Sport Sciences for Health (2019) 15:167–174
https://doi.org/10.1007/s11332-018-0506-6

ORIGINAL ARTICLE

# Core and plyometric training for recreational marathon runners: effects on training variables, injury, and muscle damage

Christopher J. Lundstrom[1] · Hayley C. Russell[2] · Kayla J. O'Donnell[1] · Stacy J. Ingraham[1,3]

Received: 18 June 2018 / Accepted: 28 September 2018 / Published online: 22 October 2018


## Abstract

**Purpose** Core and plyometric training may reduce injury and enhance muscle function in some athletes, but the effects on recreational marathon runners are unknown. Thus, the purpose of this study was to compare the effects of plyometric or core training on injury, muscle damage, and training variables in marathon runners.

**Methods** This study was a randomized-controlled trial. 34 subjects, ages 18–23 (20.7 ± 1.3) following the same marathon training program, were allocated to one of three groups for a weekly training session: core, plyometric, or no additional training (control). Subjects kept a training log throughout training. Outcomes were assessed during the 8-week run-in (RI) and 13-week marathon training (MT) periods. The plyometric and core training group subjects were assessed pre- and post-marathon for creatine kinase (CK), a marker of muscle damage.

**Results** The plyometric group did not change in any training variables between RI and MT. The core group increased in days missed due to injury ($p = 0.003$) and rate of perceived exertion (RPE) ($p = 0.028$). The control group increased in RPE ($p = 0.010$) and soreness ($p = 0.010$). The plyometric group had lower pre-marathon CK levels than the core group (81 ± 36 vs. 136 ± 59 U/L; $p = 0.042$). During MT, the plyometric group missed fewer days of training (plyometric: 1.7 ± 2.9; core: 4.2 ± 5.1; control: 4.5 ± 4.8) and missed fewer days due to injury (plyometric: 1.2 ± 2.6; core: 2.7 ± 5.1, control; 4.1 ± 4.9) but the differences were not significant.

**Conclusions** A weekly plyometric training session may be superior to core or no additional training in improving training variables of recreational marathon runners.

**Keywords** Running · Explosive training · Concurrent training · Creatine kinase · Endurance exercise

**Electronic supplementary material** The online version of this article (https://doi.org/10.1007/s11332-018-0506-6) contains supplementary material, which is available to authorized users.

✉ Christopher J. Lundstrom
lund0982@umn.edu

Hayley C. Russell
hrussell@gustavus.edu

Kayla J. O'Donnell
odon0171@umn.edu

Stacy J. Ingraham
ingrahams@crown.edu

1 School of Kinesiology, University of Minnesota, 217 Cooke Hall, 1900 University Ave. SE, Minneapolis, MN 55455, USA

2 Health and Exercise Science, Gustavus Adolphus College, Lund 212F, Saint Peter, USA

3 Present Address: Mathematics and Science Department, Crown College, 8700 College View Dr., St. Bonifacius, MN 55375, USA

## Introduction

While many individuals run for health benefits, it is common for runners to experience injuries in training [1–3]. Marathon runners appear to be at particularly high risk of injury, both in training and during or immediately after the event [2, 4–6]. Compared with more experienced runners, novice runners or those who train either very little or very infrequently are at increased risk of injury [3, 7, 8] and experience greater levels of muscle damage after very long runs [9]. A number of definitions of running injury and methods of gathering data on injury have been utilized. Self-reported pain in the lower extremities attributed to running that led the runner to alter training, use medication, or seek medical attention has been used as a definition of running injury [10]. Several cohort studies have examined the prevalence of injury in marathon runners over a 1-year period, with results ranging from 31 to 58% of participants experiencing an injury over the year [4, 6, 11]. Characterizing the severity of sports injury has been approached in previous studies in a number of ways. Days of training or sport participation missed due to injury has commonly been used, though categories and definitions have varied [12, 13]. In much of the research, running injury is classified by site, rather than by medical diagnosis, with the knee, calf, and foot being the most common areas of injury [4, 6]. Clinical data can give us more detailed insight into the nature and severity of running injuries. A report of over 2000 running injuries seen at a sports medicine clinic identified patella-femoral pain syndrome (PFPS) as the most common running injury, followed by iliotibial band friction syndrome (ITBS), plantar fasciitis, meniscal injuries, tibial stress syndrome, patellar tendonitis and Achilles tendinitis [14]. The lower leg (from the knee down) appears to be the most frequently affected area of the body.

