©Journal of Sports Science and Medicine (2018) **17,** 525-532
http://www.jssm.org

Research article

The Addition of Transcutaneous Electrical Nerve Stimulation with Roller Massage Alone or in Combination Did Not Increase Pain Tolerance or Range of Motion

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Abstract
Roller massage (RM) can be painful and induce muscle activity during application. Acute increases in pain pressure threshold (PPT) and range of motion (ROM) have been previously reported following RM. It is unclear whether the RM-induced increases in PPT and ROM can be attributed to changes in neural or muscle responses. To help determine if neural pain pathways are affected by roller massage, transcutaneous electrical nerve stimulation (TENS) was utilized as a form of electroanalgesia during RM with PPT and ROM tested on the affected and contralateral quadriceps. The purpose of this study was to evaluate in both quadriceps, the effect of brief intense TENS on PPT and ROM following unilateral RM of the quadriceps. A randomized within subjects' design was used to examine local and non-local effects of TENS and roller massage versus a control condition (rolling without TENS application). Four 30s bouts of roller massage of the dominant quadriceps were implemented with 30s of rest. The researcher applied the RM using a constant pressure device with approximately 70% of the maximum tolerable load. Perceived pain was monitored using a visual analog scale (VAS) during RM. Ipsilateral and contralateral quadriceps ROM and PPT were measured immediately following RM. Significant main effects for time showed increased PPT and ROM in both the treated and contralateral quadriceps, with no significant main effects for intervention or interactions for intervention and time. Moderate to large effect sizes and minimal clinically important differences (MCID) were detected when comparing baseline to pre- and post-tests respectively. VAS scores were significantly (main effect for intervention) and near significantly (interactions) reduced with MCID when TENS was applied during rolling. The addition of TENS to rolling did not increase PPT or ROM in the affected or contralateral quadriceps, likely due to a repeated testing effect.

Key words: Pain, stretching, flexibility, foam roller, self-myofascial release.

Introduction

Foam rolling (FR) and roller massage (RM) studies have increased dramatically in the literature recently, in parallel with their increased popularity within the training population. An acute session of rolling can increase static hip flexor (Behara and Jacobson, 2017; Bradbury-Squires et al., 2015; Mohr et al., 2014; Monteiro et al., 2017), hip extensor (MacDonald et al., 2013; Markovic, 2015; Monteiro et al., 2017; Sullivan et al., 2013) and ankle (Halperin et al., 2014; Kelly and Beardsley, 2016; Skarabot et al., 2015) range of motion (ROM), as well as dynamic hip extensor ROM during a lunge (Bushell et al., 2015). Su et al. (2016) reported greater hip flexor ROM with foam rolling versus static stretching. Improved flexibility can persist for up to 20 minutes after rolling (Junker and Stoggl, 2015; Kelly and Beardsley, 2016; Mohr et al., 2014) with increases in ROM ranging from 2.8% (Skarabot et al., 2015) to 23.4% (Grieve et al., 2015). Despite the abundance of findings of increased ROM, there is not unanimity in the rolling literature. Thoracolumbar fascia mobility significantly increased with foam rolling, but there was no significant effect on lumbar flexion (Griefahn et al., 2017). Some studies have reported no significant change in ROM of the hip extensors (hamstrings) (Couture et al., 2015), hip flexors (quadriceps) (Murray et al., 2016) and knee flexors (hamstrings) (Vigotsky et al., 2015) following rolling. Thus, the literature is not entirely consistent regarding the effects of rolling on ROM.

Rolling is often referred to as a self-myofascial release technique (Barnes, 1997; Beardsley and Skarabot, 2015; Cheatham and Kolber, 2017; Cheatham et al., 2015; Grieve et al., 2015; Healey et al., 2014; MacDonald et al., 2013; Okamoto et al., 2014; Peacock et al., 2014; Skarabot et al., 2015; Vaughan, 2014); however, it is unlikely that the predominant mechanism for rolling-induced increases in ROM is a modification of the myofascia. According to Schleip (Schleip, 2003a; 2003b), supra-physiological forces are needed to alter the mechanical properties of the fascia. Similar to an acute bout of stretching, a distinct possibility is that stretch (pain) tolerance (Magnusson, 1998; Magnusson et al., 1996) may be a primary mechanism underlying rolling-induced increases in ROM. Global pain reduction responses have been demonstrated with increased pain pressure threshold (PPT) in the plantar flexors (Aboodarda et al., 2015; Cavanaugh et al., 2017), quadriceps (Cheatham and Kolber, 2017) and hamstrings (Jay et al., 2014) following RM or manual massage (Jay et al., 2014) of the contralateral limb. Furthermore, rolling-induced improved flexibility has occurred in non-rolled muscles such as improved hamstring and lumbar spine flexibility after rolling the plantar surface of the feet (Grieve et al., 2015), improved dorsiflexion ROM with rolling of the contralateral plantar flexors (Kelly and Beardsley, 2016) and a tendency for contralateral (p = .095) increases in medial gastrocnemius PPT (Casanova et al., 2017). However, not all studies have found this effect with a lack of increase in sit and reach flexibility scores after rolling the plantar surface of the feet (Grabow et al. 2017a). Thus, the non-local rolling effects provide strong evidence for a global increase in pain or stretch tolerance.

