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The Effects of Ice and TENS Combination Treatment on Knee and Hip Joint Neuromechanics in Individuals with Experimentally Induced Knee Pain During Running

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ABSTRACT

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Context: Knee injury is a common problem for runners. Knee pain is a common symptom in knee injury and is associated with alterations in knee and hip muscle activation and hip joint angles. Relieving pain through intervention may help to restore neuromuscular function. **Objective:** To examine the effects of ice and transcutaneous electrical nerve stimulation (TENS) combination treatment on perceived knee pain, hip frontal plane angle, and muscle activation during running in individuals with experimental knee pain (EKP). **Design:** Crossover. **Setting:** Laboratory. **Subjects:** 19 participants (11 males and 8 females, 23.2 ± 1.9 y, 176 ± 11.6 cm, 71.5 ± 16.9 kg; right leg dominant). **Interventions:** Hypertonic saline was infused into the infrapatellar fat pad for 74 minutes (total 11.1 mL). Subjects underwent 2 treatment conditions (sham; ice/TENS combination). Measurements were recorded during running at 4 time points (preinfusion, postinfusion, posttreatment, and postinterval). **Main Outcome Measures:** Perceived knee pain on a 100-mm visual analog scale (VAS), knee and hip muscle peak electromyography (EMG) amplitude, and hip adduction angles. **Results:** Hypertonic saline infusion increased perceived anterior knee pain in all participants. The average of peak perceived knee pain was 28 mm on a 100-mm VAS in EKP application. While the increased perceived knee pain level stayed consistent across time in the sham session, ice/TENS combination treatment significantly reduced perceived knee pain by 35% at 6 minutes after the treatment start ($p = 0.049$), and the reduced knee pain lasted for 22 minutes ($p > 0.05$). Peak EMG amplitude of the gluteus medius was decreased by 13.5% and 14.3% ($p = 0.023$; $p = 0.013$) during running after EKP in sham and treatment sessions, respectively. However, the peak EMG amplitude was not restored to pain-free level during running after the treatment ($p = 0.026$). No other muscles changed their peak EMG amplitude due to EKP or treatment. Hip adduction angles during running were also not altered by EKP or treatment ($p > 0.3$) in both sham and treatment sessions. **Conclusions:** EKP increased perceived knee pain and decreased peak muscle activation of the gluteus medius during running. Ice/TENS combination treatment reduced perceived knee pain quickly, but did not restore neuromechanics during running.

Key Words: ice/TENS combination treatment, peak EMG amplitude, hip adduction angle, hypertonic saline infusion

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Introduction

Knee injury is a common problem, and the related annual costs are approaching $20 billion in the United States.[1,2] Anterior knee pain (AKP) is a chief symptom in patients with knee pathology and is characterized as acute or chronic peripatellar pain.[3] This pain often occurs over time with an increase in physical activity. Patients with AKP may curtail physical activity due to the limping from the perceived pain and knee stiffness. This restricted physical activity may lead to weight gain, increased knee joint loading,[4,5] and poor quality of life.[6]

AKP occurs in the patellofemoral joint during and after patellofemoral loaded activities (ie, jump landing, squatting, climbing stairs, hiking, and running),[7,8] and often causes movement dysfunction. AKP triggers abnormal afferent sensory information.[9] The abnormal sensory transfer can cause neuromuscular dysfunction (eg, delayed onset) of the quadriceps and hip abductors.[10-12] For example, patients with patellofemoral pain (PFP) commonly present with weak activation of the vastus medialis oblique,[13,14] vastus lateralis,[13,14] and gluteus medius[15] due to AKP characteristics (eg, abnormal afferent information). AKP can also adversely affect knee and hip joint motion in physical activity. AKP via knee injuries can lead to a decreased knee flexion angle and extension moment,[16] and a greater degrees of knee valgus[17] and adduction moment[18] during a landing task. Also, previous experimental-knee-pain (EKP) studies reported that AKP might cause decreased knee-flexion angle during walking[19] and decreased hip-adduction angle during running.[20] These dysfunctions on lower extremities can lead to a higher impact on the knee joint (ie, tibiofemoral and patellofemoral joints) and increase the risk of potential knee injuries during physical activity (eg, ACL sprain).[21]

Although analgesic medications are effective to alleviate musculoskeletal pain such as AKP, most analgesic medications have undesirable side effects.[22,23] Due to the side effects of the

medications, clinicians have been investigating therapeutic modalities for reducing pain.[24,25] Two of the most common therapeutic modalities for pain control are cryotherapy and electrotherapy. Cryotherapy (eg, ice pack) is the most useful treatment modality to relieve the acute pain of soft-tissue injuries immediately.[26,27] Cryotherapy has been shown to slow nerve conduction velocity,[28,29] decrease the discharge rate of mechanoreceptors (ie, pacinian corpuscles),[30] and decrease mechanoreceptor sensitivity.[31] These neurological responses result in a reduction of knee joint pain[25,32-36] and an increase in activation of quadriceps muscles.[33,37] Cryotherapy has minimal side effects and is low cost, making it a common treatment for lower extremity joint pain within sport and clinical settings.[27] Electrotherapy is also an effective modality for pain control and muscle function. Transcutaneous electrical nerve stimulation (TENS) intervention is a common and traditional noninvasive treatment for pain modulation[38] in electrotherapy. TENS uses surface electrodes to deliver a pulsed electrical current through the skin to stimulate nerves for the purpose of controlling and relieving pain.[39] The physiological effect of TENS is selective depolarization of afferent nerves; the depolarization prevents delivery of perceived pain to the brain.[39] TENS treatment can increase quadriceps motor neuron pool excitability[40] and decrease pain perception of the knee joint.[24]

While cryotherapy and electrotherapy have been effective at AKP treatment individually,[36,41,42] many clinicians suggest ice and electrical stimulation (eg, TENS) combination as the most effective therapeutic approach for reducing joint pain. Although clinicians suggest that the combination may lead to a stronger treatment effect, only one study reported ice and TENS (ie, burst mode) combined has a potentiating effect in reducing induced pain (ie, pressure pain) by increasing pain threshold and tolerance.[43] Furthermore, it is not clear how much more effective the combination treatment is than the ice or TENS single treatment on

reducing perceived knee pain or improving lower-extremity neural activation during dynamic athletic movements such as running.

Although pain is a primary feature in many knee pathologies, it is difficult to isolate the effects of pain in patients with clinical AKP from other pathological features such as inflammation or altered joint and muscle function.[44] Experimental knee pain (EKP) models are useful in establishing a constant level of pain in a controlled laboratory setting because they produce strong knee pain in regions similar to those in patients presenting with AKP.[25,45] EKP models safely mimic anterior knee joint pain by infusing hypertonic saline (5%) into the medial infrapatellar fat pad.[45] The AKP from EKP application provides further insight into the nature of pain production from specific anatomical structures.[44,45] Previous studies have used EKP models to better understand the independent effects of knee pain on lower extremity neuromechanics.[12,20,46-50] EKP models appear to trigger abnormal afferent sensory information, then independently alter quadriceps activation characteristics and function.[46,51] Further, the altered quadriceps activation via EKP have been observed during functional movements, including static standing,[47,48] stair climbing,[46] and strength training exercises.[52] Also, EKP may inhibit muscle activation in the gastrocnemius, medial hamstring, and gluteus medius during landing.[12] Our recent studies have shown that EKP independently and acutely alters kinematics, kinetics, and muscle activations of the pain-induced knee joint during physical activities (ie, running, walking, and jump-landing).[12,20,50]

The purpose of this study was to answer three research questions: Does ice and TENS, applied simultaneously, (1) reduce perceived knee pain, (2) restore inhibited knee and hip muscle activations during running, and (3) restore altered hip angles, during running? We hypothesized that simultaneous ice and TENS treatment would reduce perceived knee pain within 10 minutes

during the treatment, and the decreased pain would last for 20 minutes after the treatment. Also, we hypothesized that simultaneous ice and muscle electrical stimulation treatment would restore inhibited knee and hip muscle function and altered biomechanics during running.