Muscle damage and a temporary impairment of muscular function are known consequences of marathon running [15–18]. Damage to the muscle membrane leads to the release of enzymes, such as creatine kinase (CK), into the blood plasma [9, 19, 20]. While many biomarkers change with muscle damage, CK is a reliable indicator of exercise-induced muscle damage, with baseline levels of around 100 U/L rising to as high as 40,000 U/L after eccentric exercise [21]. Running distances near the standard 26.2 mile marathon have been shown to dramatically increase CK levels in recreational runners, from 160 U/L at baseline to 1500–4500 U/L 24-h after the completion of the run [23, 24], though lower levels have been reported (400–550 U/L) after a marathon in more experienced runners [20]. The protective effect of repeated bouts of strenuous exercise has been well-established, with much greater muscle damage occurring in response to the first bout of exercise at a given load than to subsequent bouts [25–27]. Whether the benefits of eccentric strengthening exercises such as plyometrics transfer to a protective effect during long distance running is not known.

Core training is widely recommended to runners as a means of decreasing susceptibility to injury [28]. Increased strength in the muscles of stabilization can, in theory, serve to enhance performance and reduce injury risk [29]. While there is some evidence for improved running performance with a core training intervention [29], there is little evidence for its effectiveness for injury prevention in long distance runners. Some studies suggest that plyometric training may provide a protective effect against injury [30], and a repeated bout effect may protect against muscle damage in those engaged in a consistent and moderate training program [15]. However, plyometrics can lead to temporary muscle damage in both endurance and power athletes [16], which is a serious concern for a population such as marathon runners, who are already exposed to substantial physiological stress.

Given that lack of running experience has been identified previously as a risk factor for running injury [31], and that participants in a study on risk factors for injury in a marathon training cohort in the US were slower and less experienced runners than those previously characterized in marathon training studies [32], there is reason to believe that recreational marathon runners in the US may be a high-risk population for running injury. In our previous study on this population, there was some evidence that faster runners may have gained a performance benefit from the plyometric training, while slower runners may have experienced detrimental effects [33]. Thus, the purpose of this study was to assess the effects of an additional weekly session of either plyometric or core training on training variables, injury incidence, muscle damage and soreness in a population of recreational marathon runners.

## Methods

### Experimental design

This study was a randomized-controlled trial. The details of the training intervention and the effects of the intervention on jump, sprint, and running performance variables have been previously published [33]. An 8-week run-in (RI) period of 4–5 days per week of running was completed by all subjects prior to the commencement of the intervention and allocation to the plyometric, core, or control group. The longest run during that time was 12.5-km, and no high intensity training was prescribed in the training program. Subjects kept a training log during RI to establish baseline levels for all training variables during low-to-moderate volume running training. This allowed for the comparison of training variables during normal running training vs. marathon training (MT). During MT, the frequency of training sessions did not change, but supervised weekly long runs of up to 32-km were performed, as was a weekly supervised high intensity workout such as hill repeats, tempo runs, or fartlek style interval training. For the training variables RPE, soreness, and readiness to run, a value from 1 to 10 was entered by participants for each training day, and averages of those values were taken for each individual during both RI and MT. Data for training days missed and days missed due to injury were also gathered from the training log.

The plyometric and core training occurred during the MT period, and consisted of a 12-week exercise intervention utilizing a randomized-controlled parallel group design. In addition to the plyometric and core groups, a control group was selected at random from the class members who were not in the intervention, but who had consented to having their training log data assessed for research purposes. The plyometric and core training intervention has been previously described in detail [33]. In brief, the training consisted of one session per week, lasting 15–20 min, with six exercises per session. The plyometric group performed maximal velocity jumping and sprinting exercises, whereas the core group performed low-to-moderate velocity muscular strengthening exercises for the abdominal, hip, back, and gluteal muscles.