If a central pain-modulatory system plays a role in mediation of perceived pain and stretch tolerance following RM (Aboodarda et al., 2015; Cavanaugh et al., 2017), is it

Received: 11 June 2018 / Accepted: 13 August 2018 / Published (online): 20 November 2018

possible to augment the analgesic effect in order to further improve ROM? Transcutaneous electrical nerve stimulation (TENS) is a form of electroanalgesia, which diminishes painful sensations (Sluka and Walsh, 2003; Vance et al., 2014) by activating either large (conventional TENS) or small (intense TENS) diameter afferents to block peripheral nerves associated with pain (segmental and extra-segmental analgesia respectively) (Jones, 2009). Magnusson and colleagues (Magnusson and Renstrom, 2006; Magnusson et al., 1996) have emphasized the role of increased stretch tolerance for the enhancement of ROM. If increased pain (diminution of stretch discomfort) tolerance with TENS is possible, either during the rolling or persisting thereafter, can there be additive effects when integrating RM with TENS?

The primary objective of the study was to examine the effects of RM, TENS and the combination of RM and TENS on ROM and PPT. It was hypothesized that a TENS-induced increase in pain tolerance would augment the proposed stretch tolerance mechanisms underlying RM to provide an additive improvement in ROM and PPT.

Methods

Participants: A convenience sample of twelve healthy individuals (seven males; 26 ± 3 years, 1.80 ± 0.07 m, 81.0 ± 8.28 kg, and five females; 25 ± 3 years, 1.70 ± 0.04 m, 70.9 ± 11.18 kg) volunteered to participate in this study. All participants reported being recreationally active, engaging in resistance training and/or aerobic exercise at least twice per week for the past 6 months. All participants were right foot dominant. Exclusion criteria included any history of neurological conditions or musculoskeletal injuries in the past year. All participants were verbally informed of the experimental protocol and gave written informed consent approved by the Interdisciplinary Committee on Ethics in Human Research (ICEHR) of the University (Approval #: 20180122-HK).

Research design: Using a randomized within subject design, the acute effects of TENS and RM, alone and in combination, on PPT and ROM were investigated. One familiarization session and four experimental sessions were conducted on separate testing days with at least 24-hours between sessions, at approximately the same time of day. Sisto and Dyson-Hudson (2007) have shown that intra-day and inter-day correlations for manual muscle testing with an algometer ranges from 0.88 to 0.99 and 0.94 to 0.98, respectively. During the familiarization session, participants were exposed to the techniques used to assess quadriceps ROM and PPT, the RM device, and the TENS. Each session followed the same testing order, including baseline, pre-intervention, and post-intervention measures of quadriceps ROM and PPT. The researcher who administered the RM and TENS was blinded to the results of baseline, pre-, and post-intervention changes in PPT and ROM. The order of experimental sessions was randomized, as well as whether the dominant or non-dominant limb was evaluated first.

Experimental protocol: The experimental sessions consisted of one of the following four conditions applied to the dominant rectus femoris: RM only (RM), TENS only (TENS), both TENS and RM (BOTH), Control (No TENS or RM). Participants sat on a padded bench with the thigh exposed for the duration of the intervention. At the beginning of each session, the researchers identified the midpoint of both thighs along the rectus femoris using a black marker to ensure consistent placement of the algometer, RM device, and TENS electrodes. Baseline measures of ROM, using the modified Thomas test, and PPT, using a manual muscle tester, were recorded. After baseline measurements were collected, participants were randomly assigned to an experimental condition. Intervention conditions consisted of determining maximum tolerable intensity using either the RM device, and/or TENS unit. This was completed by gradual increases in load and/or intensity using the respective devices until the participant indicated they had reached their maximum tolerance. While the RM maximum tolerance was painful, the intensity of the TENS used was below that which elicited a painful response. Pre-intervention measurements of ROM and PPT were taken immediately after determining maximum tolerable load and/or intensity, and post-intervention measurements immediately after the 4-minute intervention period.

Modified Thomas Test (MTT): For the MTT (Harvey, 1998), participants sat on the end of a massage table, rolled back on to the table, and held both knees to the chest. The participant held the contralateral leg so that the hip was in maximal flexion. The researcher held the tested leg in full hip extension while flexing the knee until the participant reached the maximal point of discomfort. The knee flexion angle was recorded by the same researcher with a manual goniometer. Both limbs were assessed.