Methods

Design

We used a laboratory-based, pretest, posttest, crossover design. All participants completed 2 data collection sessions in a counterbalanced order. We applied the EKP model to subjects in each data collection session. The independent variables were (1) treatment (ie, sham and ice/TENS combination treatment) and (2) time (ie, baseline, after EKP model application, immediately after treatment, and 20 minutes after treatment). Three classes of dependent variables were measured: perceived knee pain (using a visual analog scale (VAS)), electromyography (EMG) amplitudes of knee and hip muscles, and hip adduction angles during running.

Participants

Nineteen healthy volunteers (11 males and 8 females; age, 23.2 ± 1.9 y; height, 176 ± 11.6 cm; mass, 71.5 ± 16.9 kg; right leg dominant) participated in this study. Each participant was required to be participating in physical activity at least 3 days each week for a total of 90 minutes (recommended by the World Health Organization) in the past 3 months.[50] Exclusion criteria included any history of knee joint pathology, current pain of either knee, or any history of fainting during blood draw. All participants were asked to avoid exercising 48 hours before data collection and taking any analgesic agent or anti-inflammatory medicines 12 hours before data collection. We estimated the appropriate sample size using an a priori power analysis, with alpha and beta values 0.05 and 0.80 (ie, 80% power), respectively. Our effect size was based on (1)

pain threshold and (2) amount of gluteus medius activation, as reported in the previous studies summarized below.[53] Macedo et al[43] studied the ability of burst TENS in combination with cryotherapy to reduce pressure pain threshold and tolerance of the elbow joint. They reported that mean pain tolerance was significantly increased (+ 4.9) in a group who received burst TENS in combination with cryotherapy ($p < 0.001$, effect size = 3.47) after the combination treatment. Further, Willson et al[53] found that females with patellofemoral pain presented 42 ms shorter ($p = 0.01$, effect size = 0.88) gluteus medius activation duration than healthy females during running. Using data from these two studies, we estimated at least 15 participants to detect statistical differences in the dependent variables of greatest interest.

Procedures

Our research protocol was approved by the university's Institutional Review Board (IRB). All subjects provided informed consent prior to any data collection. Participants visited the biomechanics laboratory (RB 124) for 3 different sessions (first session: the orientation; second and third sessions: data collection). During the orientation session, we (1) obtained informed consent, (2) evaluated physical activity history using International Physical Activity Questionnaire (IPAQ-long), (3) screened participants for knee joint health using Knee injury and Osteoarthritis Outcome Score (KOOS), and (4) collected demographic data (ie, age, height, weight, and history of knee pathology) from each participant. If any participants presented any symptoms, pain or discomfort in the KOOS screening, we excluded the subject from this study. Further, if any participants did not meet our criteria (ie, participating in physical activity at least 3 days each week for a total of 90 minutes) from the IPAQ-long evaluation, we also excluded the participant from this study. During the orientation, participants decided on a preferred running-

speed. This speed was determined subjectively by each participant as a comfortable speed that could be maintained for 3 minutes.

Data collection sessions were completed at the same time of day, 48 hours apart. Each of these data collection sessions corresponded to a separate treatment condition: sham and ice/TENS combination. Condition order was determined using a randomized block procedure. Other than the physical exercise that directly resulted from participation in this project, participants were required to refrain from physical exercise between 48 hours before the first data collection and the end of the last data collection. During each of the 2 data collection sessions, participants first changed into tight-fitting (spandex) shorts and shirt, athletic socks, and shoes provided by the researchers. Next, the participants stood while 4 wireless, bipolar, Ag/AgCl surface electrodes (Trigno, Delsys Inc, Boston, MA, USA) were applied to subjects using double-sided tape. The electrodes facilitate evaluation of unilateral neuromuscular activation patterns for the vastus medialis oblique (VM), vastus lateralis (VL), gluteus medius (Gmed), and gluteus maximus (Gmax). We followed recommended guidelines[54] while preparing the skin and applying the electrodes. After the application, the electrode location was evaluated and adjusted using manual muscle tests and visual inspection of the EMG signal. Next, 38 reflective markers were applied to participants to facilitate motion analysis—reflective markers were applied bilaterally over the iliac crest, anterior-superior iliac spine, posterior-superior iliac spine, medial and lateral femoral condyle, medial and lateral malleolus, head of the fifth metatarsal, superior-distal aspect of the second metatarsal, dorsum (ie, navicular bone of the foot), and heel (ie, posterior calcaneus). Lastly, rigid clusters of 4 reflective markers were also applied bilaterally to the distal-lateral thigh and shank using elastic tape. To eliminate interrater variability, the same investigator attached all of the reflective markers and EMG electrodes. A

14-camera motion capture system (250 Hz; VICON, Denver, CO, USA) and an instrumented force-sensing treadmill (2000Hz; AMTI, Watertown, MA, USA) were used to record the running motion. Marker trajectories were collected via VICON Nexus software.

Before the running tasks, we obtained a static pose to provide the anatomical reference for human movement. For this static video, subjects stood in anatomical position. Next, the subjects underwent a 5-minute warm-up task (ie, low-intensity jogging) on the treadmill. After the 5-minute warm-up, each subject performed the running tasks 4 times: (1) baseline, (2) with EKP model, (3) immediately posttreatment, and (4) 20 minutes posttreatment (Figure 1). The running task required the subjects to run for 3 minutes at each participant's preferred speed. The baseline running task (running task #1) provided the reference EMG amplitude.[55] EMG was recorded (2000 Hz) during the final 30 seconds of this run. The peak EMG amplitudes for each muscle were averaged during the running stance phase. We normalized the EMG amplitude of subsequent running trials with the EKP model using the reference EMG amplitude.

Experimental Knee Pain (EKP) Model

After the first running task (baseline), subjects lay down on their back (supine position) on a nearby treatment table. Subjects lay still while we inserted a 20-gauge flexible catheter (BD Medical, Sandy, UT, USA) into the right infrapatellar fat pad. We inserted the catheter from the lateral side, at an angle of 45° above horizontal, in an inferior-medial direction, to a depth of 1 cm, to the middle of the infrapatellar fat pad, under the patellar tendon. Then the inserted catheter was connected to a 30-cc syringe via an extension tube (B. Braun, Bethlehem, PA, USA). We attached the syringe to a portable infusion pump (Graseby Medical, Hertfordshire, UK) that was set to produce a constant saline flow of 0.15 $ml \cdot min^{-1}$ for 74 minutes (11.1 mL of saline). After connecting the catheter, syringe, and infusion pump, we initiated the saline

infusion. Hypertonic saline (5% saline; B. Braun, Irvine, CA, USA) was continuously infused to induce pain throughout the remaining 3 running tasks (running tasks 2, 3, and 4), a treatment task, and a posttreatment interval task.

