EFFECTS OF PERCUSSIVE MASSAGE ON SYMPTOMS ASSOCIATED WITH ECCENTRIC EXERCISE-INDUCED MUSCLE DAMAGE

A Thesis By

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Abstract:
Due to the lack of research, this study aimed to investigate the effects of percussive massage (PM) on maximal isometric torque (MIT), range of motion (ROM), and a numerical rating scale (NRS) of soreness from 24 to 72 h post-eccentric exercise (P-EE). Seventeen healthy, untrained volunteers (14 females and 3 males) performed 60 eccentric elbow flexion actions. Nine participants received 60 s of PM on their nondominant arm’s biceps brachii immediately, 24, 48, and 72 h P-EE, whereas eight participants rested quietly (control [CON]). NRS of soreness, ROM, and MIT were assessed after treatment (AT), in that order, at 24, 48, and 72 h P-EE. NRS was also assessed before treatment (BT) on those visits. Electromyographic and mechanomyographic root mean square (EMG\textsubscript{RMS} and MMG\textsubscript{RMS}) values were collected during the MIT. The results indicated that PM did not significantly affect MIT and muscle activation (EMG\textsubscript{RMS} and MMG\textsubscript{RMS}). However, the PM group had significantly higher ROM from 24 to 72 h P-EE, returned their ROM to baseline values (48 h) faster than the CON (72 h), and increased their ROM at 72 h from baseline. There was no significant difference in NRS of soreness between groups BT 24 to 72 h P-EE, but the PM group recovered to their baseline (BT 72 h) faster than the CON (never recovered). In addition, the PM significantly reduced NRS from BT to AT within every P-EE visit, which resulted in the PM group having significantly lower values than the CON AT from 24 to 72 h P-EE. In conclusion, after an intense eccentric exercise targeted for the nondominant arm’s biceps brachii, the PM improved ROM without affecting MIT and muscle activation 24 to 72 h P-EE. Additionally, although the PM did not improve the recovery of perceived soreness until 72 h P-EE, it consistently provided immediate, temporary relief when used 24 to 72 h P-EE.
# TABLE OF CONTENTS

LIST OF TABLES ........................................................................................................ iv

LIST OF FIGURES ..................................................................................................... v

ACKNOWLEDGMENTS .............................................................................................. vi

1. INTRODUCTION .................................................................................................. 1

   Assumptions ........................................................................................................... 4

   Delimitations ......................................................................................................... 4

2. REVIEW OF LITERATURE ................................................................................. 6

   Exercise-Induced Muscle Damage ....................................................................... 6

   Proposed Physiological Mechanisms ................................................................... 6

   Symptoms ............................................................................................................. 8

   Sex Differences .................................................................................................. 10

   Percussive Massage ............................................................................................ 11

   Effects on Symptoms Associated with Exercise-Induced Muscle Damage .......... 11

   Acute Effects on Muscular Performance .......................................................... 14

   Potential Physiological Mechanisms .................................................................. 16

   Local Vibration Therapy ...................................................................................... 18

   Effects on Symptoms Associated with Exercise-Induced Muscle Damage .......... 18

   Acute Effects on Muscular Performance .......................................................... 21

   Tapotement Massage ......................................................................................... 23

3. METHODS ............................................................................................................. 26

   Experimental Approach to the Problem ............................................................ 26

   Subjects ............................................................................................................... 27

   Procedures .......................................................................................................... 28

   Concentric 1-Repetition Maximum .................................................................. 28

   Eccentric Exercise .............................................................................................. 28

   Treatment Intervention ....................................................................................... 29

   Delayed Onset Muscle Soreness ....................................................................... 30

   Range of Motion .................................................................................................. 30

   Maximal Isometric Torque .................................................................................. 31

   Electromyographic and Mechanomyographic Measurements and Signal Processing 31

   Statistical Analyses ........................................................................................... 32

4. RESULTS ............................................................................................................... 33

   Maximal Isometric Torque .................................................................................. 33

   Electromyographic and Mechanomyographic Amplitude .................................. 34

   Range of Motion .................................................................................................. 35

   Delayed Onset Muscle Soreness ....................................................................... 36
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Mean ± SD values for normalized (% of baseline [i.e., pre-eccentric exercise]) maximal isometric torque (MIT) and mechanomyographic root mean square (MMGRMS)</td>
<td>34</td>
</tr>
<tr>
<td>2.</td>
<td>Mean ± SD values for normalized (% of baseline [i.e., pre-eccentric exercise]) range of motion (ROM)</td>
<td>36</td>
</tr>
<tr>
<td>3.</td>
<td>Mean ± SD values for numerical rating scale of soreness (0-10)</td>
<td>37</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Research design</td>
<td>27</td>
</tr>
<tr>
<td>2.</td>
<td>The handheld percussive massage device (Hypervolt 2) that was used in this study</td>
<td>30</td>
</tr>
<tr>
<td>3.</td>
<td>Mean ± SD changes in normalized (% of baseline [i.e., pre-eccentric exercise]) maximal isometric torque (MIT)</td>
<td>33</td>
</tr>
<tr>
<td>4.</td>
<td>Mean ± SD changes in normalized (% of baseline [i.e., pre-eccentric exercise]) mechanomyographic root mean square (MMG\textsubscript{RMS})</td>
<td>34</td>
</tr>
<tr>
<td>5.</td>
<td>Mean ± SD changes in normalized (% of baseline [i.e., pre-eccentric exercise]) range of motion (ROM)</td>
<td>35</td>
</tr>
<tr>
<td>6.</td>
<td>Mean ± SD changes in the numerical rating scale (NRS) of soreness</td>
<td>37</td>
</tr>
</tbody>
</table>
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CHAPTER 1

INTRODUCTION

Exercise-induced muscle damage (EIMD) commonly occurs after performing highly intense eccentric actions or unaccustomed forms of exercise.\textsuperscript{1–5} Although the precise pathogenesis of EIMD remains unclear,\textsuperscript{4,5} research suggests that it likely results from ultrastructural muscle tissue damage caused by highly intense eccentric actions or unaccustomed exercise.\textsuperscript{1} In response, a secondary muscle damage process may occur via increased intracellular calcium,\textsuperscript{1–4} ultimately resulting in an inflammatory response.\textsuperscript{2,3,6} Delayed onset muscle soreness (DOMS) has been a commonly reported symptom.\textsuperscript{2,3,5} This term has been used to describe the symptom since individuals have often reported muscle soreness that peaks in intensity 24 to 72 h post-exercise and subsides after 5 to 7 days.\textsuperscript{2,3,5} Other potential symptoms include decreased range of motion (ROM),\textsuperscript{2,5,7} strength and power,\textsuperscript{2,3,5,7–9} proprioception,\textsuperscript{1,5,9,10} and altered joint kinematics.\textsuperscript{5,11–14} As a result, researchers have investigated numerous forms of treatments that could accelerate recovery,\textsuperscript{15–18} because this may benefit athletes needing to regain performance levels following frequent training sessions and competitions\textsuperscript{19,20} or individuals wanting a faster return to daily activities. Handheld percussive massage (PM) devices (e.g., Hypervolt or Theragun), which provide rapid mechanical percussions via different attachment tips, have recently gained popularity\textsuperscript{21} and are commonly marketed as a tool for enhancing recovery and performance; however, there is limited research to confirm those claims.

Only a few studies\textsuperscript{22–24} have investigated the effects of PM on symptoms associated with EIMD. García-Sillero et al\textsuperscript{22} used a limb-to-limb design (i.e., treatment vs. control limb) with the gastrocnemius muscle to compare PM to three other treatment groups. They found that PM (2 min) immediately post-eccentric exercise (P-EE) was able to accelerate muscle recovery, represented by restored muscle compliance and reduced stiffness, greater than local vibration therapy (1 min) or foam rolling (2 sets of 30) but similarly effective than conventional massage (15 min). Leabeater et al\textsuperscript{23} also used a limb-to-limb design with the same muscle and gave 5 min of PM immediately post-exercise (3 sets of 20 calf
raises). The authors found that PM had no immediate effects on performance (isometric strength and
dynamic endurance) or calf circumference, and it did not significantly affect perceived muscle soreness
immediately, 4, 24, and 48 h post-exercise. Lastly, Rogers and Rogers\textsuperscript{24} examined the effects of 10 min
of PM on the quadriceps at 48 h post-exercise (10 sets of 10 back squats), but their comparisons were
made within subjects and without a control. The PM significantly reduced pain and improved vertical
jump performance compared to the same participants’ measures taken before the PM at 48 h post-
exercise. The varying results within these studies are likely due to the varying research designs and
methods.

More research has been devoted to investigating the acute effects of PM in ways not associated
with EIMD. For example, when examining its effects on ROM as a pre-exercise treatment, most
studies\textsuperscript{25–30} have observed significant increases primarily with lower limb muscles,\textsuperscript{25–28,30} but there are a
few studies\textsuperscript{31–33} that reported no improvements primarily with the muscles and fascia of the back.
Moreover, two of the studies\textsuperscript{28,30} that observed PM to be effective in increasing ROM found that it was
not more effective than static stretching. Although, unlike static stretching, which has abundant evidence
suggesting it may acutely decrease strength and power,\textsuperscript{34–38} the majority of the current PM studies have
reported no acute effects on jumping performances,\textsuperscript{26,27,39,40} isometric strength,\textsuperscript{25} or agility.\textsuperscript{27} However,
in contrast, one study\textsuperscript{27} observed an acute decrease in anaerobic power during a Wingate test following
PM. Lastly, unrelated to using PM as a pre-exercise treatment, García-Sillero et al\textsuperscript{41} concluded that PM
was effective in delaying a loss in bench press velocity when used as an inter-set rest treatment.

Research on the mechanisms by which PM may affect recovery or performance is also limited.
Due to the lack of studies at the time, Cheatham et al\textsuperscript{21} surveyed 425 healthcare and fitness professionals
to investigate their beliefs on PM’s potential clinical benefits. Most of the respondents (85.88%) believed that PM has therapeutic effects, and of those 85.88% respondents, more than half of them
believed it could potentially increase blood flow (69.10%), modulate pain (65.09%), enhance myofascial
(61.79%), and break up myofascial trigger points (54.01%). Recent studies have confirmed that PM may
acutely increase blood flow\textsuperscript{42,43} and enhance oxygen availability and consumption,\textsuperscript{44} which may help support muscle recovery.\textsuperscript{42,43,45} Additionally, studies have confirmed that PM may decrease perceived muscle pain\textsuperscript{46} or stiffness;\textsuperscript{31} however, these observations were not paired with morphological changes in myofascial trigger points\textsuperscript{46} or fascial thickness.\textsuperscript{31} Lastly, Yang et al\textsuperscript{31} reported that PM reduced echo intensity and increased skin temperature of the thoracolumbar region in healthy males.

Since PM devices provide rapid percussions (~17 to 53 Hz), researchers have speculated that it uses a component of local vibration therapy (LVT).\textsuperscript{21,25} Therefore, since more research has been conducted on LVT, it may provide helpful insight into PM’s potential effects on treating symptoms associated with EIMD. Studies have examined applying LVT before and after EIMD protocols, and there is evidence to suggest that it may help reduce pain or soreness,\textsuperscript{47–53} improve ROM\textsuperscript{48,50,52} and strength,\textsuperscript{48,51,54} reduce biochemical indicators of muscle damage (e.g., creatine kinase or lactate dehydrogenase),\textsuperscript{48,51–53,55} and increase oxygen re-saturation rates.\textsuperscript{45} However, on the contrary, some researchers have observed no improvements in strength,\textsuperscript{48,50} muscle stiffness,\textsuperscript{56} swelling,\textsuperscript{49} creatine kinase,\textsuperscript{49,50} and lactate dehydrogenase levels.\textsuperscript{49} Similar to the PM studies, the differences in results may likely be due to heterogenous research designs and methods. Furthermore, when researchers investigated LVT’s acute effects unrelated to EIMD (i.e., pre-exercise treatment), they found that it acutely increased ROM.\textsuperscript{57–61} Additionally, two review papers concluded that it was effective in acutely increasing strength,\textsuperscript{61,62} power,\textsuperscript{61} and muscle activation (i.e., EMG amplitude),\textsuperscript{61} which have been primarily attributed to the tonic vibration reflex.\textsuperscript{63,64}

If PM were to affect strength performance in the present study, simultaneous surface electromyography (EMG) and mechanomyography (MMG) measurements during the strength testing could provide electrical and mechanical insights, respectively, on the neuromuscular activation patterns.\textsuperscript{65–67} Surface EMG measures the electrical activity of muscles by detecting the sum of motor unit action potentials within the vicinity of the sensors.\textsuperscript{68} MMG has been suggested to be the mechanical counterpart to EMG\textsuperscript{69} since it quantifies the lateral oscillations and dimensional changes of active
muscle fibers. The amplitude content of EMG has been suggested to represent muscle activation, which may be influenced by motor unit recruitment, firing rate, and synchronization, whereas the amplitude content of MMG has been suggested to reflect motor unit recruitment. To date, researchers have yet to investigate the effects of PM on EMG and MMG activity; however, as discussed earlier, there are reports of LVT acutely increasing EMG amplitude.