Pain pressure threshold: The algometer (Lafayette Manual Muscle Test SystemTM, Model 01163, Lafayette Instrument Company, Indiana, USA) was a hand-held muscle tester with a range of 0-136.1 kg that consists of a padded disc with a surface area of 1.7 cm^2 attached to a microprocessor-control unit that measures peak force. The unit has a digital readout for peak-applied pressure and provides a built-in calibration routine that verifies valid calibration. In order to determine PPT, the researcher applied the algometer to a marked location on the rectus femoris until the participant verbally informed the researcher that the sensation had become painful (Aboodarda et al., 2015; Fischer, 1987; Ohrbach and Gale, 1989). PPT values were obtained every 5-sec over the target area and PPT was measured five times. Both limbs were assessed. This number and length of trials has been used in previous research studies and was found to be a reliable measurement of pain tolerance if 2 to 5 trials were averaged (Aboodarda et al., 2015; Fischer, 1987; Ohrbach and Gale, 1989).

Roller massage: A Thera-band® RM (Hygienic Corporation, Akron, OH, USA) was used for the duration of the experiment. The RM consisted of a hard rubber material (24 cm in length and 14-cm circumference) with low amplitude, longitudinal grooves surrounding a plastic cylinder (Halperin et al., 2014; Sullivan et al., 2013). The RM was placed in a specially designed constant pressure roller apparatus (Designed by Technical Services, Memorial University) (Bradbury-Squires et al., 2015; Casanova et al., 2017; Grabow et al., 2017a; Sullivan et al., 2013). To determine maximum tolerable load, weighted plates were added to the vertical poles until the load of the device for

one full cycle of rolling reached a 10/10 on a visual analog scale (VAS)(Aboodarda et al., 2015). Once this value was established, 70% of the maximum tolerable load used for the subsequent RM intervention.

Transcutaneous Electrical Nerve Stimulation: A protocol using brief intense TENS was chosen for the rapid onset of analgesia and stimulation of both gate control and opioid mechanisms of pain control (Cheng et al., 2014). The TENS unit (NeuroTrac MultiTENS, Model C6V350, Verity Medical Ltd, Romsey, UK) was set to a frequency of 150Hz and a pulse width of 250ms. After baseline measurements were recorded, participants were given 30-sec to increase the stimulation intensity until they reached their maximum tolerable intensity, defined as one setting below that which elicited a painful response. TENS electrode placement used an X pattern, with the previously marked location on the rectus femoris at the centre of the X.

Interventions: *RM only:* Participants sat with the dominant leg in the RM device. the researcher applied RM at 70% of maximum tolerable load for four sets of 30-sec with 30-sec rest. Participants recorded the pain associated with RM using a VAS at 5, 15, and 30-sec intervals during each bout of RM. (Bradbury-Squires et al., 2015; Grabow et al., 2017a; Sullivan et al., 2013),

TENS only: Participants sat with the dominant leg outstretched. TENS was applied at the predetermined setting, for four sets of 30-sec with 30-sec rest.

RM and TENS (BOTH): Participants sat with the dominant leg in the RM device. Participants were given 30-sec to increase the TENS intensity until they reached the predetermined setting. Once the appropriate setting was reached, the researcher applied RM at 70% of maximum tolerable load for four sets of 30-sec with 30-sec rest. Participants recorded the pain associated with RM using a VAS at 5, 15, and 30-sec intervals during each bout of RM.

Control: Participants sat with the dominant leg outstretched. Immediately following a 4-min rest period, post-intervention measurements were collected.

Data Processing: Based on the recommendation of Aboodarda et al. (2015), the first two trials for each PPT test were discarded and the remaining three trials were averaged to determine the value for that specific test. The ROM score from the MTT was the angle obtained at the position in which the MTT was stopped. The three VAS scores taken during each of the RM sessions were averaged and this was the score used for that specific test.

Statistical analysis: Statistical analyses were computed using IBM SPSS Statistics software (IBM Corp, SPSS Statistics for Macintosh, Version 23.0. Armonk, NY: IBM Corp.). A 4x3 repeated measures (within subjects) ANOVA was used to analyze the ROM and pain tolerance of the dominant and non-dominant quadriceps during the four interventions (RM, TENS, BOTH, Control) and three testing times (baseline, pre-intervention, post-intervention). A 2x4 repeated measures (within subjects) ANOVA was used to analyze the pain perception associated with RM during the two interventions involving RM (RM and BOTH) and four RM bouts during each intervention. If a significant effect was found, a Bonferroni correction post-hoc analysis was performed to determine where the differences occurred. Bonferroni correction was chosen since violations of sphericity and normality were present in the data and the post-hoc test helps control for type I errors (Field, 2013).