Treatments

When the second running task was finished, we treated the participant's perceived knee pain 1 of 2 ways (ie, sham or ice/TENS combination) for 20 minutes before the third running task. Each participant received the treatments in a supine position on a treatment table. For the ice/ TENS combination session (Figure 2), we used a TENS 3000 unit and 4 (5 × 5 cm) self-adhesive electrodes (Omnistim electrodes). Each participant shaved (if needed) and cleaned the skin with an alcohol wipe to enhance adherence for the electrodes. Four electrodes were attached around the borders of the right patella with 5 to 7 cm distance between them (Figure 3).[42] TENS treatment protocol was a continuous asymmetric biphasic square-pulse wave with a pulse width of 120 microseconds and a pulse rate of 180Hz.[24] Two plastic ice bags (1.5 L of crushed ice) were also secured to the knee joint with an elastic wrap (6 inches × 10 yards) for 20 minutes. Each ice bag was placed on the anterior and the posterior surfaces of the knee joint, respectively.[25] For the sham session, subjects also had four (5 × 5 cm) self-adhesive electrodes around the borders of the right patella as in the ice/TENS combination condition,[42] but TENS mode was off. Two bags of fake ice (1.5 L), consisting of crushed clear acrylic crystals, were secured to the knee joint with an elastic wrap (6 inches ×10 yards) for 20 minutes.

Perceived Knee Pain

Using a 100-mm VAS,[45] we measured the perceived AKP magnitude every 2 minutes, from immediately before the first running task to the completion of the last (fourth) running task.

Data Analysis

Three-dimensional coordinates of reflective markers and EMG signals were digitized in VICON Nexus software (VICON, Santa Rosa, CA, USA) and then imported into Visual 3D software (C-Motion, Germantown, MD, USA). The EMG signals were filtered through hardware during acquisition (bandpass filter, 20 to 450 Hz). In Visual 3D, the mean offset of the filtered EMG signals was removed using a high pass filter (20 Hz cutoff), then the data were smoothed using a root mean square moving window algorithm, with a moving window width of 125 ms.[50] The coordinate data were digitally filtered using a fourth order low-pass Butterworth filter (10 Hz cutoff).[56] The smoothed marker coordinates were used to calculate 3D hip joint kinematics. Joint angles were calculated using a Cardan rotation sequence of flexion-extension, abduction-adduction, and internal-external rotation. We sampled only the last 30 seconds of each 3-minute running trial.[50] In the samples, smoothed EMG data and calculated hip adduction angles were time normalized to 100% of the stance phase (from initial ground contact to take-off) as determined using the force plates and a 25-N vertical GRF threshold (2000 Hz; AMTI; Watertown, MA).

All of the 100-mm VAS were normalized by the peak perceived knee pain during EKP model application. Normalization was performed due to unexpected effects of the crossover design. Many participants presented significantly lower levels of induced AKP at their second session compared to the first session, regardless of the type of treatment. Participants might have adjusted to our EKP application in their second session through an EKP experience at the first session. To minimize errors related to EKP experience, we normalized the perceived knee pain level of each participant.

Statistical Analysis

We examined subject-perceived knee pain between the 2 treatments using 2 mixed model analyses of variance with repeated measures. The first analysis of variance (ANOVA) examined the effect of ice and TENS treatment on the perceived knee pain (2 × 10: treatment × time) during the 20-minute treatment. The second ANOVA examined posttreatment effects on the perceived knee pain (2 × 18: treatment × time). We also examined neuromechanical variables (ie, peak EMG amplitude and peak hip adduction angles) between the 2 treatments using a 2 × 3 (treatment × time) mixed model analysis of covariance with repeated measures. Tukey-Kramer post hoc tests ($p < 0.05$ for all tests) was used for pairwise comparisons. The baseline running data was considered as a covariate to assess changes in peak hip adduction angle and mean EMG amplitudes for 2 treatment sessions over 3 time points. We calculated means and 95% confidence interval for these 2 variables using JMP 13 software (SAS, Cary, NC, USA).

Results

All participants successfully conducted 2 running sessions (ie, sham and ice/ TENS combination; running speed, 5.7 ± 0.6 mph) with hypertonic saline infusion (Figure 4). The saline infusion increased perceived AKP in all participants. Perceived knee pain changed within 2 minutes after the hypertonic saline infusion started. The mean peak perceived knee pain during the 20-minute EKP application was 28 mm on a 100-mm VAS. The ANOVA across the treatment section was significant for session ($F_{1,10} = 9.23$, $p = 0.007$) and interaction ($F_{1,10} = 6.83$, $p < 0.001$). While the increased perceived knee pain level stayed consistent across time in the sham session, the ice/TENS combination treatment reduced the perceived knee pain by 41% at the end of the treatment time (Figure 5, $p = 0.005$). The ice/TENS combination treatment significantly reduced perceived knee pain by 35% at 6 minutes after the treatment started ($p =$

0.049). This treatment effect remained significantly different through the 20-minute treatment phase ($p < 0.049$). In addition, perceived knee pain level following ice/TENS treatment did not show significant changes until 22 minutes ($p > 0.05$).

Peak EMG amplitude of Gmed was decreased by 13.5% and 14.3% (Figure 6, $p = 0.023$; $p = 0.013$) during running after EKP in sham and treatment sessions, respectively. Also, the peak EMG amplitude was not restored to the pain-free level during running after the 20-minute ice/TENS combination treatment ($p = 0.026$). Also, peak EMG amplitudes of VM and VL were decreased by 19.1% and 17.2% (Figure 7, $p = 0.009$; Figure 8, $p = 0.005$) during running after EKP in the sham session. Although peak EMG amplitude of VM and VL were decreased by 11.5% and 9%, respectively, during running after EKP in the treatment session, these results were not statistically significant ($p = 0.335$; $p = 0.437$). Further, there were no significant differences between running after EKP and running after treatment in both VM ($p = 0.82$) and VL ($p = 0.99$) peak EMG amplitudes in the treatment session. The ice/TENS combination treatment did not significantly increase peak EMG amplitude of both VM and VL. On the other hand, the peak EMG amplitude of Gmax (Figure 9) during running was not changed at all 3 time points (after Induced AKP; after treatment; after a 20-minute interval, $p > 0.3$) compared to the running before EKP application in both sham and treatment sessions. Also, hip adduction angles during running were not changed through all 3 times ($p > 0.8$) in both sham and treatment sessions (Figure 10).

Discussion

The aim of this study was to examine the effects of ice/TENS combination treatment on perceived knee pain, hip frontal plane angle, and muscle activation during running in individuals with EKP. We hypothesized that ice/TENS combination treatment would reduce perceived knee

pain closer to the prepain level within 10 minutes during the treatment, and the decreased pain level would last for 20 minutes after the treatment. Consistent with this hypothesis, ice/TENS combination treatment showed a significant decrease in perceived knee pain level within 10 minutes during the treatment. Also, the reduced perceived knee pain level did last for 22 minutes after treatment. We also hypothesized that ice/TENS combination treatment would restore normal (prepain) running mechanics. While the EKP infusion model decreased peak muscle activation of Gmed, VL, and VM during running task, the ice/TENS combination treatment did not affect any of these variables.