PM is growing in popularity, but the literature on how it may affect symptoms associated with EIMD is limited. As a result, multiple authors have called for more research on this topic. Researchers have yet to investigate the effects of PM on maximal isometric strength (MIT) and ROM 24 to 72 h P-EE. Those two performance measures have been suggested to be one of the most valid and reliable measures for quantifying the effects of EIMD. Therefore, this study aimed to investigate the effects of applying PM on the nondominant arm’s biceps brachii immediately, 24, 48, and 72 h P-EE on MIT, ROM, and DOMS (11-point numerical rating scale [NRS] of soreness). All variables were collected after the treatment intervention at 24, 48, and 72 h P-EE, but NRS of soreness was also collected before the treatment intervention during those P-EE visits. Also, EMG and MMG amplitude were collected during MIT testing to provide insight on muscle activation. The author hypothesized that PM would improve all three measures at all P-EE times, and PM would immediately reduce NRS of soreness from before to after the treatment intervention within every P-EE visit.

Assumptions

1. Participants were assumed to have met all of the inclusion criteria.
2. Participants were assumed to refrain from strenuous physical activity, maintain their same diet and hydration habits, and avoid other treatments throughout the entire study.
3. Participants were assumed to give maximal effort during all tests.
4. When recording NRS of soreness, participants were assumed to assess their perceived soreness to the best of their abilities.

Delimitations

1. The selection of participants was delimited to healthy, untrained male and female volunteers from 18 to 30 years old and those who completed the Informed Consent.
2. For the eccentric exercise, participants were delimited to performing 6 sets of 10 eccentric repetitions, with two minutes of rest between sets, for the elbow flexors through a full ROM with a dumbbell that weighed approximately 85% of their concentric 1-repetition maximum.

3. Participants were delimited to attending three P-EE laboratory visits separated by 24 h (i.e., 24, 48, and 72 h P-EE).

4. Participants in the treatment group were delimited to the PM device (Hypervolt 2), type of attachment (round ball), frequency (40 Hz), duration (60 s), and muscle targeted (biceps brachii of the nondominant arm).

5. Participants in the treatment group were delimited to receiving PM immediately, 24, 48, and 72 h P-EE.

6. Participants in the control group were delimited to receiving no treatment and resting quietly for an equal amount of time as the PM intervention.
CHAPTER 2
REVIEW OF LITERATURE

Exercise-Induced Muscle Damage

Proposed Physiological Mechanisms

Several hypotheses or theories (e.g., muscle spasms, muscle damage, connective tissue damage, inflammation, etc.) have attempted to describe the pathogenesis of EIMD; however, the precise mechanism has yet to be established. The pathogenesis of EIMD is a complex process; therefore, a singular mechanism may likely not fully represent the multiple, cascading events that cause it. Instead, authors have attempted to detail the sequences of events that result in EIMD to their best knowledge based on the current literature.

Unaccustomed forms of exercise or increases in intensity and duration may result in EIMD; however, it is most commonly caused by exercises involving highly intense eccentric contractions. Eccentric (i.e., lengthening of muscle) contractions can generate more force and require less energy than isometric (i.e., no change in muscle length) and concentric (i.e., shortening of muscle) contractions. However, eccentric exercise results in the most mechanical stress and damage compared to concentric and isometric since fewer motor units are recruited, resulting in a greater force per active motor unit. Furthermore, under eccentric contractions, sarcomeres lengthen in a non-uniform manner, resulting in some of the weakest sarcomeres being overstretched beyond their myofilament overlap (termed as “popped sarcomeres”). Since these “popped sarcomeres” cannot produce tension, passive structures increase tension production to halt further lengthening, and the structural integrity of the sarcomere is disrupted. This process likely repeats with the next weakest sarcomere in repeated eccentric contractions. When the region of sarcomere disruption is large enough, further damage to other muscle cell structures may occur, such as the sarcolemma, t-tubule system, and sarcoplasmic reticulum (SR). Damage to these structures could negatively affect excitation-contraction coupling and lead to further strength decrements. Additionally, it should be noted that damage to muscle connective tissue (i.e.,
extracellular matrix) has also been observed and likely contributes to the pain, inflammation, and adaptation responses seen with EIMD.3,74,75

Following this initial muscle damage process, a secondary muscle damage process may occur from an increase in intracellular calcium (CA\(^{2+}\)).1–4 Since CA\(^{2+}\) concentrations are higher in the extracellular space and SR compared to the sarcoplasm under normal conditions, damage to the sarcolemma and SR results in an influx of CA\(^{2+}\) into the sarcoplasm.2 Not only will increased intracellular CA\(^{2+}\) concentrations increase passive tension and decrease active tension,1,3 but it also activates the phospholipase-prostaglandin and calpain proteolytic pathways.2,3 The phospholipase-prostaglandin pathway activates phospholipase A2, which promotes further damage to the sarcolemma and results in a loss of intracellular molecules. The calpain proteolytic pathway activates Calpain 3, which cleaves cytoskeleton proteins that make up the Z-disc and is thought to explain why researchers have prevalently found Z-disc damage following eccentric exercise.2 Additionally, high intracellular CA\(^{2+}\) concentrations increase the CA\(^{2+}\) concentrations in mitochondria, which promotes the production of reactive oxygen species (ROS).3

The ultrastructural damage from eccentric exercise may induce an inflammatory response, resulting in swelling and sensations of pain, soreness, and stiffness.2,3,6 Neutrophils are the first type of leukocyte to enter the injured tissue (approximately 45 min to 2 h P-EE).2,3 Then neutrophils are replaced with macrophages,2,3 which become the predominant type of leukocyte in injured muscle tissue.6 Macrophages differentiate into M1 and M2 phenotypes to provide a pro- or anti-inflammatory response, respectively.2,3,6 Initially, M1 macrophages replace neutrophils and secrete pro-inflammatory cytokines.6 Both M1 macrophages and neutrophils play a role in removing cellular debris and producing proteolytic enzymes and ROS.3 ROS exacerbate cellular damage but also play an important role in the recovery process.3,76 After approximately one to two days, M2 macrophages replace M1 macrophages and secrete anti-inflammatory cytokines. This shift is believed to help start the tissue repair and
adaptation processes, which consist of M2 macrophages releasing growth factors that activate satellite
cells.\textsuperscript{2,3,6}

In review, ultrastructural and functional muscle tissue damage is commonly caused by eccentric
exercise.\textsuperscript{1,8,73} Following the damage from the eccentric exercise, a rise in intracellular CA\textsuperscript{2+} causes
further secondary muscle damage.\textsuperscript{1–4} An inflammatory response is then triggered. Initially, the response
is pro-inflammatory, which can cause further damage but helps remove cellular debris. Afterward, the
response is anti-inflammatory and meant to repair and adapt muscle tissue.\textsuperscript{2,3,6}

\textbf{Symptoms}

\textit{Delayed Onset Muscle Soreness}

Delayed onset muscle soreness (DOMS) is a hallmark symptom of EIMD and has been well
documented.\textsuperscript{2,3,5} DOMS has been primarily measured with a visual analog scale, or other subjective test
equivalents, and pain pressure thresholds. Manifestations of DOMS include pain, soreness, or tenderness
to the palpation, stretch, or contraction of skeletal muscle.\textsuperscript{2,3,5} The symptom is termed DOMS since they
typically do not occur immediately after exercise; instead, they typically peak in intensity around 24 to
72 h after exercise and subside after 5 to 7 days.\textsuperscript{2,3,5} Regarding the location of DOMS, there are some
reports of soreness felt around the entire muscle;\textsuperscript{2} however, some studies have demonstrated soreness
concentrated near the distal portion of the muscle,\textsuperscript{2,5} which may be attributed to the high amount of pain
receptors found in the myotendinous junction.\textsuperscript{5} A few mechanisms have been proposed as to why
DOMS develops. Swelling and increased pressure from swelling due to the inflammatory response may
activate nearby mechanical nociceptors.\textsuperscript{2,3,5} Additionally, chemical changes from EIMD have been
suggested to activate polymodal nociceptors that are sensitive to changes in chemical signals. Polymodal
nociceptors are likely activated by increases in the following inflammatory cells: histamines,
bradykinins, and prostaglandins.\textsuperscript{2,3}
**Decreased Range of Motion**

Another commonly reported symptom of EIMD is a decrease in ROM,\textsuperscript{2,5} and it has been suggested to be one of the most reliable and valid measures for quantifying EIMD.\textsuperscript{7} Reductions up to 20 to 45° have been found to occur immediately after exercise, and although recovery typically begins within 24 h, full recovery may not be achieved until 10 days after exercise.\textsuperscript{2} A few different mechanisms have been suggested to explain its cause. Reductions in ROM may be from the muscle’s inability to contract due to the ultrastructural damages that occurred from the EIMD processes.\textsuperscript{1,2} Movement may also be affected by local swelling,\textsuperscript{2,3,5} damage to muscle connective tissue,\textsuperscript{3,5} or impairments to proprioception.\textsuperscript{3}

**Decreased Strength and Power**

Significant reductions in strength and power have also been well documented.\textsuperscript{2,3,5,7–9} Measuring maximal voluntary contraction torque has been one of the most popular ways to measure strength losses,\textsuperscript{3,7} and alongside ROM, it has been suggested to be one of the most valid and reliable measures for quantifying EIMD.\textsuperscript{7} When comparing isometric, concentric, and eccentric isokinetic strength at a single velocity, there appears to be no significant differences in the magnitude or rate of strength loss.\textsuperscript{9} However, research is mixed on the effects of varying angular velocities. This might be partly due to the studies varying EIMD protocols.\textsuperscript{9} It has been suggested that the small amount of tissue damage following eccentric exercise does not fully explain the large reductions in strength;\textsuperscript{2} instead, the early loss may be more-so attributed to reductions in excitation-contraction coupling.\textsuperscript{2,8} Warren et al\textsuperscript{8} quantified this notion, based on three studies that examined 824 muscles in vitro (primarily from animals), by estimating that a majority (75%) of the strength loss within the first three days post-exercise may be attributed to a failure in the excitation-contraction coupling pathway. In addition to strength loss, EIMD has been reported to reduce power-generating abilities and performances, primarily measured via maximal cycling and vertical jump performances.\textsuperscript{9}
**Altered Motor Control**

In addition to strength and power losses, EIMD may affect motor control via reduced proprioception\(^1,5,9,10\) and altered joint kinematics.\(^5,11-14\) Reduced proprioception has been observed via participants’ inabilities to complete match forcing or joint angle tasks successfully.\(^1,5,9,10\) It has been theorized that this would be in part to impairments in muscle sense organs (e.g., muscle spindles and Golgi tendon organs);\(^1,10\) however, research is limited and inconclusive on that explanation.\(^10\) Instead, Proske and Allen\(^10\) have suggested that if not due to impaired muscle organs, individuals might have failed these tasks due to central drive disturbances in senses of effort caused by the effects of EIMD. Altered joint kinematics have primarily been observed with 3D motion capture gait analysis;\(^5,11-13\) however, alterations have also been seen during a drop jump performance.\(^14\) Suggestions as to why joint kinematics are affected by EIMD have been because of the effects of reduced ROM,\(^5\) decreased reflex sensitivity from impaired muscle sense organs,\(^11,13,14\) DOMS causing individuals to adopt compensatory movements to avoid pain and injury,\(^5,11,13,13\) or insufficient strength causing impaired neuromuscular coordination.\(^13\)

**Sex Differences**

When comparing males and females, there may not be any significant differences in EIMD responses;\(^77\) however, the female menstrual cycle phases might affect strength loss and DOMS symptoms.\(^78\) To illustrate, a recent 2020 meta-analysis\(^77\) of 23 studies revealed no significant differences between sexes in strength loss or DOMS symptoms following intensive eccentric exercise. More importantly, since the present study contained untrained individuals, the meta-analysis indicated no significant differences in relative muscle strength and DOMS responses between untrained males and females. There were significant differences in that males displayed higher creatine kinase concentrations following eccentric exercise; however, this measure was not considered in the present study. Furthermore, a meta-analysis\(^78\) of 19 articles revealed that hormone fluctuations within different phases
of the menstrual cycle (early follicular phase, late follicular phase, and mid-luteal phase) might affect strength loss and DOMS responses to EIMD.