Effect sizes (ES), 95% confidence intervals (CI) and minimal clinically important differences (MCID) were calculated. ES with the magnitude of change descriptors were calculated and reported as trivial (<0.2), small (0.2-0.49), medium (0.5-0.79) or large (≥0.8) ES (Cohen, 1988). CI and standard error of the mean (SEM) were used to illustrate MCID (95% CI > SEM) (Page, 2014).

Mauchly's test indicated that the assumption of sphericity had been violated for the main effect of time, $\chi2(5) = 15.75$, $p = .008$, and the interaction effect, $\chi2(5) = 19.34$, $p = 0.002$, for the VAS measures and for the interaction effect, $\chi2(20) = 40.84$, $p = 0.006$, for the PPT measures of the dominant limb. Therefore, degrees of freedom were corrected using Greenhouse–Geisser estimates of sphericity ($\varepsilon < .75$ for each of the effects)(Field, 2013). Tests for normality were performed. The Shapiro-Wilk normality test reported that the baseline PPT test of the dominant limb during the BOTH intervention ($D(12) = 0.807$, $p = .011$), the baseline PPT test of the non-dominant limb during the CTRL intervention ($D(12) = 0.788$, $p = 0.007$), and the post-intervention PPT test of both the dominant ($D(12) = 0.810$, $p = 0.012$) and non-dominant ($D(12) = 0.823$, $p = 0.017$) limb during the CTRL intervention were not normally distributed. Numerous variables showed significant skewness and/or kurtosis, most variables were PPT measures. There is currently no non-parametric test to replace the RM ANOVA (Field, 2013). No transformation was performed; however, the increased potential for type I error was noted for the tests containing non-normal data (Field, 2013). Boxplots were used to observe for outliers, no outliers were removed from the data prior to running the statistical tests.

Results

Pain Pressure Threshold: *Dominant limb:* There was no significant main effect of the intervention ($F_{(3, 33)} = 0.242$, $p = 0.867$). There was a significant main effect of time on PPT in the dominant limb ($F_{(2, 22)} = 8.004$, $p = 0.002$). Bonferroni correction post-hoc test revealed that PPT was significantly higher during pre-intervention measures compared to baseline measures ($\Delta = 1.2 \pm 0.34$, (95% Confidence Intervals (CI): 0.29, 2.18)), and significantly higher during post-intervention measures compared to pre-intervention measures ($\Delta = 1.5 \pm 0.50$, (CI: 0.08, 2.88)). However, none of these comparisons proved to be MCID (CI overlapped with SEM). Whereas the pre- to post-test PPT change posted a trivial (0.08) magnitude effect size, baseline to pre-test and post-test achieved moderate magnitude changes (0.61 and 0.67 respectively).

A near significant interaction effect was detected between the intervention and time ($F_{(2.918, 32.097)} = 2.496$, $p = 0.079$) on PPT in the dominant limb. Table 1 illustrates that the TENS and RM conditions increased from trivial to small magnitude effect sizes when comparing PPT at baseline to pre- and post-test respectively. With TENS, there

were MCID (CI > SEM) exhibited when comparing baseline to post-test (CI: 0.75-4.16 vs. SEM: 0.46-0.62). In addition, with the TENS pre- to post-test comparison (CI: 0.51-3.29 vs. SEM: 0.56-0.62), the CI only exceeded the SEM by 3.9% indicating that 96.1% of the scores were assumed not to be due to measurement error. The BOTH condition exhibited small magnitude effect size increases in PPT at pre- and post-test when compared to baseline, whereas the Control session had trivial magnitude changes. Furthermore, with the BOTH condition, MCID were only detected when comparing baseline to pre-test. There were no MCID with the RM or Control conditions.

Non-dominant limb: There was no significant main effect of the intervention ($F_{(3, 33)} = 0.556$, $p = 0.648$) or interaction effect between the intervention and time ($F_{(6, 66)} = 0.106$, $p = 0.995$) on PPT in the non-dominant limb.

There was a significant main effect of time on PPT in the non-dominant limb ($F_{(2, 22)} = 11.226$, $p < 0.001$). Post-hoc test revealed that PPT was significantly higher during post-intervention measures compared to baseline measures ($\Delta = 1.8 \pm 0.40$, (CI: 0.65, 2.88)). This baseline vs. post-test result was also evident as a MCID (CI: 0.65-2.88 vs. SEM: 0.54-0.58).

Range of Motion: *Dominant limb:* There was no significant main effect of the intervention ($F_{(3, 33)} = 2.099$, $p = 0.11$) or significant interaction effect between the intervention and time ($F_{(6, 66)} = 0.325$, $p = 0.92$) on ROM in the dominant limb.