Our results further established the EKP model as a safe and effective method for inducing AKP in healthy participants. Our EKP model effectively increased perceived knee pain within 16 minutes (Figure 5), with a mean maximum perceived knee pain level of 28 mm on a 100-mm VAS during EKP model application. Hypertonic saline injected into the infrapatellar fat pad in healthy individuals produces moderate to strong knee pain in regions similar to those in patients presenting with AKP and of similar quality.[19,45,48]

The current study found the ice/TENS combination treatment can relieve perceived knee pain quickly. The ice/TENS combination treatment effectively reduced perceived knee pain (35% decrease, $p = 0.049$) at 6 minutes in this study. Both Ice and TENS are effective noninvasive treatment interventions to control and relieve pain in musculoskeletal injuries.[36,57,58] Ice disinhibits and facilitates motorneuron pool activity during and up to 30 minutes after the treatment. Disinhibition may be attributed to decreases in sensory nerve conduction velocity[59] and discharge rate of mechanoreceptors located in skeletal muscle.[60] TENS unit delivers a pulsed electrical current through the skin to stimulate sensory nerves.[39,61,62] The sensory nerve stimulation alters cutaneous sensory input to the central nervous system in controlling and

reducing perceived pain.[63] While not tested in this study, a comparison of our results to previous studies suggests that the ice/TENS combination treatment may be more effective than ice or TENS alone. For example, Long et al[25] reported ice application reduced the induced AKP at 16 minutes. Also, a previous study by our group (with similar methodology) reported perceived knee pain level substantially decreased after 16 minutes of TENS treatment.[64]

The present findings suggest that AKP inhibits neuromuscular activation. Previous studies have reported that induced AKP might result in altered quadriceps neuromuscular activation.[42,49,50] We also observed that increased perceived knee pain from hypertonic saline infusion decreased muscle activation (ie, peak EMG amplitude) of VM and VL. Furthermore, we examined how induced AKP altered neuromuscular activation of hip abductors. Our study found that induced AKP decreased peak EMG amplitude of Gmed, but not Gmax. Several previous studies reported that AKP inhibited the muscle activation pattern of Gmed during static and dynamic motion (eg, single leg standing and landing).[12,53,65] Willson et al[53] found that females with patellofemoral pain (PFP) demonstrated delayed onset and shorter duration of Gmed activation compared with healthy females during running. On the contrary, two other previous studies showed no difference in Gmed activation between patients with PFP and healthy controls during running.[66,67]

The results from this study show that ice/TENS combination treatment may not be an effective intervention to restore the inhibited knee and hip muscle activation during running. While our results did not show a therapeutic effect on muscle activation with ice/TENS combination, previous studies have reported that a single ice or TENS application improved muscle activation. Ice over the knee joint has been shown to improve quadriceps function during a short duration in individuals with arthrogenic muscle inhibition.[37] Ice application disinhibits

and facilitates motorneuron pool activity during and up to 30 minutes after the treatment. Disinhibition may be attributed to a decrease in sensory nerve conduction velocity[59] and discharge rate of mechanoreceptors located in skeletal muscle.[60] Also, TENS treatment may improve quadriceps weakness and voluntary activation deficits associated with arthrogenic muscle inhibition.[68] TENS treatment has been reported to effectively decrease the perception of knee pain through disinhibitory effects[69-71] and increase quadriceps activation in OA patients with knee pain.[33,58,72] Electrical stimulation over the knee joint may stimulate femoral cutaneous nerve branches (Ia, Ib), which may decrease Ib inhibitory activation and increase Ia excitatory activation during interneuronal relays.[40,68,73,74] Son et al[64] reported that sensory TENS treatment restored the reduced quadriceps strength and activation due to noxious pain signals. Despite the aforementioned treatment effects, our results did not support the second hypothesis that ice/TENS combination may be an effective therapeutic intervention to restore peak EMG amplitude of VM, VL, and Gmed. It is not clear why ice/TENS combination treatment did not provide any synergetic therapeutic benefit related to peak EMG amplitude.

The present results has shown that the peak hip-adduction angle during running was not significantly influenced through induced AKP. Also, ice/TENS combination treatment did not affect peak hip-adduction angle in individuals with EKP during running. We hypothesized that ice/TENS combination treatment would increase muscle activation of Gmed and Gmax. However, the combination treatment was not effective in improving muscle activation on Gmed and Gmax. Seeley et al.[20] suggested a compensatory motor strategy that might shift body weight (the trunk) toward the involved leg. This type of body weight shift might prevent hip-adduction angle change during running. Further, hip abductor muscles (eg, Gmed and Gmax) contribute to control hip adduction during running gait. Excessive hip adduction angle has been associated

with knee valgus angle and many lower-extremity overuse running injuries.[75] Patients with PFP present a greater knee valgus angle on unilateral limb loading than either their contralateral asymptomatic limb or healthy individuals.[17] The weakness of hip abductor muscles may increase hip adduction angle in running. It has been thought that AKP may inhibit muscle activation of the hip abductors, then result in increased hip adduction angle. Our study has shown that induced AKP reduced peak muscle activation of Gmed, but the knee pain did not affect hip-adduction angle during running. Also, peak muscle activation of Gmax was not influenced by the induced AKP. Gmed and Gmax eccentrically act to control hip adduction and internal rotation during weight-bearing. Gmax, unaffected by induced AKP, may control hip-adduction angle in place of Gmed during running. However, our results might not have suggested the compensatory muscle function of Gmax because we did not examine the effect of induced AKP on overall strength changes in Gmed and Gmax. We need to better understand how the induced AKP affects overall strength in Gmed and Gmax.

Conclusion

In our study we observed that EKP significantly increased perceived knee pain and decreased peak muscle activation of hip abductor (Gmed) and quadriceps (VM and VL) during running. However, EKP did not change hip adduction angle and peak muscle activation of Gmax during running. Compared with sham treatment, Ice/TENS combination treatment effectively reduced perceived knee pain (40%) quickly and lasted for 22 minutes, whereas peak muscle activation of hip abductor and quadriceps in running were not restored by Ice/TENS combination treatment. Also, this treatment did not affect hip adduction angle and peak muscle activation of Gmax during running.

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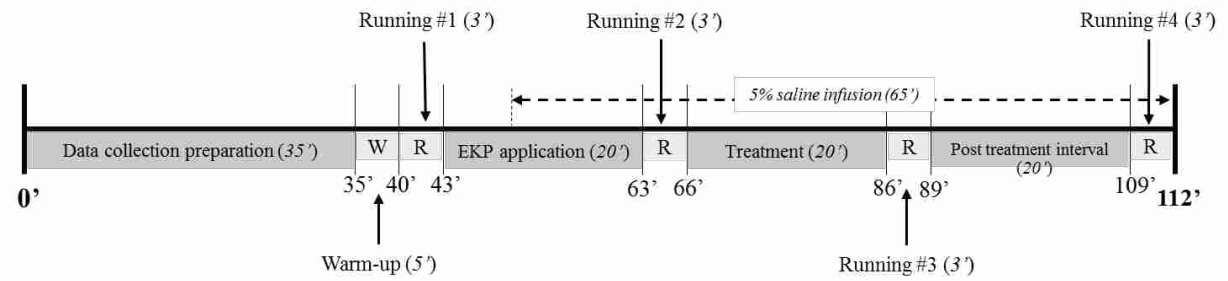


Figure 1. A description of the general timeline for each data collection session.