**Percussive Massage**

The devices used for PM are electric, handheld devices that generate rapid mechanical percussions, similar to how a jackhammer operates. The popular commercially sold devices, such as Hypervolt and Theragun, have multiple speed settings that allow them to run at varying frequencies (i.e., 17 to 53 Hz), and they come with different attachment tips (e.g., round ball, flat, fork, or bullet/pointy) that are intended for different treatment areas or purposes.\(^{21}\) Brands that commercially sell these devices commonly claim they can enhance performance and recovery, but researchers, especially peer-reviewed articles, have yet to substantiate those claims with sufficient evidence.

Due to the rise in popularity but lack of research, Cheatham et al\(^{21}\) surveyed 425 exercise and healthcare professionals to determine how they use the devices to help guide future practitioners and researchers. Their survey revealed that almost half (42.82%) of the respondents use PM for post-exercise treatment. When using it as a post-exercise treatment, a majority of the respondents reported that they prefer to use frequencies (i.e., speeds) of 33 to 40 Hz (32.71%) for 30 s to 3 min (35.76%) at a pace of 2 to 5 s (28.94%) up and down the body region. Additionally, out of all the different attachments, the round ball attachment was the most popular among the surveyors (large round ball [33.88%], small round ball [45.53%]). These PM parameters were considered when developing the PM intervention for the present study.

**Effects on Symptoms Associated with Exercise-Induced Muscle Damage**

The research on the effects of PM on symptoms associated with EIMD is lacking. Only three studies\(^{22-24}\) have examined this topic, and one\(^{24}\) of those was an abstract that did not have a control limb or group. The abstract by Rogers and Rogers\(^{24}\) in 2020 was the first study, and they investigated if PM could improve vertical jump height and decrease perceived pain 48 h after 10 sets of 10 repetitions of barbell back squats at 60% of the subject’s (25 untrained adults [16 females and 9 males]) 1-repetition
maximum (1-RM). At 48 h post-exercise, the participants rated their pain and performed a vertical jump before receiving 10 min of PM on their quadriceps (5 sets of 1 min per leg). Immediately after the PM, participants re-rated their pain and performed another vertical jump. Comparisons were made within subjects and without a control limb or group, meaning all subjects received PM on both limbs’ quadriceps. Following PM, the subjects had significantly lower perceived pain and higher vertical jumps than their values taken before the PM at 48 h post-exercise. However, the main limitation of this study was the lack of a control. The lack of a control is particularly important for the vertical jump assessment, because it may be difficult to know if the participants’ improvements were from the PM or a warmup/learning effect.

Following Rogers and Rogers, García-Sillero et al. compared the recovery effects of 2 min of PM (29 Hz) to three other treatments: 1 min of local vibration therapy (40 Hz), 15 min of massage therapy, and 2 sets of 30 repetitions of foam rolling. A limb-to-limb (treated [right] vs. untreated [left] limb) design was used in this study, and 40 university student-athletes (38 males and 2 females) were split into four treatment groups (10 participants per treatment group). The EIMD protocol was conducted with a flywheel device and consisted of 4 sets of 12 eccentric repetitions at an individualized load (0.035 or 0.050 kg·m⁻²) for both limbs’ gastrocnemius. Gastrocnemius recovery was assessed with a tensiomyography, and the variables examined were radial displacement, which reflects muscle stiffness, and contraction time, which is associated with muscle fiber type and degree of fatigue. Measurements were taken at baseline, immediately post-eccentric exercise (P-EE), immediately after the treatment, and 24 and 48 h P-EE. The treatments were given after the initial P-EE assessments and before the 24 and 48 h P-EE assessments. As evident from faster recoveries in radial displacements and contraction times compared to local vibration therapy and foam rolling, the authors concluded that PM effectively improved muscle recovery P-EE. Additionally, the PM was similarly effective when compared to the massage therapy. However, a major limitation that the authors mentioned was that there
were large variations in the durations between treatments, and this could have affected the dose-response relationships. Additionally, there was no comparison to a control or placebo.

Similar to García-Sillero et al., Leabeater et al. also used a limb-to-limb design (randomized treatment and control limbs) with the same muscle, but they investigated if 5 min of PM could affect perceived muscle soreness, ROM, calf circumferences, isometric strength, and endurance. Sixty-five active adults (34 females and 31 males) completed three sets of 20 double-leg calf raises through a full range of motion on a 30 cm platform at 60 bpm. Immediately after the exercise and never again, the gastrocnemius of the participant’s treatment limb was given 5 min of PM at 53 Hz, and the participants remained seated for an additional 15 min before performing the immediate recovery tests. The performance and calf circumference tests were only measured after the PM, whereas perceived muscle soreness was measured after the PM and 4, 24, and 48 h after the exercise. There were no significant differences for any measurements at all times.

The varying results are likely due to the different research designs and methods, such as the type of muscle targeted (quadriceps vs. gastrocnemius), population (untrained vs. recreationally active vs. student-athletes), EIMD protocol, and PM (duration and frequency). Neither of these studies investigated the recovery effects of PM on ROM or MIT 24 to 72 h P-EE. Warren et al. suggested that those two measures are among the best for quantifying the effects of EIMD. Additionally, no one has examined, with a control, the effects of giving PM 24 to 72 h P-EE on perceived muscle soreness 24 to 72 h P-EE. Leabeater et al. did observe perceived muscle soreness 24 and 48 h post-exercise, but they only gave PM immediately after the exercise. Also, Rogers and Rogers did examine giving PM 48 h P-EE on perceived pain, but they did not compare their results to a control. Therefore, to fill the gap within the literature, the following study aimed to investigate if giving PM immediately and 24 to 72 h P-EE would affect MIT, ROM, and perceived muscle soreness 24 to 72 h P-EE.
**Acute Effects on Muscular Performance**

Compared to the research on recovery, more studies have investigated the effects of using PM as a pre-exercise treatment.\textsuperscript{25–33,39,40} Within these studies, ROM\textsuperscript{25–33} and explosive jumping\textsuperscript{26,27,39,40} are the most commonly observed performance measurements; however, isometric strength,\textsuperscript{25} agility,\textsuperscript{27} and anaerobic power\textsuperscript{27} have also been examined. Similar to the literature on recovery, these studies are a mix of peer-reviewed articles\textsuperscript{25–29,31,40} and abstracts.\textsuperscript{30,32,33,39} Lastly, unrelated to a pre-exercise treatment, one study\textsuperscript{41} investigated using PM as an inter-set rest treatment.

The majority of the ROM literature has observed increases in ROM with PM.\textsuperscript{25–30} Improvements have been primarily seen with the lower limb muscles, such as the plantar flexors,\textsuperscript{25,26,28} hip extensors,\textsuperscript{26,27,30} and knee extensors,\textsuperscript{26} of healthy males and females. In addition, one study\textsuperscript{29} reported improvements in shoulder horizontal adduction and internal rotation among subjects with posterior shoulder tightness. There have been a few suggestions for why PM may acutely increase ROM. Konrad et al\textsuperscript{25} suggested that, similar to what Behm et al\textsuperscript{81} suggested with foam rolling, the friction and pressure to muscle, skin, and fascia may decrease intra- and extracellular fluid viscosity, thereby decreasing the resistance of movement (i.e., increase ROM). Yang et al\textsuperscript{31} confirmed this by observing a decrease in echo intensity with PM, which is described in more detail in the next section. Another suggestion, by Jung and Ha,\textsuperscript{29} has been that the tonic vibration reflex observed with vibration may explain the increased ROM seen with PM. The tonic vibration reflex is described in more detail at the end of the local vibration therapy section, but in short, the potential for an increase in agonist activation and reciprocal inhibition with vibration\textsuperscript{82–84} might aid in the enhanced performance of a ROM test. Lastly, Konrad et al\textsuperscript{25} and Alvarado et al\textsuperscript{26} suggested that it might be due to decreased perceived pain or soreness. Previous studies have confirmed this by reporting decreases in pain\textsuperscript{24,46} and stiffness.\textsuperscript{31}

Within those observations of improvement, there are two studies\textsuperscript{28,30} that compared it to static stretching, which also has been known to acutely increase ROM.\textsuperscript{34,35} Both studies\textsuperscript{28,30} found that PM and static stretching acutely increased ROM, but neither treatment was more effective than the other. One
might then suggest that static stretching would be a preferable pre-exercise treatment for those seeking improvement in ROM since it does not require any costly equipment. However, there are multiple reports of static stretching acutely decreasing strength and power performance,\textsuperscript{34–38} whereas the vast majority of PM studies have seen no changes in strength,\textsuperscript{25} power,\textsuperscript{26,27,39,40} and agility\textsuperscript{27} activities.

Despite most studies seeing improvements, there are three studies\textsuperscript{31–33} that found PM to be ineffective at acutely altering ROM. Rogers and Rogers\textsuperscript{33} observed no increases in a sit-and-reach test with PM on the hamstrings and low back, and Yang et al\textsuperscript{31} and Williams et al\textsuperscript{32} reported no differences in thoracolumbar ROM with PM on the erector spinae and soft-tissue of the thoracolumbar spine region, respectively. The different research designs and PM parameters could explain why these results contradict the previously mentioned studies, but one common characteristic of these studies is that they involved the muscles and fascia of the back region. Therefore, the muscles and fascia of the back may not be as responsive to improvements in ROM as lower limb muscles, which have consistently seen positive results.\textsuperscript{25–28,30}

Furthermore, studies have also investigated the acute effects of using PM as a pre-exercise treatment for power,\textsuperscript{26,27,39,40} strength,\textsuperscript{25} and agility.\textsuperscript{27} Researchers have primarily seen no effects on explosive jumping performances, such as countermovement/vertical,\textsuperscript{26,27,39} squat,\textsuperscript{27} and drop\textsuperscript{26,40} jumps. Additionally, Konrad et al\textsuperscript{25} saw no differences in isometric strength with PM, and Canbulut et al\textsuperscript{27} reported no changes in agility. Furthermore, although Canbulut et al\textsuperscript{27} reported no differences in countermovement/vertical jumps and agility, they did observe a significant decrease in anaerobic power (peak power, average power, and power drop) during a Wingate test. Therefore, based on the current literature, PM may not acutely affect vertical power but may acutely decrease cycling power.

Lastly, unrelated to using PM as a pre-exercise treatment, García-Sillero et al\textsuperscript{41} studied the use of PM as an inter-set rest treatment on the velocity of 4 sets of bench press at 70\% 1-RM. The study contained 24 male university students and used a between-subjects (PM vs. control group) design. During the rest periods between sets, the PM group received 3 min of PM on the pectoral muscles.
Results indicated that the PM group performed more repetitions than the control group before reaching a 30% decline in velocity. Thus, the authors concluded that PM might be an effective inter-set rest treatment for delaying a loss in bench press velocity.