This study was designed to assess the training variables of the three groups, to determine if there were differences in the level of soreness, readiness to run, rate of perceived exertion (RPE) during running, training days missed, and days missed due to injury. Rate of perceived exertion has been validated to provide a reproducible scale of intensity of exercise [34, 35]. Similarly, numeric scales have been used to assess degree of muscle soreness [36] and perceived recovery status [37]. The present study adopted the terminology "readiness to run," rather than perceived recovery status.

In addition, CK levels were taken for the plyometric and core groups before and after the marathon to determine whether there was a difference between groups. Participants in the core and plyometric groups were also asked to report their level of soreness at the following time-points after the completion of the marathon: in the first hour, the night of the marathon, and 1, 2, and 3 days after the completion of the run. See Fig. 1 for a flowchart capturing the timeline and steps involved in this study.

## Subjects

This study was approved by the Institutional Review Board at the University of Minnesota (IRB Code Number: 1312M46121, 1/16/2014). Subjects were recruited from a university marathon training class. All subjects were informed of the benefits and risks of the investigation before signing an institutionally approved informed consent form prior to data collection.

The study population consisted of healthy young adults training for a marathon through a university marathon training class. Baseline and demographic characteristics are shown in Table 1. Running training consisted of 16.5 ± 5.9 miles per week during RI (from December through mid-January) and 27.1 ± 5.0 during MT (from mid-January through the end of April). All subjects followed the same training plan, which consisted of 4–5 days per week of running, including two supervised runs per week during MT: a long run, and a higher intensity session such as hill repeats, tempo runs or fartlek workouts. The plyometric and core groups were recruited from the class to participate in a 12-week exercise intervention. The intervention began after the RI

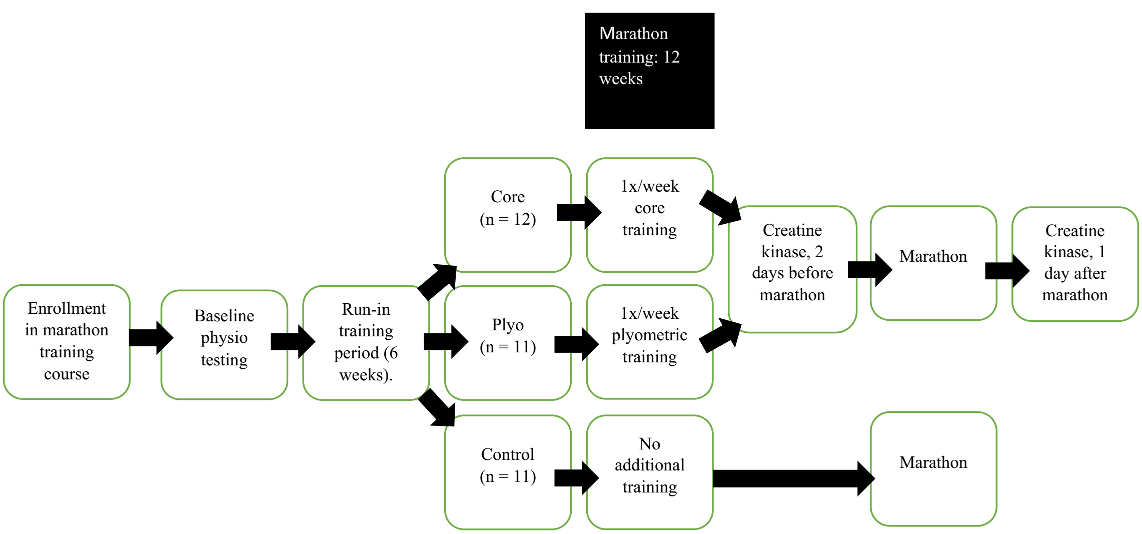


**Fig. 1** Study timeline

**Table 1** Demographic/baseline data

| Group | *N* | Sex | Age (years) | % Body fat | BM (kg) | $VO_{2MAX}$ |
|---|---|---|---|---|---|---|
| Core | 12 | *f* = 6 | 20.2 ± 1.4 | 19.2 ± 8.3 | 72.6 ± 9.5 | 52.8 ± 8.5 |
| Plyometric | 11 | *f* = 7 | 21.0 ± 1.0 | 19.2 ± 7.7 | 65.0 ± 8.0 | 50.5 ± 8.8 |
| Control | 11 | *f* = 6 | 21.0 ± 1.1 | 19.3 ± 5.6 | 70.3 ± 8.3 | 46.2 ± 14.5 |