Figure 2. Ice/TENS combination treatment

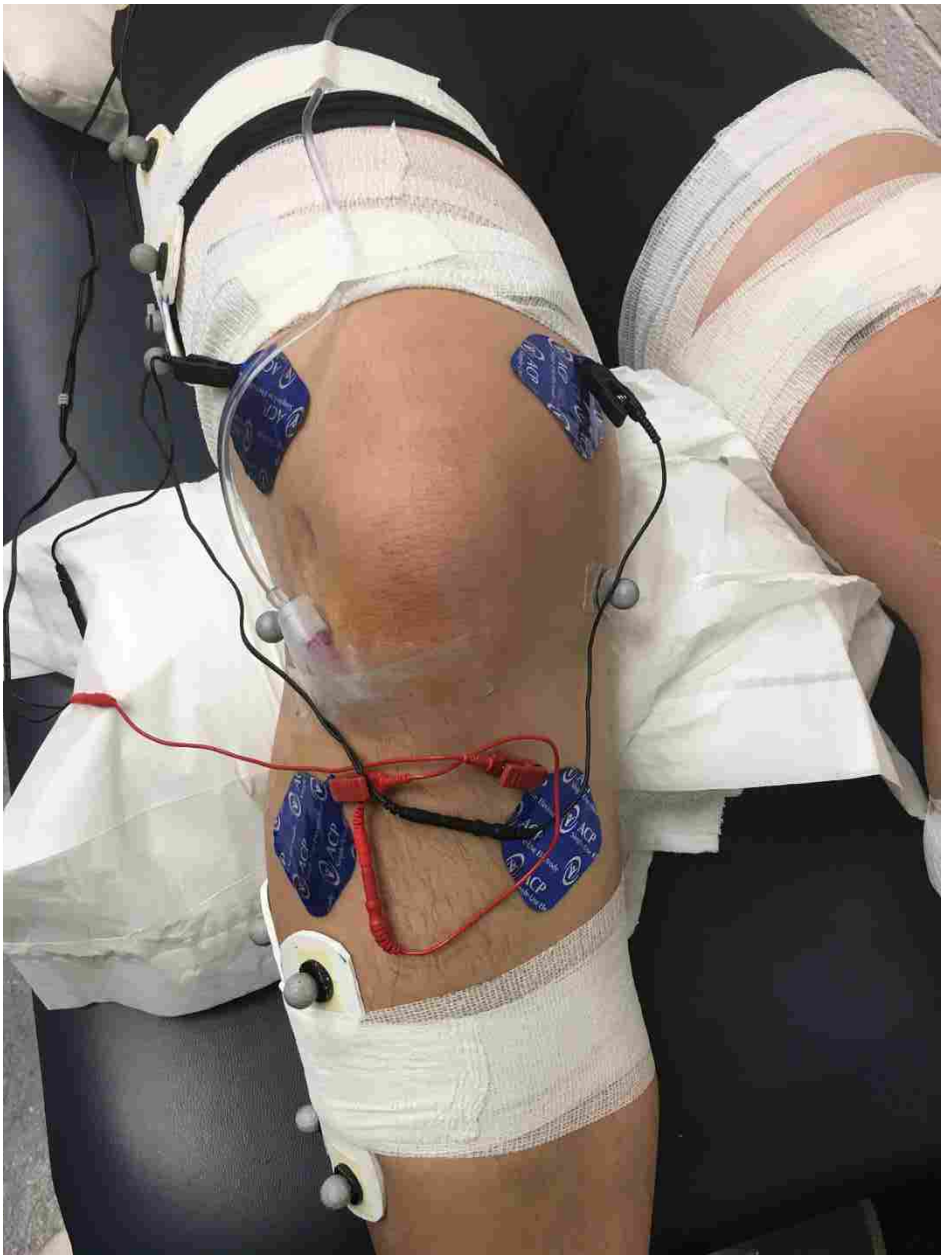


Figure 3. TENS electrodes placement

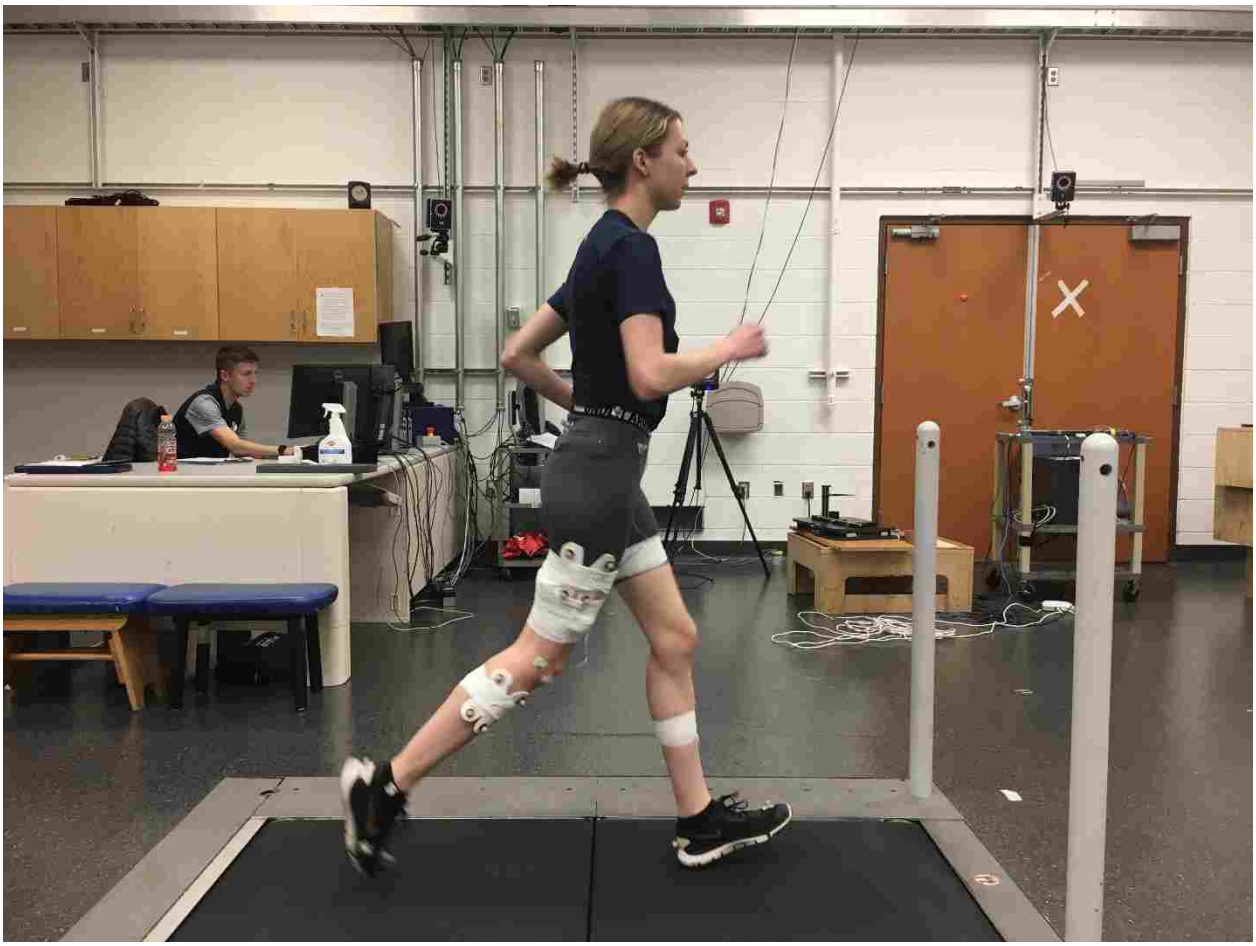


Figure 4. Running task with EKP model

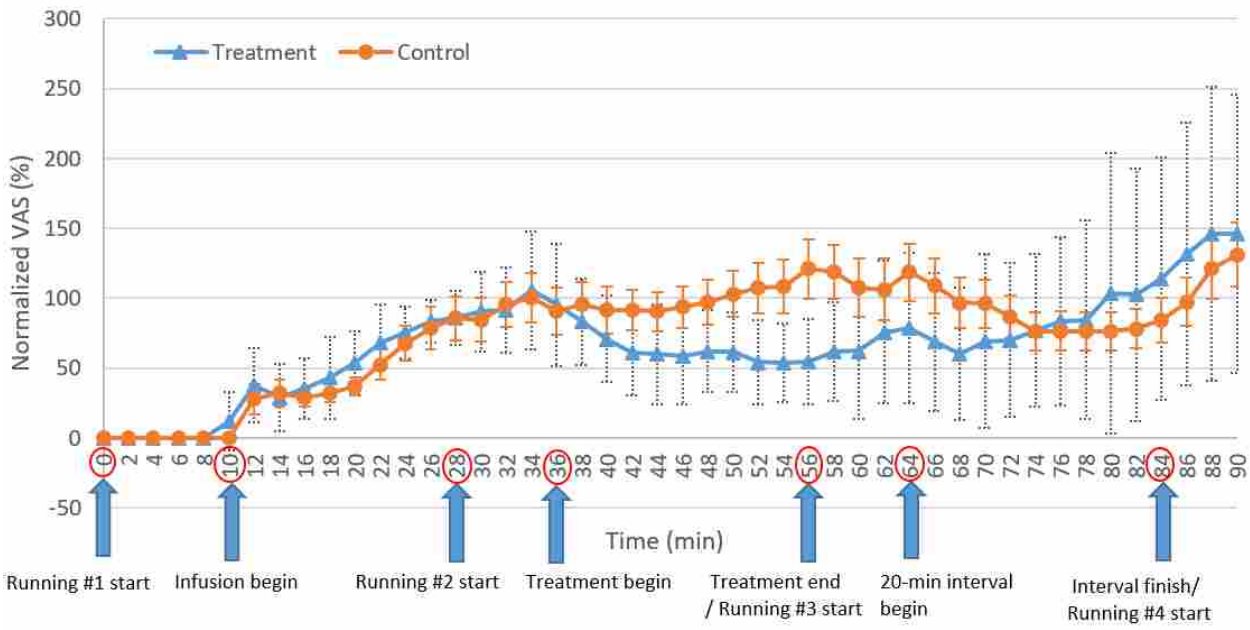


Figure 5. Perceived Knee Pain. Perceived knee pain normalized to the maximum value of the 20-minute EKP model application. Induced AKP started within 2 minutes after the hypertonic saline infusion start. The average of maximum perceived knee pain during the 20-minute EKP application was 28 mm on a 100-mm VAS in all participants. While the increased perceived knee pain level stayed consistent across time in the sham session, the ice/TENS combination treatment