In summary, when implemented as a pre-exercise treatment, PM may acutely increase ROM without affecting vertical power and isometric strength. Additionally, PM may not increase ROM more than static stretching; however, unlike PM, static stretching has abundant literature suggesting it may decrease strength and power. Thus, PM may be a helpful tool for individuals needing to increase their ROM without affecting their performance. Lastly, based on one study, PM may be an effective inter-set rest intervention for delaying a loss in bench press velocity.

**Potential Physiological Mechanisms**

Not much research has been devoted to understanding the physiological mechanisms by which PM may affect recovery or performance. Therefore, due to the limited understanding of PM, the survey by Cheatham et al aimed to determine what 425 exercise and healthcare professionals believed to be the causes of PM’s potential clinical benefits. Most (85.88%) respondents reported using it for therapeutic treatment. Of those 85.88% respondents, the five most popular responses for why they believe PM has a therapeutic effect were (1) increased blood flow (69.10%), (2) pain modulation (65.09%), (3) enhanced myofascial (61.79%), (4) breaking up myofascial trigger points (54.01%), and (5) enhanced post-exercise recovery (38.29%).

Recently, there has been confirmation that PM may increase blood flow and enhance skeletal muscle hemodynamics. Needs et al studied a combination of frequencies (30, 38, and 48 Hz) and durations (5 and 10 min) to investigate if PM on the calf muscles could increase popliteal artery blood flow. Twenty-six subjects (14 males and 12 females) underwent all PM conditions and control conditions. Their results indicated that PM could increase blood flow (volume flow and mean velocity), and the increases were dependent on frequency and duration. Greater blood flow was observed with higher frequencies and longer durations. Furthermore, a dissertation from Rusciano and Woods
confirmed these results with their findings that 5 min of PM to the forearm (wrist flexors and extensors) increased systolic blood flow (an average of peak systolic velocities) in the brachial artery. Lastly, a published abstract by Lee et al\textsuperscript{44} also investigated the effects of 5 min of PM but to the dominant limb’s quadriceps on skeletal muscle oxygen saturation, total hemoglobin, oxy-hemoglobin, and deoxy-hemoglobin. These variables were assessed 10 min post-PM. Their results indicated that the PM significantly increased skeletal muscle oxygen saturation, total hemoglobin, and oxy-hemoglobin and decreased deoxy-hemoglobin. Thus, the authors concluded that PM may acutely increase oxygen availability and consumption, which may help improve performance. However, as established earlier, no studies have yet to find PM to be effective in increasing strength or power performance. These are predominately anaerobic exercises; therefore, future research may want to investigate the effects of PM on exercises dependent on oxygen delivery (i.e., aerobic or endurance exercise).

Recent studies have also confirmed that PM may decrease perceived muscle pain\textsuperscript{46} or stiffness;\textsuperscript{31} however, these were not accompanied by morphological changes in myofascial trigger points\textsuperscript{46} or fascial thickness.\textsuperscript{31} Pearce et al\textsuperscript{46} applied PM (duration not stated) to myofascial trigger points of the upper back of 30 male and female participants and used a contralateral site with no myofascial trigger points within the same participant. They found that PM decreased perceived pain, primarily in latent or less painful myofascial trigger points, but it did not result in ultrasound-based morphological changes to the myofascial trigger points. Thus, the authors concluded that PM provided immediate, but likely temporary, pain relief. Similar results were seen with Yang et al,\textsuperscript{31} but they found that 15 min of PM on the erector spinae of 60 healthy males decreased their perceived muscle stiffness. However, there were no changes in average thoracolumbar fascia thickness.

Despite no changes in thoracolumbar fascia thickness, Yang et al\textsuperscript{31} found that PM decreased echo intensity and increased skin temperature. The authors suggested that a decrease in echo intensity values may represent a reduction in the viscosity of hyaluronic acid in loose connective tissue. They provided a few suggestions as to why this may have occurred. The vertical pressure from PM may have
squeezed hyaluronic acid towards the fascial rim region, or the hyaluronic acid might have reduced its viscosity due to an increase in temperature with PM. Yang et al. confirmed the latter suggestion in the same study by observing an increase in skin temperature with PM.

**Local Vibration Therapy**

Since handheld PM devices create rapid percussions (i.e., 17 to 53 Hz), they likely utilize a vibration component within their treatment; therefore, the literature on local vibration therapy (LVT) should be examined to help understand PM’s potential effects. Many exercise and rehabilitation researchers have studied vibration to examine its effects on neuromuscular performance and alleviating DOMS. Most initial investigations on vibration looked at whole-body vibration since evidence indicated that it might enhance strength and power. However, more research has recently been devoted to LVT since whole-body vibration is costly, timely, not portable, and struggles to target specific muscles or muscle groups.

**Effects on Symptoms Associated with Exercise-Induced Muscle Damage**

When studies gave LVT post-eccentric exercise (P-EE), results so far have consistently observed decreased muscle pain or soreness perception (i.e., DOMS) and improved ROM. These results have been seen with varying populations (untrained, recreational, and professional futsal players), LVT parameters (120 Hz for 15 min, 40 Hz for 3 min, and 65 Hz for 30 min), eccentric exercises (downhill running, elbow flexion, knee extension and flexion), and research designs (between-subjects and within-subjects). There are a few suggestions for why LVT may reduce muscle pain or soreness perception. For example, vibration has been reported to activate sensory fibers in muscles, which could affect the pain sensation via group III and IV afferent fibers. Another suggestion has been that vibration may stimulate Ruffini cylinders and Pacinian corpuscles, potentially resulting in muscle relaxation by decreasing sympathetic activity. Regarding ROM, Cochrane suggested that the improvements might have been from decreased pain thresholds seen with LVT or decreased passive muscle stiffness.
When studies gave LVT P-EE, the research is mixed on its ability to improve muscle strength. Koh et al\textsuperscript{54} reported significant improvements in maximal isometric strength 72 h P-EE (3 sets of 12 eccentric contractions of the extensor carpi radialis longus). The authors used a between-subjects design with 60 college students (30 male and 30 female), and the LVT was given daily for 10 min at 20 Hz for three days P-EE. Percival et al\textsuperscript{45} also reported significant improvements in maximal isometric strength with LVT but with the wrist flexors. The authors also used a between-subjects design but with 10 untrained adults (6 males and 4 females). The eccentric exercise consisted of 10 sets of 10 eccentric wrist flexion actions at 70\% of participants’ 1-RMs. The LVT, which was for 10 min at 40 Hz, was given 1 h P-EE and twice daily up to 48 h P-EE.

On the contrary, Cochrane\textsuperscript{48} saw no difference in maximal isokinetic concentric strength of the elbow flexors at 60°s\textsuperscript{-1}, and Cochrane\textsuperscript{48} and Lau and Nosaka\textsuperscript{50} observed no differences in maximal isometric strength of the elbow flexors. Both studies used an arm-to-arm comparison and had subjects complete 60 eccentric contractions of the elbow flexors. Cochrane\textsuperscript{48} gave 15 min (120 Hz) of LVT immediately and 24 to 72 h P-EE, whereas Lau and Nosaka\textsuperscript{50} gave 30 min (65 Hz) of LVT immediately and 24 to 96 h P-EE. Many factors may explain the differences in results (i.e., types of muscles, methods, and research designs), but a possibility for why Koh et al\textsuperscript{54} and Percival et al\textsuperscript{45} observed improvements may be that they used shorter durations and lower frequencies with their LVT. A literature review\textsuperscript{61} on the effects of LVT on various performance measures suggested that pairing lower frequencies of LVT with shorter durations typically provides positive clinical outcomes.

Furthermore, Pournot et al\textsuperscript{56} found no significant differences in muscle stiffness, measured via a muscle shear elastic modulus, in 11 physically active adults (5 females and 6 males) 5 min post-exercise. The authors used an arm-to-arm comparison to evaluate the effects of LVT after subjects completed 40 bilateral barbell curls (including 1 to 2 s of flexion and 5 s of extension) at 70\% of their 1-RM. The LVT was given after performing the barbell curls and lasted for 10 min with a frequency of 55 Hz. These results relate more to LVT’s acute or immediate recovery effects after strenuous exercise since the LVT
and post-test occurred immediately P-EE and not again when symptoms of DOMS typically peak (i.e., 24 to 72 h P-EE).

The effects of P-EE LVT on biochemical and other indicators of recovery also have mixed results. In the study by Cochrane, LVT significantly reduced creatine kinase (CK) at 72 h compared to the control, but there were no significant differences 24 and 48 h P-EE. However, Piotrowska et al saw reductions in CK, lactate dehydrogenase (LDH), and myoglobin with LVT at 24 h after prolonged exercise. The participants in this study were 12 untrained, college-aged males, and EIMD was evoked via running for 180 min at an intensity of 50 ± 2% VO\textsubscript{2} peak. The LVT was applied for 60 min immediately after exercise and with varying frequencies and amplitudes that cycled from 25 to 52 Hz and 0.1 to 0.5 mm, respectively. Furthermore, Percival et al\textsuperscript{45} found a greater oxygen re-saturation rate with LVT at 1, 24, and 48 h P-EE. This may be a beneficial sign of recovery since Hogan et al\textsuperscript{94} has suggested that the reduction in muscle strength from EIMD might be partly from decreased oxygen availability.

Although those previous articles observed beneficial results, other studies have reported no significant differences in CK, LDH, and swelling with P-EE LVT. Iodice et al\textsuperscript{49} found no differences in CK and LDH within the knee extensors and flexors of 30 male professional futsal players 24, 48, and 72 h P-EE (75 maximal eccentric contractions at 60°s\textsuperscript{-1}). The authors used a between-subjects design, and the LVT was 15 min per muscle with a frequency of 120 Hz. Additionally, to see if LVT could increase lymphatic flow, Iodice et al\textsuperscript{49} assessed for swelling by measuring the circumference of the upper arms, and their results showed no significant differences from 24 to 72 h P-EE. Lastly, the study by Lau and Noska\textsuperscript{50} also saw no reductions in CK levels 1-7 days P-EE.

When researchers gave LVT pre-eccentric exercise, results indicated improvements in maximal isometric strength\textsuperscript{51} and ROM\textsuperscript{52} and reductions in muscle pain or soreness,\textsuperscript{51-53} CK,\textsuperscript{51-53} and LDH levels. Bakhtiary et al\textsuperscript{51} had 50 non-athletic participants (25 males and 25 females) perform 30 min of downhill treadmill walking with a 10° decline and speed of 4 km. Before the treadmill, the treatment
group received 1 min of LVT with a frequency of 50 Hz for both limbs’ quadriceps, hamstring, and calf muscles. Measurements were taken 24 h after exercise, and their results showed that the LVT group had higher maximal isometric strength and pain pressure thresholds and lower visual analog scale scores and CK levels compared to the control group. Kim et al\textsuperscript{53} compared the effects of pre- and post-eccentric exercise LVT with 30 adult males. Their eccentric exercise protocol consisted of 75 eccentric (8 s) repetitions of the elbow flexors at 60\% 1-RM. The LVT was 5 min and had a frequency of 60 Hz. At 24, 48, and 72 h P-EE, both LVT groups had higher pain pressure threshold, CK, and LDH compared to the control, but the pre-eccentric exercise LVT group showed a significantly greater recovery for all three measures. Lastly, Imtiyaz et al\textsuperscript{52} had 45 non-athletic females receive 5 min of LVT (50 Hz) to the elbow flexors prior to completing 30 dumbbell eccentric (5 s) contractions at 80\% of their maximal voluntary isometric contraction. Their results showed that pre-eccentric exercise LVT reduced muscle soreness (24, 48, and 72 h), CK (48 h), and LDH (48 h) and improved ROM (24, 48, and 72 h P-EE). However, pre-eccentric exercise LVT did not significantly affect muscle function, which was measured by a maximal voluntary isometric contraction and 1-RM of the elbow flexors.