There was a significant main effect of time on ROM in the dominant limb ($F_{(2, 22)} = 49.478$, $p < 0.001$). Post-hoc test revealed that ROM was significantly better during pre-intervention measures compared to baseline measures ($\Delta = 2.8 \pm 0.49$, (CI: 1.44, 4.19)), during post-intervention measures compared to baseline measures ($\Delta = 6.0 \pm 0.67$, (CI: 4.17, 7.92)), and during post-intervention measures compares to pre-intervention measures ($\Delta = 3.2 \pm 0.65$, (CI: 1.39, 5.07)). All the aforementioned comparisons exhibited MCID (Table 2) and large magnitude effect size increases (baseline to pre-test: 0.89, baseline to post-test: 1.97, pre- to post-test: 0.95).

Non-dominant limb: There was no significant main effect of the intervention ($F_{(3, 33)} = 1.374$, $p = 0.268$) or significant interaction effect between the intervention and time ($F_{(6, 66)} = 0.705$, $p = 0.644$) on ROM in the non-dominant limb.

There was a significant main effect of time on ROM in the non-dominant limb ($F_{(2, 22)} = 36.496$, $p < 0.001$). Post-hoc test revealed that ROM was significantly better during pre-intervention measures compared to baseline measures ($\Delta = 2.2 \pm 0.64$, (CI: 0.37, 3.97)), during post-intervention measures compared to baseline measures ($\Delta = 5.3 \pm 0.66$, (CI: 3.48, 7.19)), and during post-intervention measures compares to pre-intervention measures ($\Delta = 3.2 \pm 0.59$, (CI: 1.52, 4.82)). MCID were evident when comparing non-dominant baseline to post-test (CI: 3.48-7.19 vs. SEM: 0.87-1.01) and pre- to post-test (CI: 1.52-4.82 vs. SEM: 0.99-1.01)(Table 2). Furthermore, effect sizes were moderate to large respectively (baseline to pre-test: 0.65, baseline to post-test: 1.62, pre-test to post-test: 0.81).

Visual Analog Scale: There was a significant main effect of the intervention on VAS during RM ($F_{(1, 11)} = 18.279$, $p = 0.001$). Post-hoc test revealed that there was more perceived pain associated with the RM during the RM only intervention compare to both the TENS and RM intervention ($\Delta = 1.6 \pm 0.38$, (CI: 0.78, 2.44)).

There was a significant main effect of time on VAS during RM ($F_{(1.726, 18.982)} = 16.183$, $p < 0.001$). Post-hoc test revealed that there was more perceived pain during the second round of RM compared to the first round ($\Delta = 0.9 \pm 0.21$, (CI: 0.19, 1.50)), during the third round of RM compared to the first round ($\Delta = 1.5 \pm 0.29$, (CI: 0.59, 2.42)), and during the fourth round compared to the first round ($\Delta = 1.8 \pm 0.34$, (CI: 0.66, 2.85)). All the aforementioned comparisons were MCID.

There was a near significant interaction effect between the intervention and time ($F_{(1.437, 15.811)} = 3.388$, $p = 0.072$). Table 2 illustrates that VAS scores exhibited moderate (first bout) to large (bouts 2-4) effect size magnitude higher scores with RM versus BOTH for all rolling bouts. Furthermore, the increase in VAS scores with RM condition were all large magnitude effect sizes when comparing

Table 1. Mean (±standard deviation) and effect sizes of ROM and PPT values.

Measures		Dominant Limb			Non-dominant limb		
	Intervention	Baseline	Pre	Post	Baseline	Pre	Post
PPT (kg)	TENS	16.1 (5.61)	16.7 (6.75)	18.6 (7.47)	15.7 (4.38)	16.4 (4.89)	17.3 (5.70)
	RM	17.3 (8.02)	18.4 (8.16)	17.1 (8.91)	16.6 (7.43)	17.8 (8.63)	18.5 (8.52)
	BOTH	15.9 (7.82)	18.2 (7.40)	17.5 (7.48)	16.1 (8.32)	17.1 (6.79)	18.0 (7.43)
	CTRL	16.8 (8.40)	17.7 (8.35)	18.8 (10.09)	15.7 (7.40)	16.3 (6.89)	17.3 (7.72)
ROM (degrees)	TENS	74.1 (14.05)	71.1 (13.71)	67.2 (12.53)	77.3 (13.10)	74.8 (14.16)	73.2 (15.78)
	RM	69.5 (9.47)	65.8 (9.47)	63.7 (9.28)	74.3 (7.64)	72.3 (10.99)	67.5 (11.90)
	BOTH	69.3 (10.36)	67.0 (13.11)	63.4 (11.87)	76.9 (13.67)	73.9 (13.36)	71.3 (14.07)
	CTRL	72.4 (12.38)	70.3 (13.27)	66.9 (12.15)	75.7 (10.51)	74.6 (12.00)	70.9 (9.78)
Effect Sizes and (Power)		**Dominant Limb**			**Non-dominant limb**		
	Intervention	**Baseline to Pre**	**Baseline to Post**	**Pre-Post**	**Baseline to Pre**	**Baseline to Post**	**Pre-Post**
PPT (kg)	TENS	.09	.38	.26 **(.84)**	.16	.31	.51 **(.16)**
	RM	.13	.23	.15 **(.45)**	.14	.23	.10 **(.21)**
	BOTH	.30	.21	.10 **(.24)**	.13	.24	.12 **(.35)**
	CTRL	.10	.19	.12 **(.31)**	.08	.19	.13 **(.35)**
ROM (degrees)	TENS	.21	.51	.30 **(.90)**	.18	.27	.10 **(.27)**
	RM	.39	.61	.22 **(.72)**	.21	.69	.41 **(.99)**
	BOTH	.19	.53	.28 **(.91)**	.22	.40	.21 **(.6)**
	CTRL	.16	.44	.26 **(.84)**	.09	.47	.33 **(.95)**