reduced the perceived knee pain by 41% at the end of treatment time ($p = 0.005$). Ice/TENS combination treatment significantly reduced perceived knee pain by 35% at 6 minutes after the treatment start ($p = 0.049$). Also, the reduced knee pain level did last for 22 minutes ($p > 0.05$).

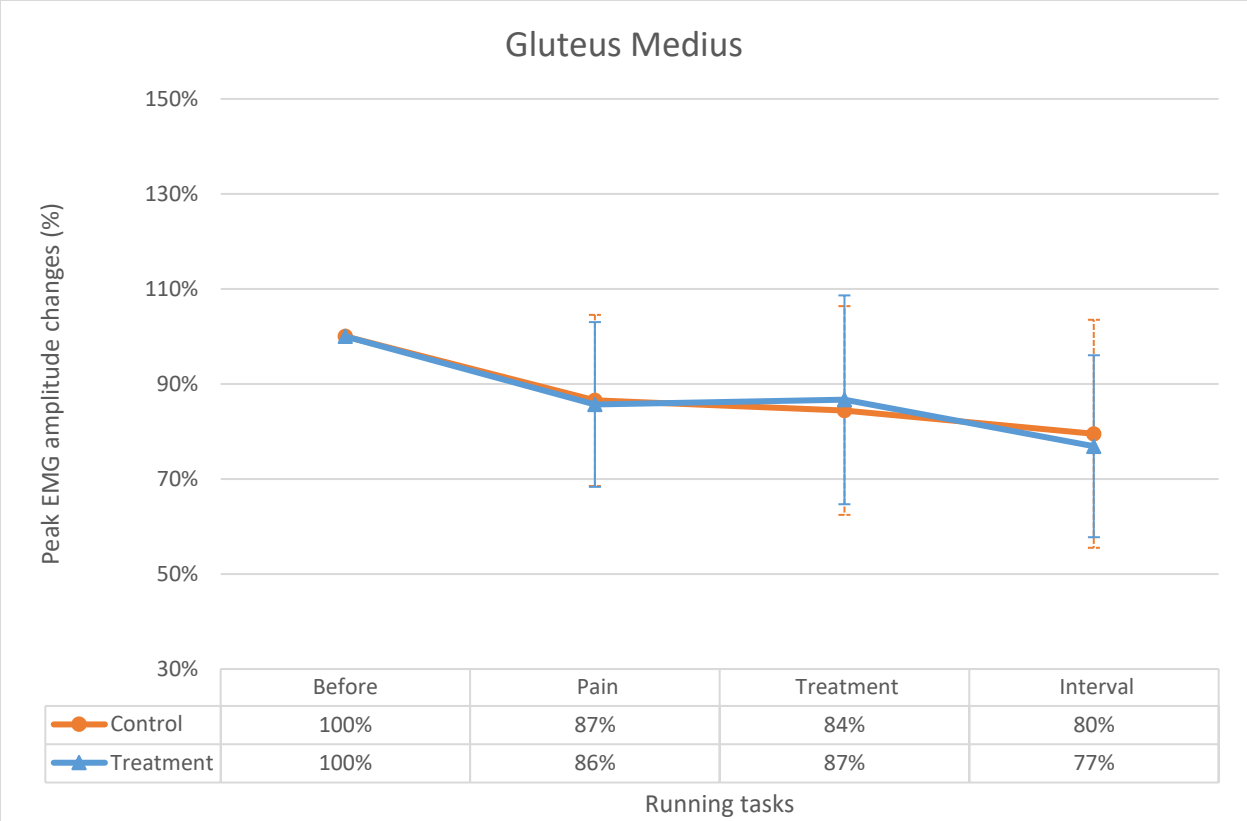


Figure 6. Average peak EMG amplitude of Gluteus Medius (Gmed). Peak EMG amplitude of Gmed was decreased by 13.5% and 14.3% ($p = 0.023$; $p = 0.013$) during running after EKP in sham and ice/TENS treatment sessions, respectively. Also, the peak EMG amplitude was not restored to pain-free level during running after the 20-minute ice/TENS combination treatment ($p = 0.026$).