In summary, LVT P-EE appears to be effective in reducing pain or soreness\textsuperscript{47–50} and improving ROM\textsuperscript{,48,50} but the evidence on other recovery measures (e.g., strength and biochemical indicators) is mixed\textsuperscript{.45,48–50,54–56} When LVT was given pre-eccentric exercise, it improved maximal isometric strength\textsuperscript{51} and ROM\textsuperscript{52} and reduced soreness or pain\textsuperscript{,51–53} CK,\textsuperscript{51–53} and LDH.\textsuperscript{52,53} Additionally, there was one report\textsuperscript{53} of pre-eccentric exercise LVT being more effective than P-EE LVT for lowering pain, CK, and LDH. The varying results could be from the studies’ heterogeneous methods (i.e., LVT parameters, types of muscles, populations, and research designs).

**Acute Effects on Muscular Performance**

Similar to the recovery studies, researchers have observed increases in ROM with LVT when used as a pre-exercise treatment.\textsuperscript{57–60} Kurt\textsuperscript{59} compared the effects of LVT to whole-body vibration, static stretching, and dynamic stretching by using a within-subjects design that contained 24 well-trained male
combat athletes. Participants significantly increased their sit-and-reaching scores with LVT, and LVT significantly outperformed whole-body vibration and dynamic stretching. However, similar to PM, LVT was similarly effective than static stretching. Furthermore, Peer et al.\textsuperscript{60} studied the effects of 20 min of ice, compression, and elevation followed by 10 min of LVT on ankle (dorsiflexion, plantar flexion, eversion, and inversion) and hamstring ROM and perceived stiffness in 10 adults who had a grade I or II ankle sprain ($n = 5$) or hamstring strain ($n = 5$). Their results showed that LVT significantly improved ankle (dorsiflexion and eversion) and hamstring ROM and decreased perceived stiffness. Benedetti et al.\textsuperscript{57} observed the effects of high-frequency (150 Hz) LVT on quadriceps muscle function of 30 male and female patients, aged 40 to 65 years, who had knee osteoarthritis. The LVT was applied for 20 min to the knee extensor muscles. A between-subjects design was used to compare the effects of LVT to a control treatment, which was neuromuscular electrical stimulation. The knee extensor muscles’ ROM significantly increased in the LVT group compared to the control group. Lastly, Goebel et al.\textsuperscript{58} compared traditional resistance training to traditional resistance training with LVT during the prescribed hamstring exercises. The LVT was applied to the hamstrings, and the frequencies varied from 18 to 38 Hz. The LVT training group significantly increased their hamstring’s ROM, whereas the traditional resistance training group made no significant improvements, suggesting LVT may be effective in acutely enhancing ROM.

In addition to ROM, two review papers\textsuperscript{61,62} have suggested that acute and chronic LVT might increase strength and power. Alghadir et al.\textsuperscript{62} aimed to conduct a systematic review and meta-analysis on the effects of LVT on muscle strength in healthy adults. The authors could not complete the meta-analysis due to varying research designs, targeted muscles, and vibration parameters (e.g., frequency [8 to 300 Hz], amplitude [0.4 to 6.0 mm], and duration [6 s to 3 min]); thus, they performed a systematic review on 11 articles, which had an average PEDro score of 5.36/10. Most of the studies within the review saw improvements in strength. The reported improvements were mainly through maximal isometric tests; however, there were two reports of increased dynamic strength. Therefore, based on the
systematic review, the authors concluded that LVT could increase muscle strength, but they advised for future research with homogeneous designs to provide more concrete evidence. Germann et al.\textsuperscript{61} also performed a literature review on the effects of LVT on strength, but the authors also included a search for other performance parameters, such as muscle activation, power, and ROM. The authors evaluated 21 studies that had an average PEDro score of 5.97/10. Like Alghadir et al.,\textsuperscript{62} the authors reported heterogeneous research designs. For example, the LVT frequency, amplitude, and duration varied from 5 to 300 Hz, 0.12 to 12 mm, and 6 s to 30 min, respectively. The authors concluded that most of the studies observed enhancements in all the performance parameters examined in the review. Furthermore, the authors noted an interesting relationship between LVT frequencies and durations. Typically, shorter durations (1 to 2 min) were effective when the frequency was low (5 to 50 Hz), and longer durations (15 to 30 min) were effective when the frequency was high (100 to 300 Hz).

The primary neurophysiological explanation for an acute increase in performance with LVT has been the tonic vibration reflex.\textsuperscript{63,64} Vibrations transmit oscillating forces to muscles, which causes muscles to quickly cycle through shortening (concentric) and lengthening (eccentric) contractions. The rapid, cyclical changes in muscle length from vibrations are thought to repetitively activate muscle spindles,\textsuperscript{82–84} primarily through the type Ia afferent neuron since it responds to the rate of change in muscle length.\textsuperscript{95} Activation of the muscle spindles may provide excitatory input to the alpha motor neuron pool associated with the agonist muscle (i.e., muscle receiving vibration) and result in reciprocal inhibition,\textsuperscript{82} which theoretically could enhance muscle performance (e.g., strength, power, & activation) in the muscle(s) receiving LVT.

**Tapotement Massage**

Massage is a common therapeutic treatment that has been used for thousands of years by athletes and non-athletes.\textsuperscript{96,97} The intended uses of massage therapy (MT) for athletes have been to increase recovery, performance, and injury prevention.\textsuperscript{97,98} The potential physiological mechanisms of action for those purported benefits are increased muscle or skin temperature, blood and lymphatic flow, and
parasympathetic activity. Additionally, MT is thought to reduce stiffness via a reduction in neuromuscular excitability, as evident from a reduced Hoffmann reflex amplitude, and improve psychophysiological factors such as reduced anxiety and increased relaxation.

Sports MT often involves a combination of techniques throughout the treatment, such as petrissage, effleurage, tapotement, and others. Petrissage involves lifting and kneading deep muscle tissue, whereas effleurage consists of continuous gliding strokes via the palm and in the direction of blood and lymphatic flow. Tapotement massage (TM), which most closely resembles PM, involves repetitive and rapid strikes to muscle tissue with the edge of the hands. TM essentially provides manual percussions; however, they are delivered at a much lower frequency (≈2 to 4 Hz) than the mechanical percussions produced by PM devices (≈17 to 53 Hz). Researchers have hypothesized that manual percussions stimulate cutaneous tissue and superficial muscle, which could improve performance; however, these hypotheses have yet to be validated by research. The overall literature on the isolative effects of TM is minimal because the MT given in studies typically incorporates a combination of techniques, which is representative of Classical Western or Swedish massage.

Currently, only two studies have investigated the isolative effects of TM. Mckechnie et al compared the effects of petrissage and TM on ankle ROM and power with 8 male and 11 female university students. Both massage treatments were given to the plantar flexor muscles for 3 min per limb, and the frequency of the TM was 4 Hz. Ankle ROM was significantly higher with both massage conditions compared to the control. However, neither massage intervention affected muscle power. Muscle power was analyzed via rate of force development and peak torque during a concentric calf raise and drop jump height divided by contact time. Behm et al also observed the acute effects of TM on the plantar flexors, but only for 30 s at 2 Hz. The TM was compared to musculotendinous massage, and both massages were combined with static stretching. A submaximal electrical stimulation was applied to the tibial nerve to evoke a maximal H-reflex response in the soleus muscle. Then, after 5 s, a maximal electrical stimulation was given to evoke a maximal M-wave response for the soleus and collect
contractile properties of the plantar flexors. The contractile properties investigated were peak twitch torque, time to peak twitch torque, half-relaxation time, and electromechanical delay. Their results showed that TM reduced spinal reflex excitability the most, as evident from an H-reflex depression, but it did not affect the twitch contractile properties.
CHAPTER 3

METHODS

Experimental Approach to the Problem

Participants visited the laboratory for five separate visits. A between-subjects design (PM \( n = 9 \) vs. control \( n = 8 \)) with repeated measures was used to assess the effects of multiple PM treatments (immediately, 24, 48, and 72 h P-EE) on the DOMS (via an 11-point NRS of soreness), ROM, and MIT of the nondominant arm’s biceps brachii at 24, 48, and 72 h P-EE (Figure 1). A between-subjects design was selected since other forms of massage, such as foam rolling or roller massage, have been suggested to affect the central nervous system via reports of unilateral limb massage affecting the contralateral (i.e., non-massaged) limb’s pain,\(^{101}\) soreness,\(^{102}\) and ROM.\(^{103}\) The biceps brachii was chosen since upper limb muscles may be more susceptible to symptoms associated with EIMD, likely from the muscles not being used as often than lower limb muscles during daily activities.\(^{104}\) Furthermore, the nondominant arm was selected to decrease the potential outside factors that may affect muscle recovery since it might be used less often than the dominant arm during daily activities. The nondominant arm was identified as the arm of the participant’s non-preferred writing hand.

In sequential order, the first visit consisted of participants performing a concentric 1-repetition maximum (1-RM), familiarizing them with every procedure to minimize learning effects, and randomly assigning them to the PM or control (CON) group. The second visit was 1 to 7 days after the first visit and consisted of the following in order: baseline measurements, eccentric exercise, and treatment intervention. The baseline measurements were collected in the following order: numerical rating scale (NRS) of soreness, ROM, and MIT. EMG and MMG data were collected during the MIT testing. Visits three, four, and five were the sessions where NRS of soreness, ROM, and MIT were measured 24, 48, and 72 h P-EE. All of these visits were identical. The visits started with collecting participants’ NRS of soreness. Then, the appropriate treatment intervention was given to the participant. Afterward, they completed the same order of procedures described for the baseline measurements. Throughout the study,
participants were instructed to refrain from strenuous physical activity, maintain their same diet and hydration habits, and avoid other forms of treatment (e.g., supplements, medications, massage, stretching, foam rolling, etc.).

Figure 1. Research design. The bullet points within each box represent the sequence of procedures for that visit. Abbreviations: CON: control, h: hours, MIT: maximal isometric torque, NRS: numerical rating scale, P-EE: post-eccentric exercise, PM: percussive massage, RM: repetition maximum, ROM: range of motion.

**Subjects**

The study consisted of 17 healthy, untrained volunteers (14 females and 3 males; age 23.8 ± 2.8 years; height 163 ± 9 cm; body mass 70.3 ± 17.1 kg). The PM group consisted of 7 females and 2 males, and the CON group consisted of 7 females and 1 male. The sample size was determined from a previous LVT study that used a similar research design (i.e., between-subjects with repeated measures) with 10 participants (LVT: n = 5, CON: n = 5) and reported significant improvements in grip strength and oxygen re-saturation rate with LVT after 100 eccentric repetitions for the wrist flexors. Untrained was defined as not having performed upper body resistance training for more than one time per week for the past six months. Participants were excluded from the study if they had any upper limb injuries in the past six months. Participants with prior PM experience within the past six months were also excluded to
limit participants having differences in sensitization to the treatment. Before participating, subjects were required to read and sign an Informed Consent. The study was approved by the California State University, Fullerton Institutional Review Board.

**Procedures**

**Concentric 1-Repetition Maximum**

To determine the dumbbell weight for the eccentric exercise, participants completed a single-arm concentric 1-repetition maximum for their nondominant arm’s elbow flexors. A dumbbell set increasing in 2.5 lb and Rogue Add-On Change Plates (0.5, 1, and 1.5 lb pairs) (Rogue, Columbus, Ohio) were used to increase the accuracy of identifying participants’ 1-RMs and selecting their weight for the eccentric exercise. Participants were seated on a preacher curl machine with their nondominant elbow on the support pad in front of them and their dominant arm resting to their side. The starting position consisted of participants extending their nondominant elbow on the pad with a slight bend (~2 to 5° of elbow flexion) and supinated forearm. The investigator placed a dumbbell in the participant’s hand, and they were instructed to lift the dumbbell to a maximally flexed position while maintaining their elbow on the pad, a supinated forearm, and a neutral wrist position. To initiate another repetition attempt, the investigator grabbed the dumbbell from the participant’s hand so the participant could extend their elbow back to the starting position without loading the eccentric action. Participants performed multiple trials (~5) with 3 min of rest between trials until they completed a trial where they successfully lifted a weight for only a single repetition and failed to complete a second repetition (i.e., 1-RM). A repetition was considered successful when the participant curled the dumbbell into a maximally flexed position while maintaining proper form.