All data are ± SD

period of training to control for training status of the participants. Inclusion and exclusion criteria, and the enrollment and randomization process for those two groups have been previously published [33]. The control group was randomly selected from students from the same class. To select the control group, an assigned research ID number of all eligible students ($n = 68$) was entered into SPSS (Version 21.0; IBM, Armonk, NY, USA) and the random sample function was used to select 11 subjects, with 6 females and 5 males being selected to maintain a balance.

## Training log variables

The training log variables were gathered from an online spreadsheet that subjects filled out throughout the course of training. This allowed the researchers to confirm that data were entered regularly, thus reducing the risk of introducing recall bias. Readiness to run and soreness were characterized on a 1–10 scale for each day that the subject completed a run during training. Previous research has measured recovery from previous exercise bouts using a similar approach of self-evaluation using a subjective scale of perceived recovery status [37]. The present study adopted the terminology "Readiness to Run", rather than perceived recovery status to simplify the language, which was an important consideration given the number of variables being collected in the training log. Similarly, numeric scales have been used to assess degree of muscle soreness [36]. For readiness to run, 1 was defined as "not ready to run at all" and 10 was defined as "as ready to run as possible." For soreness, 1 was defined as "no soreness" and 10 defined as "the most soreness possible." Rate of perceived exertion (RPE) was characterized during each training run using a 6–20 Borg scale [38], with a visual scale included in the training log. The RPE was entered by subjects in their training log for each day of training. Similarly, numeric scales have been used to assess degree of muscle soreness [36]. For each individual, averages of the daily readiness to run, soreness, and RPE scores during RI and MT were used for analysis.

Data for days missed were gathered from a "yes or no" column in the training log, described as "Missed/Altered Training due to Injury, Pain, Illness". The comments column was provided and logs were assessed to interpret how many of the reported missed days were due to injury. Illness, life stress, being too busy, and no reported reason for missing a day were counted towards total days missed, but not counted toward days missed due to injury.

## Muscle damage

Blood samples were taken pre- and post-marathon to assess CK level, which is a reliable marker of muscle damage. Samples of 3-ml were collected from the antecubital vein of subjects on two occasions: 2 days prior to the marathon and 1 day after the marathon. Samples were collected in lithium heparin 3-ml vacutainer tubes (Beckton Dickinson, Franklin Lakes, NJ), stored on ice, and centrifuged @ 2600 rpm for 15 min (Eppendorf, Hamburg, Germany). The plasma was micro-pipetted into a 2.0-ml micro-centrifuge tube (Fisher Scientific, Waltham, MA) and stored at − 80 °C. All the pre-test samples were collected during the morning (7:45 a.m. to 11:30 a.m.) 2 days prior to the marathon, and all of the post-test samples, except one, were collected during the same time frame the day after the marathon. The one post-test not taken during that time was attempted, but no sample was drawn despite repeated attempts, likely due to dehydration. The subject was instructed to consume adequate fluids and return the next day, and a sample was successfully drawn the following morning.

Creatine kinase levels were determined using a colorimetric CK assay kit (BioAssay Systems, Fremont, CA) according to kit specifications. The assay relies on an enzyme-catalyzed reaction with readings of optical density at 340 nm. Samples were thawed on ice, and 10 μl samples, in triplicate, were transferred to a Corning Costar 96-well plate (Sigma-Aldrich, St. Louis, MO) and combined with the reconstituted reagent using a multi-channel pipette prior to the assay. Readings were done on a Synergy H1 96-well plate reader (Biotek Instruments, Winooski, VT). The values were calculated using the appropriate formulas according to kit specifications. Averages of the three samples are reported.