Estimated post-hoc statistical power are bolded and illustrated in brackets.

Table 2. Pain pressure threshold (PPT) and range of motion (ROM) data illustrating 95% confidence intervals (CI) and minimal clinically important differences (MCID).

	Comparison	95% CI	SEM
PPT Dominant	Baseline vs. Pre	0.29 - 2.18	.61 - .62
	Baseline vs. Post	0.08 - 2.88	.61 - .67
	Pre vs. Post	-1.20 - 0.70	.62 - .67
PPT Non-dominant	Baseline vs. Pre	-1.89 - 0.11	.54 - .53
	Baseline vs. Post	**0.65 - 2.88 ***	.54 - .58
	Pre vs. Post	-1.91 - 0.15	.53 - .58
ROM Dominant	Baseline vs. Pre	**1.44 - 4.19 ***	.87 - .93
	Baseline vs. Post	**4.17 - 7.92 ***	.87 - .89
	Pre vs. Post	**1.39 - 5.07 ***	.93 - .89
ROM Non-dominant	Baseline vs. Pre	0.37 - 3.97	.88 - .99
	Baseline vs. Post	**3.48 - 7.19 ***	.88 - 1.01
	Pre vs. Post	1.52 - 4.82 *	.99 - 1.01

*the 95% CI completely exceed the standard error of measurement (SEM) indicating a MCID.

Table 3. Mean (±standard deviation) and effect sizes of Visual Analogue Scale (VAS) scores.

Visual Analogue Scale (VAS)						
	Bout 1	**Bout 2**	**Bout 3**	**Bout 4**		
RM	3.5 (1.38)	4.8 (1.55)	5.4 (1.49)	5.9 (1.57)		
BOTH	2.6 (1.52)	3.0 (1.51)	3.7 (1.79)	3.7 (2.22)		
Effect Sizes						
	Bout 1	**Bout 2**	**Bout 3**	**Bout 4**		
RM vs. BOTH	0.62	1.17	1.03	1.16		
	1 vs. 2	**1 vs. 3**	**1 vs. 4**	**2 vs. 3**	**2 vs. 4**	**3 vs. 4**
RM	0.88	1.32	1.62	0.39	0.71	0.32
BOTH	0.26	0.66	0.58	0.42	0.37	0

Table 4. Visual Analogue Scale (VAS) rolling bouts interactions illustrating 95% confidence intervals (CI) and minimal clinically important differences (MCID).

	Comparison	95% CI	SEM
RM	1 vs. 2	**0.63 - 1.83 ***	0.11 - 0.13
	1 vs. 3	**1.20 - 2.49 ***	0.11 - 0.12
	1 vs. 4	**1.66 - 3.01 ***	0.11 - 0.13
	2 vs. 3	0.11 - 1.12	0.13 - 0.12
	2 vs. 4	**0.48 - 1.73 ***	0.13 - 0.13
	3 vs. 4	**0.18 - 0.81 ***	0.12 - 0.13
BOTH	1 vs. 2	-0.02 - 0.94	0.12 - 0.12
	1 vs. 3	**0.34 - 1.99 ***	0.12 - 0.15
	1 vs. 4	-0.03 - 2.38	0.12 - 0.18
	2 vs. 3	0.08 - 1.33	0.12 - 0.15
	2 vs. 4	-0.42 - 1.85	0.12 - 0.18
	3 vs. 4	-0.64 - 0.65	0.15 - 0.18

* the 95% CI completely exceed the standard error of measurement (SEM) indicating a MCID.

the first to subsequent bouts of rolling whereas with the BOTH condition, the effect size magnitudes were small to moderate (Table 2). Table 3 illustrates MCID and provides further evidence for the increases in VAS scores with RM with all succeeding rolling bouts (i.e. 1 vs. 2-4, 2 vs. 4 and 3 vs. 4). Furthermore, there was very little overlap when comparing RM rolling bouts 2 vs. 3 (CI: 0.11-1.12 compared to SEM 0.12-0.13). In contrast the BOTH condition only exhibited a MCID (increased VAS) with one comparison (rolling bout 1 vs. 3) (Table 4).

