles (muscles with fibers at a significant angle to the long axis). Latissimus muscles can be further divided into half feather, feather, and multiple feather muscles according to the number of muscle fiber groups with significantly different directions [32-35]. Skeletal muscle is a deformable system with spatial geometric, incompressible, and volume-invariant constraint characteristics. In other words, stress causes skeletal muscle to change shape but not volume [36-39]. In this study, we confirmed that the porcine sacrospinous muscle does not change in volume when external force is applied, and changes only in shape. Therefore, we concluded that this property of skeletal muscle was maintained in our system and could ensure inward layer-by-layer communication of the manual force.

The internal force generated by the muscle fiber depends on its current length, deformation rate, activity, and historical state [40]. To avoid experimental error caused by muscle degeneration, porcine sacrospinous muscle was freshly isolated for each experiment. An interesting observation in our study was that static force was attenuated to a greater degree when the diaphragm pressure sensor was inserted at different levels of 4-cm-thick muscle than when it was placed at the base of muscle tissues with different thicknesses. One possible explanation is that porcine sacrospinous muscle is rich, and the organization and tissue fluid have a large internal force. This internal force may generate more resistance and result in greater pressure attenuation. Another explanation could be that placing the sensor on the bench at the base of the porcine sacrospinous muscle provides no rebound force or intramuscular resistance. Therefore, the manual force is attenuated less than when the sensor is inserted in the muscle tissue.

Our results indicate that the frequency of TCM rolling manipulation massage and the pain level of the patient are important factors that significantly affect the relaxation of tendons and the relief of muscle tension. Specifically, a rolling manipulation frequency of 120 repetitions/min significantly improved the lower limb muscle tension of patients with lumbar disc herniation. Patients with severe pain from lumbar disc herniation experienced significantly greater improvement in lower limb muscle tone after rolling manipulation. Mechanistically, skeletal muscle pressure was attenuated by nearly 75% after TCM rolling manipulation at a depth of 2 cm from the muscle surface. Our findings provide important clinical and experimental insights into the therapeutic benefits of TCM rolling manipulation massage, and suggest that it effectively alleviates muscle tension under a wide range of parameters that can be optimized to improve clinical benefit.

Acknowledgements

This study was supported by the National Key R & D Program of China "Study on Modernization of Traditional Chinese Medicine" (no: 2019YFC1711800), the National Natural Science Foundation of China (no: 82074572, 81574095) and the Youth Natural Science Foundation of Hainan(no: 818QN248).

Disclosure of conflict of interest

None.

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