## Statistical analysis

Statistical analysis was done using SPSS, Version 21 (IBM, Armonk, NY, USA). Means and standard deviations were calculated for each measure using standard methods. Data were tested for normality and homoscedasticity using the Shapiro–Wilk and Levene tests. Average running mileage per week was compared between groups and between RI and MT periods using two-way ANOVA. The CK data were assessed using paired sample $t$ tests. For the other training log factors, independent sample Kruskal–Wallis ANOVA tests were used to detect differences between groups. Differences between the RI and MT were assessed using the Wilcoxon Signed-Rank test. These non-parametric tests were chosen due to the non-normal distributions of most of the training log data. Though the data appeared normally distributed for RPE and readiness to run, non-parametric tests were used due to the ordinal nature of the variables [39]. Days missed and days missed due to injury were transformed to a per week number prior to comparing RI and MT periods to account for the difference in length of those periods. Alpha level for significance was set at $p < 0.05$.

## Results

Baseline data for the three groups, including demographic variables, body mass, percent body fat, and $VO_{2MAX}$ are found in Table 1. These data are gathered as a standard practice for the class, and the methods have been previously reported [33]. During the RI period (prior to the intervention), there were no differences between the groups in any of the training log variables. Likewise, during the MT period, there were no differences between groups. The plyometric group had fewer days missed during MT (1.7 ± 2.6) than either the core training (4.2 ± 5.1) or control (4.1 ± 4.9) groups, and also fewer days missed due to injury (plyometric: 1.2 ± 2.6, core: 2.7 ± 5.1, control: 4.1 ± 4.9), but the differences were not statistically significant. Means, standard deviations and medians by group for both the RI and MT periods are reported in Table 2.

Differences between the RI period and the MT period were assessed within groups by time to assess change from baseline. There were no differences in days missed between the RI and MT periods for any of the groups. The core group missed more days due to injury during the MT period ($p = 0.003$), whereas the control group increased non-significantly ($p = 0.314$) and the plyometric group did not change between the two time periods ($p = 0.953$). The population as a whole increased in RPE between the RI and MT periods ($p = 0.003$). The plyometric group did not change ($p = 0.790$), whereas the other two groups increased in RPE during MT: core ($p = 0.028$) and control ($p = 0.010$). There were no changes in readiness to run for any of the groups. There was a trend toward an increase in soreness across the whole population ($p = 0.078$). The control group increased significantly ($p = 0.010$), whereas the core ($p = 0.583$) and plyometric ($p = 0.697$) groups did not change.

Training mileage did not differ between groups for either RI or MT, but was significantly higher for all groups during MT, as shown in Table 3. The soreness ratings taken after the marathon compared only the core and plyometric groups. There were no differences between the groups.

**Table 2** Training log variables by group

| Variable | Group | Run-in period | | | Marathon training period | | | |
|---|---|---|---|---|---|---|---|---|
| | | Mean ± SD | Median | *p* value (group) | Mean ± SD | Median | *p* value (group) | *p* value (time) |
| MISSED | ALL | 2.3 ± 3.8 | 1 | 0.645 | 3.5 ± 4.4 | 2 | 0.099 | 0.638 |
| | CORE | 1.4 ± 2.4 | 0.5 | | 4.2 ± 5.1 | 2 | | 0.182 |
| | PLYO | 2.2 ± 2.6 | 1 | | 1.7 ± 2.9 | 1 | | 0.284 |
| | CON | 3.4 ± 5.8 | 0 | | 4.5 ± 4.8 | 3 | | 0.678 |
| INJURED | ALL | 1.1 ± 3.4 | 0 | 0.133 | 2.6 ± 4.4 | 1 | 0.103 | 0.130 |
| | CORE | 0.1 ± 0.3 | 0 | | 2.7 ± 5.1† | 1 | | 0.003 |
| | PLYO | 1.1 ± 1.8 | 0 | | 1.2 ± 2.6 | 0 | | 0.953 |
| | CON | 2.3 ± 5.7 | 0 | | 4.1 ± 4.9 | 3 | | 0.314 |
| RPE | ALL | 11.7 ± 2.2 | 11.4 | 0.216 | 12.3 ± 2.0† | 12.1 | 0.379 | 0.003 |
| | CORE | 11.2 ± 2.0 | 11.3 | | 12.2 ± 2.4† | 12.2 | | 0.028 |
| | PLYO | 12.9 ± 2.6 | 12.9 | | 12.8 ± 2.3 | 12.2 | | 0.790 |
| | CON | 11.1 ± 1.6 | 11 | | 11.8 ± 1.3† | 11.2 | | 0.010 |
| READY | ALL | 6.5 ± 1.6 | 6.7 | 0.446 | 6.8 ± 1.6 | 6.9 | 0.527 | 0.203 |
| | CORE | 6.2 ± 1.7 | 6.4 | | 6.4 ± 1.8 | 6.2 | | 0.388 |
| | PLYO | 6.4 ± 1.6 | 6.7 | | 6.7 ± 1.5 | 7.0 | | 0.534 |
| | CON | 7.0 ± 1.6 | 7.3 | | 7.1 ± 1.6 | 7.3 | | 0.534 |
| SORE | ALL | 3.1 ± 1.1 | 3.0 | 0.421 | 3.4 ± 1.4 | 3.2 | 0.985 | 0.078 |
| | CORE | 3.2 ± 1.0 | 3.3 | | 3.4 ± 1.4 | 3.2 | | 0.583 |
| | PLYO | 3.2 ± 1.1 | 3.0 | | 3.3 ± 1.2 | 3.6 | | 0.697 |
| | CON | 2.7 ± 1.3 | 2.5 | | 3.3 ± 1.7† | 2.9 | | 0.010 |