Discussion

The most important finding of the study was that the simultaneous use of RM and TENS did not cause any additional effects to pain tolerance (PPT) or ROM in either the treated or contralateral quadriceps. In fact, there were no significant differences between any of the interventions, including control, on pain tolerance or ROM. Additionally, measurements of pain tolerance and ROM did show improvements with time across all four interventions for both quadriceps. Finally, in terms of the VAS measures, there was a decrease in perceived pain associated with RM when it was accompanied by TENS, and RM was reported to be more painful in the last three rounds of RM compared to the first round.

This is the first study to combine RM and TENS; therefore, there are no previous findings to which these results can be compared. It is somewhat difficult to interpret the lack of significant differences to pain perception or ROM between interventions. However, since even the control, which did not use RM or TENS, was not significantly different from the other interventions, it appears possible that the time-dependent changes in pain perception and ROM were at least partly due to the actual testing consisting of the MTT and PPT. Stretching is an effective mechanism to increase ROM, due to several mechanisms including changes to muscle viscoelasticity and increased stretch tolerance (Behm et al., 2015). While the MTT is not a lengthy test, it still involved stretching the muscle to the

point of maximal tolerable stretch. This could activate several stretch-induced adaptations, which may result in an increased ROM during subsequent tests. In terms of pain perception, Aboodarda et al. (2015) and Cavanaugh et al. (2017) showed that over a short testing period, initial PPT trials caused superficial nociceptors to have an increased sensitivity, resulting in higher PPT values. However, it is possible that over a longer testing period (i.e. between a baseline and pre-intervention test), the previous set of PPT trials may in fact desensitize the nociceptors to the sensation of the algometer. In accordance with this rationale, the present study's, baseline to pre-test PPT increased by a moderate magnitude (ES : 0.61), whereas pre- to post-test showed trivial magnitude changes. Hence, the both legs' PPT main effect for time was primarily driven by the repeated testing effect.

Albeit, there was no statistically significant interaction dominant leg PPT differences ($p > 0.05$), the results did approach significance ($p = 0.079$) with perceptible increases in effect size magnitudes. Whereas the control condition changes when comparing pre- and post-test to baseline remained at a trivial magnitude with no evidence of MCID, TENS and RM increased from trivial to small magnitude changes at pre- to post-test respectively. The increased PPT with TENS achieved MCID and 96% of MCID when comparing baseline and pre-test PPT to post-test respectively. However, the RM condition did not reach MCID for any of the comparisons. The BOTH condition had small magnitude PPT increases at pre- and post-test when compared to baseline values but only achieved a MCID when comparing baseline to pre-test. The small magnitude effect size changes with the experimental conditions versus trivial control changes might be interpreted as suggesting a possible pattern of evidence for increased PPT or decreased pain sensitivity but generally, the small magnitude changes predominately occurred in relation to the baseline rather than the subsequent pre-test. While an increased PPT finding with RM would be in accordance with the literature (Aboodarda et al., 2015; Casanova et al., 2017; Cavanaugh et al., 2017; Cheatham and Kolber, 2017; Grieve et al., 2015; Jay et al., 2014; Kelly and Beardsley, 2016), in the present study, there was limited clinical evidence for the analgesic effects of TENS (Sluka and Walsh, 2003; Vance et al., 2014) or RM, and no additive effect with the combination of TENS and RM (BOTH). As previously mentioned, a repeated testing effect seemed to diminish MCID or small magnitude changes in PPT. Prior and future RM pain tolerance results should be viewed with caution if only a single pre-test is conducted.

Previous studies measuring pain tolerance following RM have shown significant increases in PPT (Aboodarda et al., 2015; Casanova et al., 2017; Jay et al., 2014; Vaughan, 2014). However, none of these studies targeted the quadriceps muscle. There have been no evaluations of PPT following RM to the quadriceps muscle. It is possible that there are properties of the quadriceps muscle that may limit the magnitude of change in pain tolerance (less sensitivity) measured through repetitive pressure algometry. Similar to ROM, the changes in PPT may be attributed to a testing effect associated with repeated use and measurement.

The RM device used in the study has been used in previous studies (Bradbury-Squires et al., 2015; Casanova et al., 2017; Grabow et al., 2017b; Sullivan et al., 2013). These studies have all found changes in ROM to the muscle of interest; however, none of the previous studies used the MTT to measure changes to quadriceps ROM. When assessing ROM of the quadriceps, other studies have used the inline lunge test to assess ROM, which has revealed more significant findings (Grabow et al., 2017b; Macdonald et al., 2013; 2014); although it can be more difficult to control the position of the pelvis using this test. One previous study using foam rollers found no significant change in ROM assessed by the MTT (Vigotsky et al., 2015). Therefore, it is possible that the changes in ROM are not easily detected using the MTT, and that the present changes in the MTT seen in all interventions were simply due to a testing effect. All conditions including control for both legs demonstrated MCID increases in ROM from baseline to pre-test and pre- to post-test with moderate to large magnitude effect sizes.