**Eccentric Exercise**

Participants performed a single-arm eccentric exercise with a dumbbell to produce symptoms associated with EIMD in the nondominant arm’s biceps brachii. The protocol was adapted from Tseng et al. and adjusted after pilot testing. Participants were positioned in the same preacher curl machine and
used the same dumbbell equipment as the concentric 1-RM procedure. They performed 6 sets of 10 eccentric repetitions for the elbow flexors through a full range of motion with a dumbbell that weighed approximately 85% of their concentric 1-RM. Two minutes of rest were given between sets. Participants started in a maximally flexed position with a supinated forearm. An investigator placed the dumbbell in the participant’s nondominant hand, and they were instructed to lower the dumbbell to a maximally extended position in 7 s while maintaining their elbow on the pad, a supinated forearm, and a neutral wrist position. A metronome was used to assist the investigator in verbally counting the time to the participant (i.e., 0 [start], 1, 2, 3, 4, 5, 6, 7 [maximally extended]). After every eccentric repetition, the investigator lifted the dumbbell back to the starting position to eliminate loading the concentric action.

**Treatment Intervention**

The PM group received 60 s of PM, via a Hypervolt 2 (Hyperice, Irvine, California) (Figure 2), on the nondominant arm’s biceps brachii, whereas the CON group quietly rested supine for 60 s. The round ball attachment was applied to the device, and the moderate speed level, or frequency of 40 Hz, was selected for the PM intervention. The PM group received the PM intervention while relaxed in a supine position on a table. The first 30 s targeted the lateral portion of the biceps brachii (i.e., long head), whereas the last 30 s targeted the medial portion (i.e., short head). The device was applied directly on the skin and glided parallel with the muscle fibers at a pace of 5 s down-and-back from origin to insertion. The same investigator administered the PM throughout the study and attempted to apply equal pressure for every participant and treatment session. The PM parameters (attachment, duration, frequency, and pacing) were based on the most frequent responses from the survey by Cheatham et al.\textsuperscript{21} Additionally, the specific duration was determined from the Hyperice App’s multiple upper body guided sessions (“upper body flush,” “activate your upper body,” and “upper body refresh”), whereby the biceps brachii was targeted for 60 s per arm.
Figure 2. The handheld percussive massage device (Hypervolt 2) that was used in this study. The round ball (1) currently attached to the device was used for this study. Similar to other devices, other attachments may be used: (2) bullet, (3) fork, (4) cushion, and (5) flat.

Delayed Onset Muscle Soreness

The magnitude of DOMS was assessed with a NRS,\textsuperscript{23,24,49} which ranged from 0 (no soreness) to 10 (worst possible soreness). The reliability and validity of using a NRS with adults have been demonstrated.\textsuperscript{106,107} Before participants verbalized their scores, they were instructed to perform two tasks: (1) palpate their nondominant arm’s biceps brachii from origin to insertion while relaxing their arm to their side and (2) maximally flex and extend their elbow joint. The NRS of soreness was collected before and after the participant received their treatment intervention. When collecting the NRS values after the treatment intervention, an investigator always led with the following before participants verbalized their score to limit those in the PM group expecting soreness to decrease: “Do you feel the same, worse, or better? Please be honest.”

Range of Motion

The ROM of the elbow joint was determined by measuring relaxed (RANG) and flexed (FANG) elbow joint angles with a standard plastic goniometer. The protocol was adapted from Chen and
Throughout the entire testing, participants were standing and instructed to maintain a supinated forearm so that their palm faced forward. The RANG was determined by instructing participants to relax their arm to their side, whereas the FANG was determined by instructing participants to maximally flex their elbow by attempting to touch their ipsilateral shoulder with their palm while maintaining their elbow to their side. The anatomical landmarks for the goniometer's stationary arm, axis, and moving arm were the lateral midpoint of the humerus, lateral axis of the elbow joint, and lateral midpoint of the radius, respectively. These landmarks were marked before baseline testing to maximize consistency throughout the study. The FANG and RANG were both measured three times, and an average was calculated for each angle. The ROM of the elbow joint was calculated by subtracting the mean RANG from the mean FANG.

**Maximal Isometric Torque**

An isokinetic dynamometer (Humac Norm CSMI, Stoughton, MA, USA) was used for assessing the MIT of the nondominant arm’s elbow flexors. Participants were supine and positioned in accordance with the HUMAC NORM Testing and Rehabilitation System User’s Guide. The lever arm of the dynamometer was set to 65° of elbow flexion. Before the MIT trial, participants warmed-up by performing three submaximal isometric contractions at an intensity of 50% of their perceived maximal effort. After two min of rest, the MIT trial was conducted, which consisted of three maximal isometric contractions. Each isometric contraction was held for 6 s, and 30 s of rest was given between contractions. Similar verbal encouragement was given to all participants. The highest torque value of the three maximal isometric contractions was selected as the MIT for analysis.

**Electromyographic and Mechanomyographic Measurements and Signal Processing**

During the MIT testing, surface EMG signals were recorded using a bipolar surface electrode arrangement (approximately 4 cm center-to-center) placed over the muscle belly of the nondominant arm’s bicep brachii. The electrodes were positioned approximately midway between the axillary fold and the midpoint of the cubital fossa. A reference electrode was placed over the anterior end of the
forearm between the styloid processes of the ulna and radius. The electrodes were traced with a permanent marker on the second visit to ensure identical placements for the subsequent visits. Before placing the electrodes, the skin was abraded and sterilized with an isopropyl alcohol wipe to reduce electrode impedance. The EMG signals were pre-amplified (gain 1000×) via a differential amplifier (EMG 100C, BIOPAC Systems Inc., Santa Barbara, CA; bandwidth = 1-500 Hz). MMG signals were also recorded during the MIT testing via an accelerometer (EGAS-FT-10/V05; Entran, Fairfield, NJ, USA) placed between the two surface EMG electrodes. Double-sided foam tape was placed on the skin to secure the accelerometer.

The raw EMG and MMG signals were obtained and stored on a personal computer (AcqKnowledge 5.0, BIOPAC Systems Inc., Santa Barbara, CA). The EMG and MMG signals were collected at 1000 Hz and band-pass filtered (fourth-order Butterworth filter) at 10 to 500 Hz and 5 to 100 Hz, respectively. The middle 2 s of the 6 s MIT contractions were used for analyzing the EMG and MMG amplitudes. The EMG and MMG amplitudes were expressed as root mean square values (EMG\text{RMS} and MMG\text{RMS}).

**Statistical Analyses**

Five separate 2-way mixed factorial ANOVAs (group × time) were used to analyze NRS of soreness, ROM, MIT, EMG\text{RMS}, and MMG\text{RMS}. Group (PM vs. CON) was the between-subjects factor, and time was the within-subjects factor. Besides NRS of soreness, all values were normalized to participants’ baseline values. An α level of \( p < 0.05 \) was used to determine statistical significance, and post hoc tests with Bonferroni corrections were used when appropriate. All descriptive statistics were presented as mean ± standard deviation (SD). Cohen’s \( d \) was used to determine the magnitude of pairwise comparisons, and it was interpreted with a modified classification system (trivial [0], small [0.2], moderate [0.6], large [1.2], very large [2.0]). Additionally, an intraclass correlation of the baseline measurements was used to determine the reliability of the ROM and MIT testing. All of the data were analyzed with IBM SPSS Statistics (Version 28).
CHAPTER 4

RESULTS

Maximal Isometric Torque

There was no significant interaction ($p = 0.30, \eta^2 = 0.08$) for MIT, but there was a significant main effect for time ($p < 0.001, \eta^2 = 0.42$) (Figure 3). Values for the main effect are in Table 1. MIT was significantly reduced ($p = 0.02, d = 0.85$) 24 h P-EE by $13 \pm 15.3\%$. A return to baseline occurred by 48 h, indicated by no significant difference ($p = 0.26$) from baseline. Additionally, there was an approximately $8\%$ significant increase ($p = 0.02$) from 24 to 48 h P-EE. At 72 h P-EE, MIT values remained significantly higher ($p = 0.005$) than the values at 24 h P-EE, and there was no significant difference from baseline ($p = 1.00$) or 48 h ($p = 0.07$). There was no significant difference ($p = 0.35$) between the two groups’ baseline values, and an intraclass correlation indicated high reliability ($r = 0.99$) for the MIT trials taken at baseline.

![Figure 3](image)

*Figure 3.* Mean ± SD changes in normalized (% of baseline [i.e., pre-eccentric exercise]) maximal isometric torque (MIT). Values are from the main effect of time before the eccentric exercise (baseline) and 24, 48, and 72 h post-eccentric exercise. †$p < 0.05$ vs. baseline; #p < 0.05 vs. 24 h.
Electromyographic and Mechanomyographic Amplitude

There was no significant interaction ($p = 0.55$, $\eta^2_p = 0.04$) or main effect of time ($p = 0.47$, $\eta^2_p = 0.047$) for EMG<sub>RMS</sub>. There was also no significant interaction ($p = 0.20$, $\eta^2_p = 0.10$) for MMG<sub>RMS</sub>, but there was a significant main effect for time ($p = 0.001$, $\eta^2_p = 0.37$) that indicated a $50.1 \pm 50.7\%$ increase ($p = 0.006$, $d = 0.99$) at 72 h compared to baseline (Figure 4). Values for the main effect are in Table 1.

Figure 4. Mean $\pm SD$ changes in normalized (% of baseline [i.e., pre-eccentric exercise]) mechanomyographic root mean square (MMG<sub>RMS</sub>). Values are from the main effect of time before the eccentric exercise (baseline) and 24, 48, and 72 h post-eccentric exercise. †$p < 0.05$ vs. baseline.

Table 1. Mean $\pm SD$ values for normalized (% of baseline [i.e., pre-eccentric exercise]) maximal isometric torque (MIT) and mechanomyographic root mean square (MMG<sub>RMS</sub>). Values are from the main effect of time before the eccentric exercise (baseline) and 24, 48, and 72 h post-eccentric exercise.

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>24 h</th>
<th>48 h</th>
<th>72 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT</td>
<td>100 ± 0%</td>
<td>87.0 ± 15.3%†</td>
<td>95.2 ± 9%#</td>
<td>100.3 ± 9%#</td>
</tr>
<tr>
<td>MMG&lt;sub&gt;RMS&lt;/sub&gt;</td>
<td>100 ± 0%</td>
<td>114.6 ± 26.3%</td>
<td>114 ± 37.1%</td>
<td>150.1 ± 50.7%†</td>
</tr>
</tbody>
</table>

†$p < 0.05$ vs. baseline; # $p < 0.05$ vs. 24 h
Range of Motion

A significant interaction ($p < 0.001$, $\eta^2 = 0.46$) was found for ROM (Figure 5). Values for both groups are in Table 2. The PM group had significantly higher ROM than the CON at 24 ($p < 0.001$, $d = 2.4$), 48 ($p = 0.003$, $d = 1.53$), & 72 h ($p < 0.001$, $d = 2.08$) P-EE by approximately 6, 4, and 4%, respectively. In terms of degrees, the PM was higher than the CON by approximately 6, 5, and 5° of ROM at 24, 48, and 72 h, respectively. The CON group’s ROM was significantly lower than their baseline at 24 ($p < 0.001$) and 48 h ($p = 0.02$) by $8.8 \pm 2.3\%$ (~10°) and $3 \pm 2.8\%$ (~4°), respectively, but it returned to baseline ($p = 1.00$) by 72 h. Compared to their baseline, the PM group had significantly lower ($p = 0.002$) ROM at 24 h by $3.3 \pm 1.8\%$ (~4°), returned to baseline values ($p = 1.00$) by 48 h, and then significantly outperformed ($p < 0.001$, $d = 1.7$) their baseline at 72 h by $3.1 \pm 1.7\%$ (~4°). There was no significant difference ($p = 0.66$) between the two groups’ baseline values, and an intraclass correlation revealed high reliability ($r = 0.99$) for the FANG and RANG taken at baseline.