*p* value by group indicates difference between groups within the time period. *p* value by time indicates change between RI and MT period within group

All results are ± SD

*CORE* core training group; *PLYO* plyometric training group; *CON* control group; *ALL* all groups; *MISSED* missed days; *INJURED* days missed due to injury; *RPE* average rate of perceived exertion; *READY* average readiness to run; *SORE* average soreness

†Significantly different from RI @ $p \leq 0.05$

**Table 3** Running mileage in RI and MT by group

| | RI | MT | $p$ value (time) |
|---|---|---|---|
| Core | 15.8 ± 6.2 | 26.2 ± 5.0† | **≤ 0.001** |
| Plyometric | 17.3 ± 5.3 | 28.2 ± 5.0† | **≤ 0.001** |
| Control | 16.4 ± 6.6 | 27.2 ± 5.3† | **≤ 0.001** |
| $p$ value (group) | 0.827 | 0.648 | |

All results are ± SD

*RI* run-in period; *MT* marathon training period

†Significantly different from RI @ $p \leq 0.05$

**Table 4** Ratings (1–10) of soreness post-marathon, reported by group

| Time after marathon | Group | Mean ± SD | Median | $p$ value |
|---|---|---|---|---|
| 1 h | ALL | 7.5 ± 2.7 | 8 | 0.640 |
| | CORE | 7.2 ± 3.0 | 8 | |
| | PLYO | 7.8 ± 2.4 | 8 | |
| 12 h | ALL | 7.5 ± 2.3 | 8 | 0.450 |
| | CORE | 6.9 ± 2.8 | 8 | |
| | PLYO | 8.1 ± 1.7 | 8 | |
| 24 h | ALL | 7.7 ± 1.6 | 8 | 0.857 |
| | CORE | 7.6 ± 1.6 | 8 | |
| | PLYO | 7.7 ± 1.7 | 8 | |
| 48 h | ALL | 5.5 ± 1.6 | 5 | 0.496 |
| | CORE | 5.8 ± 1.5 | 6 | |
| | PLYO | 5.4 ± 1.8 | 5 | |
| 72 h | ALL | 3.1 ± 1.1 | 3 | 0.362 |
| | CORE | 2.9 ± 1.1 | 2.5 | |
| | PLYO | 3.3 ± 1.2 | 3 | |

All results are ± SD

*CORE* core training group; *PLYO* plyometric training group; *ALL* both groups

Results are shown in Table 4. Pre-marathon CK levels were significantly lower for the plyometric than the core group ($p = 0.042$). Post-marathon CK was lower for the plyometric than the core group, but the difference was not significant ($p = 0.133$). Post-marathon CK was significantly higher than pre-marathon for both groups and for the whole population ($p \leq 0.001$). Data for CK are reported in Table 5.