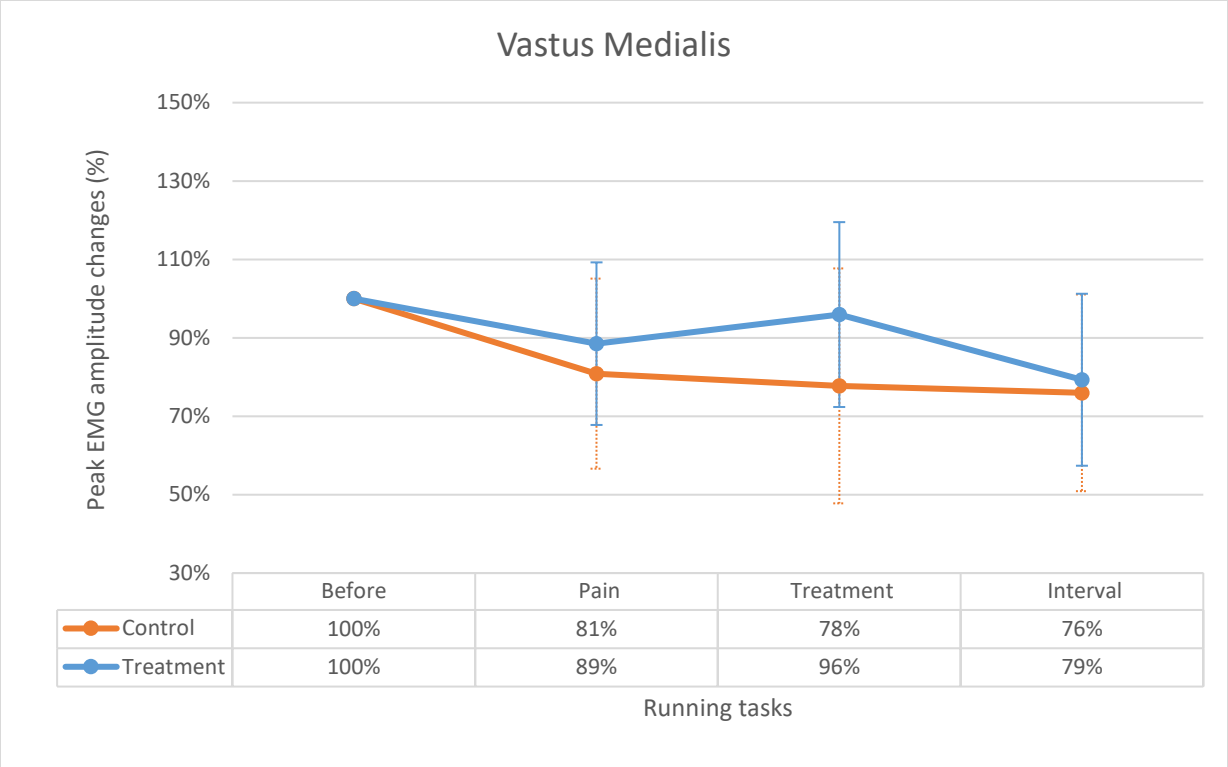
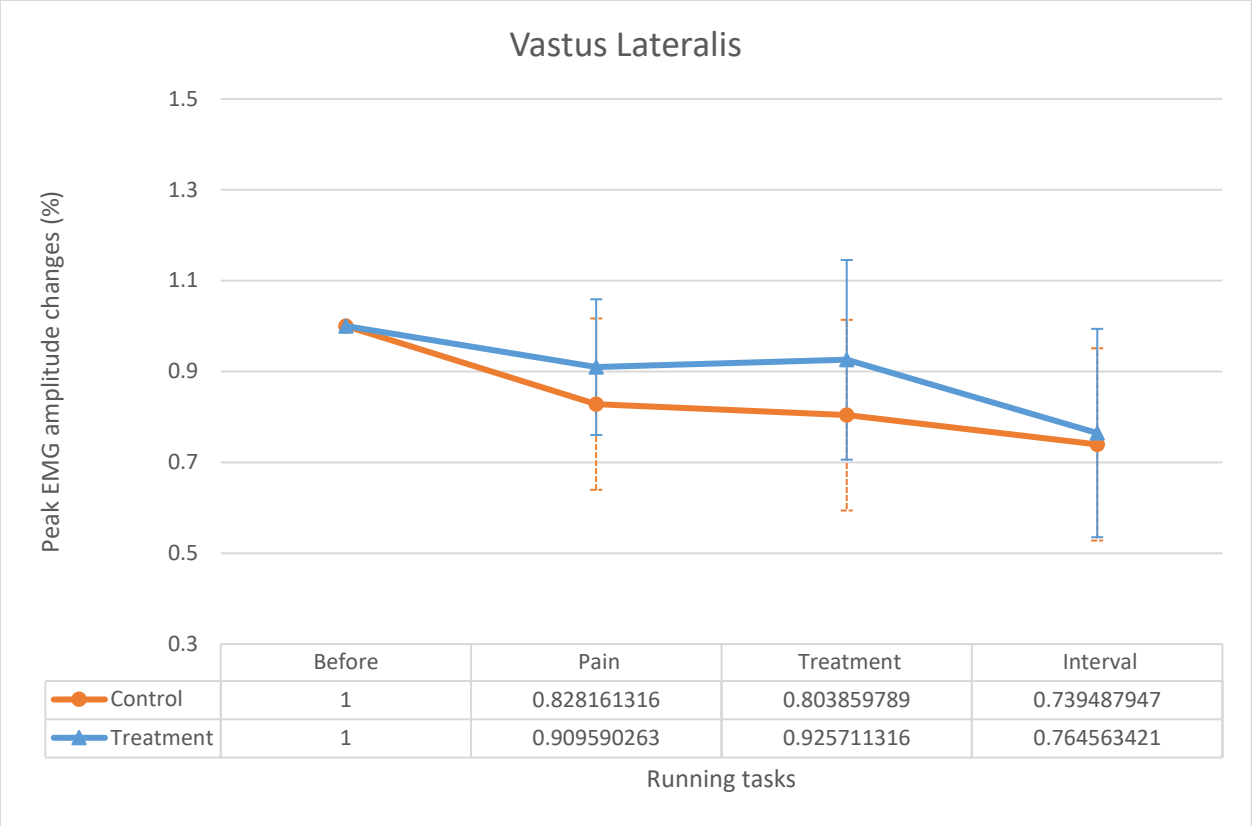


Figure 7. Average peak EMG amplitude of Vastus Medialis (VM). Peak EMG amplitude of VM was decreased by 19.1% ($p = 0.009$) during running after EKP in the sham session. Although peak EMG amplitude of VM was decreased by 11.5% during running after EKP in the treatment session, these results were not statistically significant ($p = 0.335$). Further, there were no significant differences between running after EKP and running after treatment in VM ($p = 0.82$) peak EMG amplitude in the treatment session. Ice/TENS combination treatment did not significantly increase peak EMG amplitude of VM.



	Before	Pain	Treatment	Interval
Control	1	0.828161316	0.803859789	0.739487947
Treatment	1	0.909590263	0.925711316	0.764563421

Figure 8. Average peak EMG amplitude of Vastus Lateralis (VL). Peak EMG amplitude of VL was decreased by 17.2% ($p = 0.005$) during running after EKP in the sham session. Although peak EMG amplitude of VL was decreased by 9% during running after EKP in the ice/TENS treatment session, the result was not statistically significant ($p = 0.437$). Further, there was no significant difference between running after EKP and running after treatment in VL ($p = 0.99$) peak EMG amplitude in the treatment session. Ice/TENS combination treatment did not significantly increase peak EMG amplitude of VL.