Finally, both the intervention and the particular round of RM, as determined by the VAS, affected pain perception. Since perceived pain was lower during the rounds of RM while TENS was in use, TENS did indeed produce an analgesic effect. Although not statistically significant there was a near significant ($p = 0.072$) increase in pain tolerance during the intervention with both TENS and RM compared to RM alone. The increased magnitude effect sizes of VAS scores with RM compared to the BOTH condition was classified as moderate (first bout) to large (bouts 2-4). Further evidence for increased VAS scores with each bout of rolling, with the RM condition, was shown with the 95% CI exceeding the SEM indicating a MCID when comparing all subsequent rolling bouts (i.e. 1 vs. 2, 3, 4 or 2 vs. 4 and 3 vs. 4). However, with the BOTH condition, there was only a MCID for an increased VAS score when comparing rolling bouts 1 vs. 3. This analgesic effect appeared to be transient, and only present while TENS was being administered. During the second, third, and fourth rounds of RM, pain perception was reported as higher compared to the first round of RM across all conditions. These findings indicate that as the duration of RM increased, so too did perceived pain. This increase in perceived pain could be related to an increased sensitivity of nociceptors, similar to the effects of the PPT algometer (Aboodarda et al., 2015; Cavanaugh et al., 2017).

Limitations/Caveats

There are several limitations to consider with the current study. Across all RM trials, the average VAS score associated with the rolling was 4.9/10 for RM and 3.3/10 for BOTH. These values are lower than what would be anticipated at a load equal to 70% of a load that elicited a VAS score of 10/10 and may explain the lack of significant findings. The current literature is limited on comparing RM intensities and the associated magnitudes of change of testing measures. The available research shows mixed results as to whether an intensity-dependent relationship is present (Grabow et al., 2017b; Young et al., 2018)

Part of the study was accurately determining the required intensities for TENS and RM while limiting the im-

pact on the targeted muscle prior to the actual intervention. By exposing the participant to the devices for a brief time, followed by performing the tests, and then finally performing the intervention, it is possible that some adaptations occurred. These adaptations may render the muscle less sensitive to the following intervention, resulting in a smaller and insignificant magnitude of change.

There is limited research assessing PPT of the quadriceps following rolling interventions. There is no prior RM research that uses PPT to assess pain tolerance in the quadriceps; however, there are two previous studies that found an acute increase in PPT following foam rolling of the ipsilateral (Cheatham and Baker, 2017) and contralateral (Cheatham and Baker, 2017; Cheatham et al., 2017) quadriceps muscle. Given the exploratory nature of these studies, the reliability, validity, and specificity is not totally clear.

Finally, there was the presence of some non-normally distributed data. Since there is no non-parametric equivalent for a repeated-measures ANOVA, the tests were conducted despite the lack of normal distribution. Therefore, there is an increased potential for the presence of type I errors in the ANOVAs containing non-normal data. This includes the pain tolerance tests for both the dominant and non-dominant limb, which each had a significant main effect for time. However, the inclusion of ES and MCID provide additional clarity for the results and interpretations. On the other hand, distribution-based approaches to MCID have limitations. They allow calculation of the MCID, but not the clinically important differences. Furthermore, they only define the minimum value below which a change in pain score is not due to measurement error (Katz et al., 2015).

Conclusions

In conclusion, the addition of TENS to RM of the quadriceps did not significantly improve pain tolerance or ROM with the affected or contralateral leg. Future studies should continue to observe the interactions of RM and TENS, however the RM protocol, the targeted muscle group, and the chosen test measures should more closely follow those of previous studies which have shown pain tolerance and ROM improvements with RM. The finding that TENS decreases the relative amount of perceived pain during RM is an important consideration for future research and eventually clinical application. Future studies should determine if the use of TENS can increase the maximum tolerable RM intensity an individual can maintain and analyze the resultant changes to pain tolerance and ROM measures.

Acknowledgements

No authors declare conflicts of interest. The study complied with the laws of the country of the authors' affiliation.

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Key points

- The simultaneous use of RM and TENS did not cause any additional effects to pain tolerance or ROM in the treated or contralateral quadriceps.
- A repeated testing effect seemed to diminish MCID or small magnitude changes in PPT. Prior and future RM pain tolerance results should be viewed with caution if only a single pre-test is conducted.
- TENS decreases the relative amount of perceived pain during RM. This is an important consideration for future research and clinical application.

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