_Figure 5_. Mean ± SD changes in normalized (% of baseline [i.e., pre-eccentric exercise]) range of motion (ROM). Values are from the percussive massage (PM) and control (CON) group before the eccentric exercise (baseline) and 24, 48, and 72 h post-eccentric exercise. *$p < 0.05$ vs. CON; †$p < 0.05$ vs. baseline. $p < 0.001$: significant interaction.
Table 2. Mean ± SD values for normalized (% of baseline [i.e., pre-eccentric exercise]) range of motion (ROM). Values are from the percussive massage (PM) and control (CON) group before the eccentric exercise (baseline) and 24, 48, and 72 h post-eccentric exercise.

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>24 h</th>
<th>48 h</th>
<th>72 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>100 ± 0%</td>
<td>96.7 ± 1.8%*†</td>
<td>101.2 ± 2.2%*</td>
<td>103.1 ± 1.7%*†</td>
</tr>
<tr>
<td>CON</td>
<td>100 ± 0%</td>
<td>91.2 ± 2.3%†</td>
<td>97 ± 2.8%†</td>
<td>99.3 ± 1.8%</td>
</tr>
</tbody>
</table>

*p < 0.05 vs. CON; †p < 0.05 vs. baseline

Delayed Onset Muscle Soreness

A significant interaction (\(p = 0.01, \eta_p^2 = 0.22\)) was observed for the NRS of soreness (Figure 6). Values for both groups are in Table 3. There were no significant differences between the PM and CON group when NRS was collected before treatment at 24 (\(p = 0.11\)), 48 (\(p = 0.052\)), and 72 h (\(p = 0.10\)) P-EE; however, after treatment, the PM group had significantly lower (\(p < 0.001\)) NRS values at 24 (\(d = 3.04\)), 48 (\(d = 1.77\)), and 72 h (\(d = 1.61\)) compared to the CON. The CON group’s NRS remained significantly higher (\(p < 0.001\)) than their baseline at all times, whereas the PM group was only significantly higher (\(p < 0.001\)) than their baseline from 24 to 48 h before and after treatment. The PM group returned to their baseline by 72 h (before treatment, \(p = 0.08\); after treatment, \(p = 1.00\)). The CON group had no significant differences (\(p = 1.00\)) from before to after treatment within every P-EE visit, but the PM had significant differences from before to after treatment at 24 (\(p < 0.001, d = 1.6\)), 48 (\(p < 0.001, d = 0.87\)), and 72 h (\(p = 0.005, d = 0.69\)) P-EE.
Figure 6. Mean ± SD changes in the numerical rating scale (NRS) of soreness. Values are from the percussive massage (PM) and control (CON) group before the eccentric exercise (baseline) and 24, 48, and 72 h post-eccentric exercise. On the post-eccentric exercise visits, values were collected before treatment (BT) and after treatment (AT). *p < 0.05 vs. CON; †p < 0.05 vs. baseline; ‡p < 0.05 vs. BT (same visit). p < 0.05: significant interaction.

Table 3. Mean ± SD values for numerical rating scale of soreness (0-10). Values are from the percussive massage (PM) and control (CON) group before the eccentric exercise (baseline) and 24, 48, and 72 h post-eccentric exercise. On the post-eccentric exercise visits, values were collected before treatment (BT) and after treatment (AT).

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>24 h (BT)</th>
<th>24 h (AT)</th>
<th>48 h (BT)</th>
<th>48 h (AT)</th>
<th>72 h (BT)</th>
<th>72 h (AT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM</td>
<td>0 ± 0</td>
<td>4.7 ± 1.9†</td>
<td>3.3 ± 1.5†</td>
<td>4.1 ± 1.1†</td>
<td>2.9 ± 0.8†</td>
<td>1.8 ± 1.6</td>
<td>0.8 ± 0.8†</td>
</tr>
<tr>
<td>CON</td>
<td>0 ± 0</td>
<td>5.9 ± 0.8†</td>
<td>5.9 ± 0.8†</td>
<td>5.4 ± 1.4†</td>
<td>5.4 ± 1.4†</td>
<td>3.1 ± 1.5†</td>
<td>3.1 ± 1.5†</td>
</tr>
</tbody>
</table>

*p < 0.05 vs. CON; †p < 0.05 vs. baseline; ‡p < 0.05 vs. BT (same visit).
CHAPTER 5
DISCUSSION

The present study aimed to investigate if 60 s of PM given immediately, 24, 48, and 72 h P-EE on the nondominant arm’s biceps brachii could improve MIT, ROM, and DOMS (NRS of soreness) at 24, 48, and 72 h P-EE. There are a few important takeaways. The PM did not significantly affect MIT and neuromuscular activation (EMG<sub>RMS</sub> and MMG<sub>RMS</sub>) but improved ROM from 24 to 72 h P-EE. Additionally, the PM group returned their ROM to baseline values faster than the CON (PM: 48 h, CON: 72 h), and the PM group had a significantly large ($d = 1.7$) increase in ROM from baseline at 72 h P-EE. Lastly, the PM did not improve the recovery of DOMS until 72 h P-EE; however, it consistently provided an immediate, moderate-to-large ($d = 0.69 – 1.6$) decrease in perceived muscle soreness from before to after the PM within the 24, 48, and 72 h P-EE visits.

Muscular Performance

The PM had no significant effect on MIT. The significant main effect for time revealed a typical response to eccentric exercise,$^2$ in that MIT significantly decreased 24 h P-EE. Furthermore, return to baseline values occurred by 48 h and was maintained near similar values at 72 h. To the author’s best knowledge, this is the first study to investigate the effects of PM on strength or any other physical performance measure 24 to 72 h P-EE and compared to a CON. Leabeater et al$^{23}$ reported no changes in isometric strength and dynamic endurance of the calf muscles, compared to a CON limb, with 5 min of PM after three sets of 20 calf raises; however, these were measured immediately P-EE and not 24 to 72 h P-EE. Rogers and Rogers$^{24}$ reported an increase in vertical jump height with 10 min of PM on both limbs’ quadriceps muscles 48 h after 10 sets of 10 repetitions of 60% 1-RM back squats, but this was compared to the participant’s scores taken before the PM and not to a CON group. With no comparison to a CON group, it may be possible that the participants improved from a learning or warmup effect instead of the PM.
Despite the absence of PM research, four local vibration therapy (LVT) studies\textsuperscript{45,48,50,54} have investigated its effects on maximal isometric strength from 24 to 72 h (or later) P-EE, but their results are mixed. To illustrate, Koh et al\textsuperscript{54} and Percival et al\textsuperscript{45} reported significant improvements in the wrist extensor and flexor muscles compared to a CON group with 10 min of LVT at 20 and 45 Hz, respectively. On the contrary, Cochrane\textsuperscript{48} and Lau and Nosaka\textsuperscript{50} used an arm-to-arm comparison with the elbow flexors and reported no significant differences with 15 and 30 min of LVT at 120 and 65 Hz, respectively. Besides the type of muscle and research design, the improvements seen by Koh et al\textsuperscript{54} and Percival et al\textsuperscript{45} may be attributed to their LVT having a combination of shorter treatment durations and lower frequencies than Cochrane\textsuperscript{48} and Lau and Nosaka.\textsuperscript{50} A review by Germann et al\textsuperscript{61} on the effects of LVT on various performance measures suggested that pairing lower frequencies with shorter durations may result in better, positive clinical outcomes. Moreover, although improvements have been observed with LVT, a comparison to PM should be cautioned since LVT devices typically have much lower amplitudes (~1 mm) than PM devices (~12 to 16 mm). Not only did these studies have LVT amplitudes (1 to 1.2 mm) that differed from the PM in the present study (12 mm), but they also had longer treatment durations and varying frequencies (i.e., Hz).

A few studies\textsuperscript{22,42–44} have provided evidence that suggests PM may improve muscle recovery, but the present study did not confirm their findings. For example, PM ranging from 5 and 10 min has been reported to increase blood flow\textsuperscript{42,43} and oxygen availability and consumption,\textsuperscript{44} which a few authors have suggested may help support muscle recovery.\textsuperscript{42,43,45} Additionally, García-Sillero et al\textsuperscript{22} concluded that 2 min of PM improved muscle recovery since their results indicated that PM restored muscle compliance and reduced muscle stiffness P-EE greater than LVT or foam rolling. However, the present study did not observe enhanced muscle recovery via the non-significant interaction in MIT between the PM and CON group. This may be attributed to 60 s of PM not being enough to promote a significant increase in blood flow or affect muscle compliance and stiffness to improve muscle recovery. For
example, Needs et al.\textsuperscript{42} observed increased blood flow with 5 and 10 min of PM, but 10 min was superior to 5 min.

For the previously mentioned LVT studies, the tonic vibration reflex (TVR) may explain why two studies\textsuperscript{45,54} observed acute increases in maximal isometric strength with LVT.\textsuperscript{63,64} Since vibrations transmit oscillating forces to muscles, LVT may activate muscle spindles.\textsuperscript{82–84} Activation of muscle spindles could potentially increase strength by increasing the excitatory input to the agonist muscle’s alpha motor neuron pool and inducing reciprocal inhibition.\textsuperscript{82} The TVR typically occurs during or immediately after LVT,\textsuperscript{61,62} but it has been reported to last up to 5 min after LVT.\textsuperscript{63} In the present study, MIT testing occurred well after 5 min. Therefore, as evident from the non-significant interaction in MIT in the present study, a TVR did not likely occur during MIT testing due to the timing of the PM. Additionally, although PM provides vibrations similar to LVT, there are other characteristics in which PM may differ from LVT (i.e., amplitudes, frequencies, or types of devices). Thus, future research should investigate if PM has the potential to produce a TVR response similar to LVT.

Although MIT was unaffected by PM, the PM group had significantly higher ROM than the CON 24 to 72 h P-EE, with large-to-very large effect sizes ($d = 1.53 – 2.4$). Also, the PM group had a faster return to their baseline values (48 h P-EE) compared to the CON (72 h P-EE). In addition, at 72 h P-EE, the PM group had a large ($d = 1.7$) increase in ROM from their baseline. To the author’s best knowledge, this is the first study to investigate the effects of PM on ROM 24 to 72 h P-EE. Leabeater et al.\textsuperscript{23} reported no changes in ROM with PM; however, like their other performance measures, this was measured only immediately after the exercise and PM.

Despite there being no PM articles, two LVT studies\textsuperscript{48,50} investigated its effects on the elbow flexors’ ROM immediately and 1 to 7 days P-EE via an arm-to-arm comparison, and their results confirmed Leabeater et al.\textsuperscript{23} and the present study. Cochrane\textsuperscript{48} and Lau and Nosaka\textsuperscript{50} found that LVT did not affect ROM immediately after exercise, but they reported moderate-to-large improvements in ROM 24 to 72 h\textsuperscript{48} and 3 to 7 days\textsuperscript{50} P-EE when giving LVT again on those days. Although similar muscles
were examined, the duration of treatment (15 and 30 min), frequencies (120 and 65 Hz), and amplitudes (1 and 1.2 mm) of the LVT used in these studies differed greatly from the present study’s PM (duration: 60 s, frequency: 40 Hz, amplitude: 12 mm); therefore, readers should be cautioned about the comparison.

The present study’s results of the PM group significantly increasing their ROM at 72 h P-EE after they returned to baseline values at 48 h was unsurprising given the outcomes from previous PM studies that investigated its effects as a pre-exercise treatment. Within that literature, there are twice as many studies\cite{25-30} that have indicated enhancements in ROM with PM than those that have not\cite{24-26}. Within those studies that saw no improvements, the muscles and fascia of the back were involved; thus, that region might be less responsive to changes in ROM than lower limb muscles.\cite{25-28,30} To the author’s best knowledge, this is the first study to observe the effects of PM on the ROM of an arm muscle (biceps brachii), so future research is needed to confirm if it is as responsive as lower limb muscles.