## Discussion

This study of recreational marathon runners compared a once per week exposure to low-volume plyometric training to core training and control groups, assessing injury, soreness, readiness to run, and RPE during training, as well as soreness and muscle damage after the marathon. Marathon training is a challenging undertaking, and the impact of any auxiliary exercises done in addition to running must be carefully considered. The incidence of injury during marathon training in our study was 17.6% (6 of 34 subjects). This is lower than others have reported [4, 6, 11] when we counted those injuries that led to more than 3 days of missed or altered training. However, our study covered a shorter time period than others. Activities such as core training have been proposed as a means of preventing injury [28], but the training protocol used in this study did not appear to be effective in preventing injury. Plyometric training can lead to temporary muscle soreness and damage, though the effect is diminished with repeated exposure [40]. Long distance running can also lead to muscle soreness and damage [20, 21], and we hypothesized that a proper volume of plyometric training could provide a protective effect against soreness and muscle damage from running.

The results of this study suggest that, for recreational runners, plyometric training at relatively low frequencies and volumes can be considered safe, and may provide some benefits. There were no differences between the groups during the marathon training period in days missed, days missed due to injury, readiness to run, soreness, or RPE. However, the changes within groups between the RI and the MT period, and the lower pre-marathon CK levels in the plyometric group suggest some benefit to plyometric training. The plyometric group did not increase in RPE during MT, whereas the core training and control groups reported a statistically significant increase in RPE from RI to the MT. The plyometric group reported the fewest days missed due to injury, though the difference was not statistically significant. The core group increased significantly in days missed due to injury from RI to MT, whereas the control group increased non-significantly, and

**Table 5** Pre- and post-marathon CK levels by group

| | PRE | $p$ value (group) | POST | $p$ value (group) | $p$ value (time) |
|---|---|---|---|---|---|
| All subjects | 108 ± 55 | 0.042 | 532 ± 121†† | 0.133 | **≤ 0.001** |
| Core | 136 ± 59 | | 578 ± 71†† | | **≤ 0.001** |
| Plyometric | 81 ± 36† | | 486 ± 186†† | | **≤ 0.001** |

All results are ± SD

†Significantly different from the core group @ $p \leq 0.05$. Units for CK are U/L

††Significantly different from baseline @ $p \leq 0.05$

the plyometric group remained almost exactly the same despite the much higher training load. The control group increased significantly in soreness, whereas the plyometric and core groups did not change.

The soreness ratings after the marathon showed no differences between groups, and the CK values were likewise not significantly different. However, the baseline values were lower for the plyometric group, and there was a trend toward lower CK values post-marathon. The post-marathon CK values were lower than some have reported [23, 24], but similar to those reported in a study of well-trained runners [20]. The lack of a statistically significant difference between the groups in CK post-marathon could be explained by a number of factors. The physiological challenge of running a marathon may be so great that it blunted any differences between the groups. Alternatively, it may be that the heterogeneous nature of the population precluded prescription of a proper training load for specific individuals. While some may have struggled to adapt to the plyometric training, others may have benefited more from additional time and/or sessions. This is supported by our previous research with this population, which suggested that faster runners may have benefited more in terms of distance running performance from plyometric training, whereas the slower runners may be better served avoiding the additional training stress [33].

The proper load of plyometric training for various levels of marathon runners has not yet been determined, but this study establishes that a relatively brief, once per week exposure to plyometric training appears safe and potentially beneficial for this population. Tools for monitoring adaptation to training load, such as intermittent testing and assessment of subjective factors of subjects, could assist in adjusting training volumes and frequencies to maximize individual response.

## Conclusion

When compared to core training and no additional training, a relatively low-volume weekly plyometric training session appears to have no negative impact on recreational marathon runners, and may provide some benefits specific to injury prevention, protection from muscle damage in training and avoiding an increased RPE during heavier training. Implementation of a proper training volume, frequency, and intensity presents a challenge to the practitioner, and caution should be taken in exposing runners to additional stress during a MT period. Those with higher beginning levels of fitness and competitive aspirations may be a more appropriate population to study. However, with proper caution, plyometric training can be safe and potentially beneficial to a heterogeneous population of recreational marathon runners.