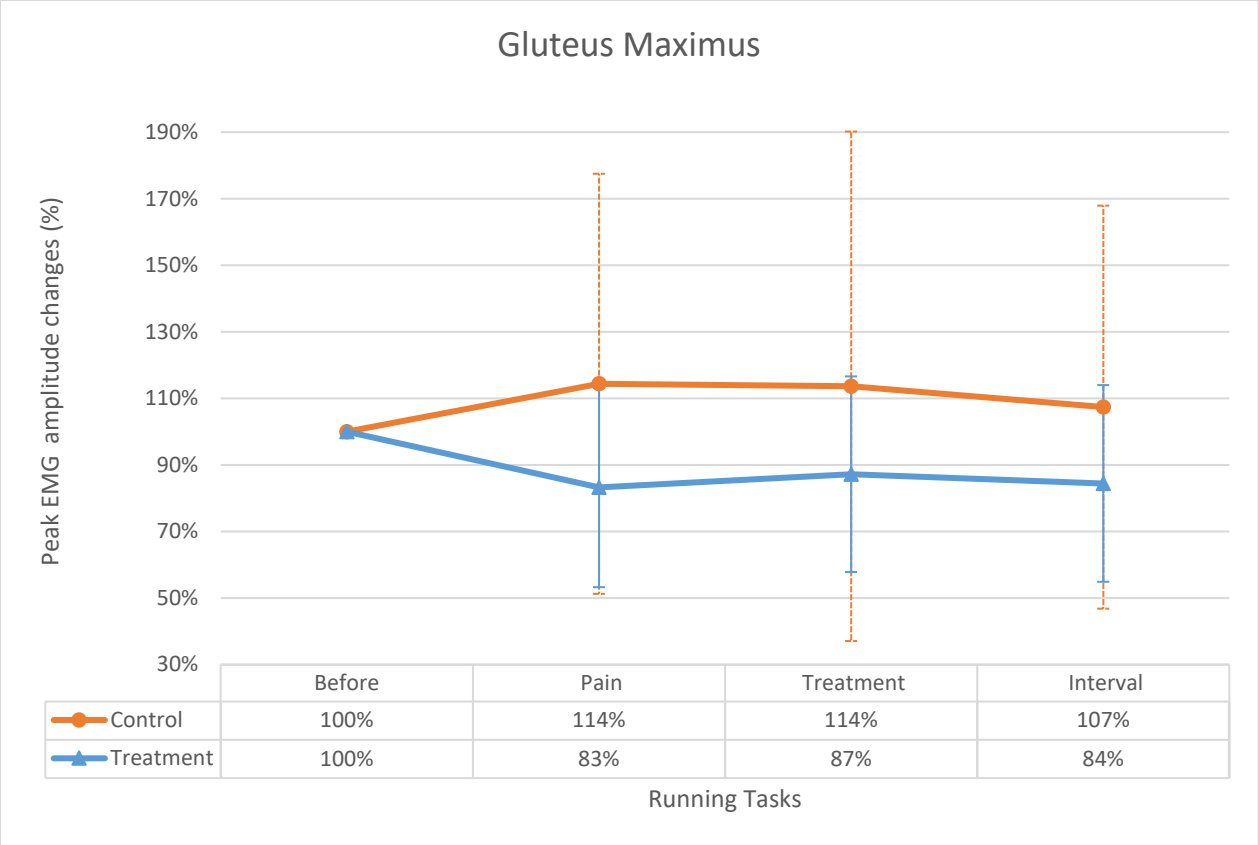


Figure 9. Average peak EMG amplitude of Gluteus Maximus (Gmax). Peak EMG amplitude of Gmax during running was not changed at all 3 time points (after Induced AKP; after treatment; after a 20-minute interval, $p > 0.3$) compared to the running before EKP application in both sham and ice/TENS treatment sessions.

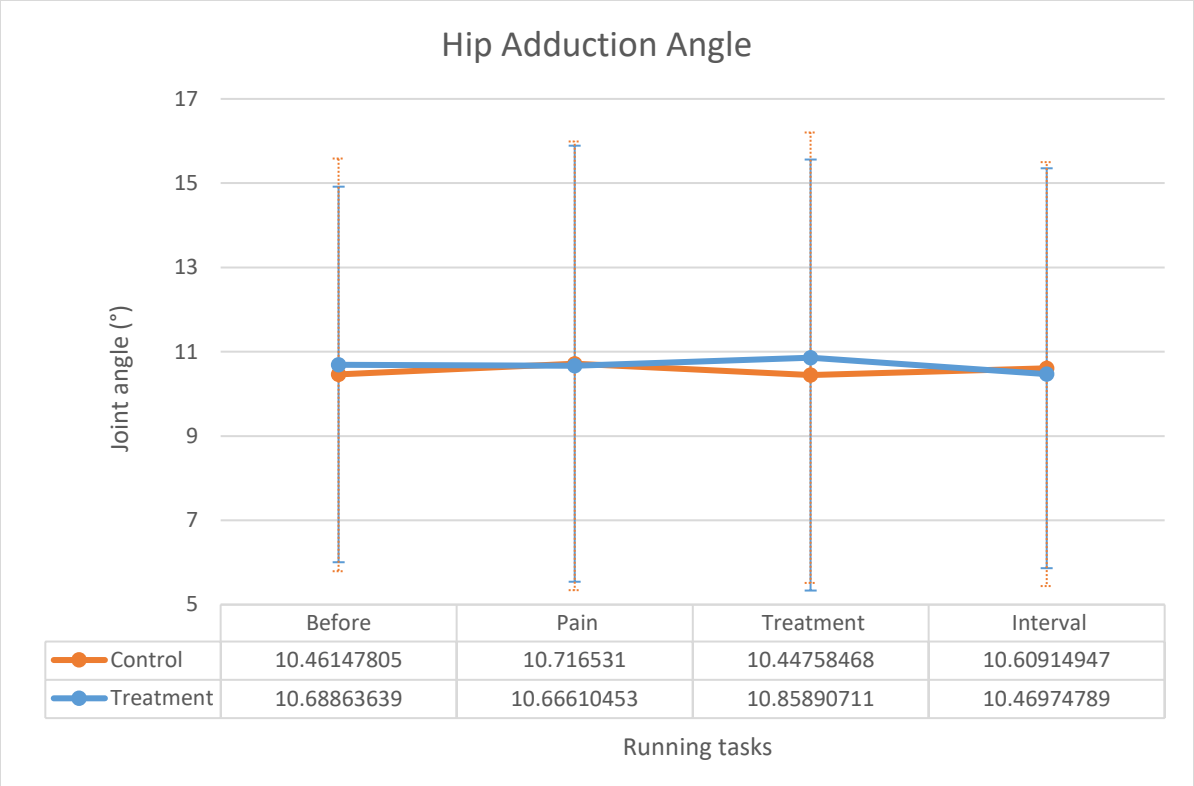


Figure 10. Average peak Hip Adduction angle during each running task. Hip adduction angle during running was not changed through all 3 times ($p > 0.8$) in both sham and ice/TENS treatment sessions.