There are a few suggestions on the potential mechanisms for which PM may enhance ROM, but the research is limited. Konrad et al\cite{25} suggested that similar to foam rolling, the friction and pressure from PM delivered to muscle, skin, and fascia may decrease intra- and extracellular fluid viscosity and result in a decrease in the resistance of movement (i.e., improving ROM).\cite{81} This has been confirmed by Yang et al\cite{31} via their results of a decrease in echo intensity for the thoracolumbar fascia after 15 min of PM. The authors speculated that a decrease in echo intensity would suggest that PM reduced the viscosity of hyaluronic acid in the loose connective tissue. Yang et al\cite{31} suggested that the decrease in echo intensity may have come from the PM squeezing hyaluronic acid toward the fascial rim region\cite{85} or from an increase in temperature.\cite{86} Yang et al\cite{31} confirmed the latter with their results of increased skin temperature with PM.

Additionally, Jung and Ha\cite{29} speculated that the TVR seen with LVT might be a factor for the increased ROM seen with PM. As described earlier, vibrations may activate muscle spindles;\cite{82-84} thus, ROM performance, specifically an active ROM performance, may also benefit from an acute increase in
agonist muscle activation and reciprocal inhibition. Unlike the MIT collected in the present study, ROM was measured immediately or well before 5 min after the PM. Thus, a TVR may have been present and helped with the increase in ROM for the PM group, but future research would be needed to confirm if the vibrations from PM can produce a TVR like LVT.

Another potential explanation, suggested by Konrad et al.\textsuperscript{25} and Alvarado et al.\textsuperscript{26} may be that a decrease in perceived pain or soreness with PM might allow participants to increase their performance. In the present study, the PM group had significantly lower NRS of soreness values than the CON after the treatment intervention, meaning the PM group began the ROM testing with lower perceived muscle soreness. Anecdotally, participants commonly expressed discomfort when performing the ROM testing, especially during the FANG portion of the test. Therefore, there is the possibility that the PM group was able to move through a greater ROM via less discomfort; however, this was not tested and is anecdotal evidence. Future studies may want to collect perceived muscle soreness or pain measurements during or after performance testing to see if there is a correlation between a decrease in perceived muscle soreness or pain and an increase in muscular performance.

**Muscle Activation**

The results of no significant interaction or main effect of time for $\text{EMG}_{\text{RMS}}$ corroborates the MIT results and previous research regarding $\text{EMG}_{\text{RMS}}$ responses to eccentric exercise. An increase in $\text{EMG}_{\text{RMS}}$ has been seen with LVT, which has been attributed to the TVR,\textsuperscript{61,63} but similar to the discussion with MIT, the timing of the PM in the present study likely explains why a TVR response was not observed. Furthermore, the present study's results of no main effect for time confirmed previous studies' results of no changes in $\text{EMG}_{\text{RMS}}$ during maximal voluntary contractions performed 24 h or later P-EE.\textsuperscript{110–115}

Similar to $\text{EMG}_{\text{RMS}}$, there was no interaction for $\text{MMG}_{\text{RMS}}$; however, there was a main effect for time, revealing a moderate ($d = 0.99$) increase from baseline at 72 P-EE. No interaction for $\text{MMG}_{\text{RMS}}$ furthers the evidence that PM had no significant effect on altering neuromuscular recruitment patterns P-
EE. The increase at 72 h P-EE likely occurred from mechanical changes in the biceps brachii due to eccentric EIMD. To illustrate, previous studies\textsuperscript{113,114} have observed increases in MMG\textsubscript{RMS} without changes in EMG activity P-EE. As a result, the researchers suspected that the increase in MMG\textsubscript{RMS} was from changes in the mechanical properties of muscle due to eccentric-EIMD, such as increased edema, instead of changes in neural activation patterns.

**Delayed Onset Muscle Soreness**

Before the treatment intervention, the NRS of soreness did not differ between groups from 24 to 72 h P-EE, but the PM group recovered faster to their baseline values (72 h) than the CON (never recovered). After the treatment intervention, the PM group had a moderate-to-large ($d = 0.69 - 1.6$) decrease compared to their values taken before the treatment intervention within each P-EE visit, and this resulted in the PM group having a large-to-very large ($d = 1.61 - 3.04$) difference between the CON from 24 to 72 h P-EE. Thus, the PM appeared to consistently provide immediate, and likely temporary, relief in perceived soreness since it did not enhance recovery until 72 h P-EE. The author cannot suggest how long this likely temporary reduction in perceived soreness may last since NRS of soreness was collected only immediately after the treatment intervention. Therefore, future research may want to examine how long this relief can potentially last by collecting perceived soreness scores for minutes or hours after a PM intervention within a P-EE visit.

These findings mostly align with the only two studies\textsuperscript{23,24} that investigated the effects of PM on DOMS. Leabeater et al\textsuperscript{23} reported no significant differences in perceived muscle soreness immediately, 4, 24, and 48 h after three sets of 20 calf raises. Since the authors only gave the PM (5 min) immediately after exercise, their results confirm the present study’s findings of no differences in the NRS of soreness collected at 24 and 48 h before the treatment intervention. However, the present study did collect NRS of soreness before the treatment intervention at 72 h P-EE and found that the PM group recovered to their baseline, whereas the CON did not recover. These findings may suggest that daily PM over multiple P-EE days may be beneficial in reducing DOMS by 72 h P-EE.
The results of Rogers and Rogers\textsuperscript{24} also align with the present study, because they reported significant reductions in perceived pain with 10 min of PM 48 h post-exercise compared to the participants’ values taken before their treatment and without a CON. These results confirmed the present study’s results of PM significantly reducing NRS values from before to after treatment 48 h P-EE within the PM group. In addition, in the present study, these immediate reductions from before to after treatment in perceived soreness were also observed within the 24 and 72 h P-EE visits. Furthermore, the present study only used 60 s of PM, suggesting that shorter durations may be as beneficial in immediately reducing perceived muscle soreness. However, it should be noted that Rogers and Rogers\textsuperscript{24} examined larger lower limb muscles (both limbs’ quadriceps), whereas the present study examined a smaller upper limb muscle of only the nondominant arm. Thus, future studies may want to investigate the relationship between different PM durations and types of muscles in alleviating DOMS.

In addition to DOMS, there are reports of PM immediately reducing other forms of perceived pain\textsuperscript{46} and stiffness,\textsuperscript{31} further confirming the present study’s findings of immediate reductions in perceived soreness. For example, Pearce et al\textsuperscript{46} applied PM on myofascial trigger points of the upper back and reported that a single treatment (duration not stated) immediately reduced pain, primarily in latent or less painful myofascial trigger points. However, there were no significant changes in the morphological structures of the myofascial trigger points, which provides more evidence to suggest PM has an immediate, but likely temporary, effect on reducing pain or soreness. Furthermore, Yang et al\textsuperscript{31} reported significant, immediate reductions in perceived stiffness when giving healthy male participants 15 min of PM on their erector spinae muscles. Again, future research should investigate if these effects are only immediate or have lasting effects for minutes and hours after a PM treatment.

The physiological mechanisms by which PM may provide immediate relief or accelerate the recovery from DOMS are poorly understood. The only relevant PM articles are the studies that indicated it increased blood flow\textsuperscript{42,43} and oxygen availability and consumption.\textsuperscript{44} The present study’s PM group may have recovered their NRS values faster than the CON due to enhanced blood flood improving the
recovery of damaged muscle;\textsuperscript{42,43,45} however, again, these studies reported improvements in blood flow with 5 and 10 min of PM and indicated that 10 min was more effective than 5 min.\textsuperscript{42} The present study only used 60 s of PM; thus, the author cannot be certain if this is a valid explanation until research confirms that 60 s of PM can significantly increase blood flow and be correlated to an enhanced recovery in DOMS. Moreover, improving blood flow does not likely provide useful insight into why the 60 s of PM in the present study immediately reduced perceived soreness.

Studies investigating the mechanisms of how vibration reduces pain may provide insight as to why the PM group in the present study had immediate decreases in NRS of soreness. For example, vibration has been seen to activate sensory fibers in muscles,\textsuperscript{84} which may potentially affect the sensation of pain associated with group III and IV afferent fibers.\textsuperscript{48,50} Vibration may also stimulate Ruffini cylinders and Pacinian corpuscles, potentially resulting in muscle relaxation via inhibiting sympathetic activity.\textsuperscript{81} However, these observations and claims\textsuperscript{81,84} were made with vibration treatments with longer durations, higher frequencies, or lower amplitudes than the PM used in the present study or previously mentioned PM studies. Thus, more research is needed to understand the precise physiological mechanisms for why studies have consistently observed immediate decreases in perceived muscle soreness, pain, and stiffness with PM.

**Practical Applications**

After performing highly intense eccentric actions or unaccustomed forms of exercise, individuals commonly experience symptoms of DOMS\textsuperscript{2,3,5} and decreased strength\textsuperscript{2,3,5,7–9} and ROM,\textsuperscript{2,5,7} which may negatively impact daily activities or athletic performance.\textsuperscript{19,20} Based on the present study’s results, using a PM intervention P-EE may immediately reduce muscle soreness and acutely improve ROM without affecting strength. Additionally, for those seeking a faster recovery in DOMS, daily PM given P-EE may be recommended since the present study did not see an improvement in recovery until 72 h P-EE. The effects of giving PM P-EE may be advantageous for various populations and scenarios. For example, athletes that require maintenance of ROM for performance or injury prevention purposes may benefit
from PM following frequent training sessions and competitions with highly intense eccentric actions or after a period of detraining, all of which may result in EIMD symptoms. Furthermore, PM may also be useful for non-athletic individuals where high levels of muscle soreness and decreased ROM may negatively impact their quality of life, daily activities, or work performance. Lastly, PM may benefit patients who are undergoing rehabilitation from an injury and require immediate decreases in soreness and increases in ROM prior to a rehabilitation session.

**Limitations**

The present study is not without limitations. Firstly, the PM group was compared to a CON group that received no treatment instead of a sham. A sham intervention was likely not feasible since almost all (16 out of 17) participants were kinesiology students who would likely be skeptical of a sham intervention. Additionally, there was no comparison to other treatments that may potentially improve symptoms associated with EIMD. The present study also did not track and control for the female menstrual cycle. Certain phases within the menstrual cycle, such as the early follicular phase, late follicular phase, and mid-luteal phase, may affect the degree of DOMS and strength losses associated with EIMD.78 Another limitation was that the ROM testing, and all testing, was conducted by a single investigator who was not blind to the participant’s treatment group. Next, the subjects were untrained, and only a nondominant arm muscle (biceps brachii) was used for analysis. Untrained individuals are more likely to have greater EIMD symptoms than trained individuals due to the repeated bout effect,4 and upper limb muscles may exhibit greater symptoms of EIMD than lower limb muscles since they are less likely to be used during daily activities.104 Thus, the effects of PM may not have been as significant with a trained population and lower limb muscle or muscle group. Lastly, MIT and ROM were not collected before the treatment intervention. The PM group was significantly higher than the CON group 24 to 72 h P-EE, but it remains unknown if the PM accelerated the recovery of ROM or only provided an immediate, acute increase similar to the response seen with NRS of soreness.
CHAPTER 6

CONCLUSION

This study was the first to analyze the effects of multiple PM treatments (immediately, 24, 48, and 72 h P-EE) on MIT, ROM, and DOMS (NRS of soreness) at 24, 48, and 72 h P-EE. The author hypothesized that the PM would improve all variables at all P-EE times, and PM would immediately lower NRS of soreness values from before to after treatment within every P-EE visit. PM did not affect MIT and muscle activation (EMG\text{RMS} and MMG\text{RMS}), but it improved ROM 24 to 72 h P-EE. Additionally, after the PM group returned their ROM to baseline values at 48 h, which was faster than the CON group’s return at 72 h, they had a large, significant increase from their baseline at 72 h P-EE. Lastly, the PM did not accelerate the recovery of DOMS until 72 h P-EE, but it consistently provided immediate, temporary relief in perceived muscle soreness within every P-EE visit. In conclusion, after an intense eccentric exercise targeted for the nondominant arm’s biceps brachii, PM may be beneficial for immediately reducing perceived soreness and increasing ROM without affecting maximal isometric strength from 24 to 72 h P-EE in untrained individuals.
REFERENCES