**Funding** No external funding was used to support this research.

## Compliance with Ethical Standards

**Conflict of interest** The authors declare that they have no competing interests.

**Ethics approval** This study and all procedures were in accordance with the ethical standards of the institution and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. It was approved by the Institutional Review Board at the University of Minnesota—Twin Cities.

**Informed consent** All participants provided written, informed consent after being informed about the protocol and purpose of the study.

## References

1. Lun V, Meeuwisse W, Stergiou P, Stefanyshyn D (2004) Relation between running injury and static lower limb alignment in recreational runners. Br J Sports Med 38:576–580. https://doi.org/10.1136/bjsm.2003.005488
2. Kluitenberg B, van Middelkoop M, Diercks R, van der Worp H (2015) What are the differences in injury proportions between different populations of runners? A systematic review and meta-analysis. Sports Med 45:1143–1161. https://doi.org/10.1007/s40279-015-0331-x
3. Malisoux L, Nielsen RO, Urhausen A, Theisen D (2015) A step towards understanding the mechanisms of running-related injuries. J Sci Med Sport 18:523–528. https://doi.org/10.1016/j.jsams.2014.07.014
4. Maughan RJ, Miller J (1983) Incidence of training-related injuries among marathon runners. Br J Sports Med 17:162–165. https://doi.org/10.1136/bjsm.17.3.162
5. Fredericson M, Misra AK (2007) Epidemiology and aetiology of marathon running injuries. Sports Med 37:437–439. https://doi.org/10.2165/00007256-200737040-00043
6. van Middelkoop M, Kolkman J, Van Ochten J, Bierma-Zeinstra SM, Koes B (2008) Prevalence and incidence of lower extremity injuries in male marathon runners. Scand J Med Sci Sports 18:140–144. https://doi.org/10.1111/j.1600-0838.2007.00683.x
7. Satterthwaite P, Norton R, Larmer P, Robinson E (1999) Risk factors for injuries and other health problems sustained in a marathon. Br J Sports Med 33:22–26. https://doi.org/10.1136/bjsm.33.1.22
8. van der Worp H, Vrielink J, Bredeweg S (2016) Do runners who suffer injuries have higher vertical ground reaction forces than those who remain injury-free? A systematic review and meta-analysis. Br J Sports Med 50:450–457. https://doi.org/10.1136/bjsports-2015-094924
9. Noakes T, Carter J (1982) The responses of plasma biochemical parameters to a 56-km race in novice and experienced ultra-marathon runners. Eur J Appl Physiol Occup Physiol 49:179–186. https://doi.org/10.1007/BF02334066
10. Macera CA, Pate RR, Powell KE, Jackson KL, Kendrick JS, Craven TE (1989) Predicting lower-extremity injuries among habitual runners. Arch Intern Med 149:2565–2568. https://doi.org/10.1001/archinte.149.11.2565
11. Holmich P, Christensen SW, Darre E, Jahnsen F, Hartvig T (1989) Non-elite marathon runners: health, training and injuries. Br J Sports Med 23:177–178. https://doi.org/10.1136/bjsm.23.3.177

12. van Mechelen W (1997) The severity of sports injuries. Sports Med 24:176–180. https://doi.org/10.2165/00007256-199724030-00006
13. Fuller CW, Eckstrand J, Junge A, Anderson TE, Bahr R, Dvorak J et al (2006) Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. Scand J Med Sci Sports 16:83–92. https://doi.org/10.1111/j.1600-0838.2006.00528.x
14. Taunton JE, Ryan MB, Clement DB, McKenzie DC, Lloyd-Smith DR, Zumbo BD (2002) A retrospective case-control analysis of 2002 running injuries. Brit J Sport Med 36:95–101. https://doi.org/10.1136/bjsm.36.2.95
15. Venckunas T, Skurvydas A, Brazaitis M, Kamandulis S, Snieckus A, Moran CN (2012) Human alpha-actinin-3 genotype association with exercise-induced muscle damage and the repeated-bout effect. Appl Physiol Nutr Metab 37:1038–1046. https://doi.org/10.1139/h2012-087
16. Kyrolainen H, Takala TE, Komi PV (1998) Muscle damage induced by stretch-shortening cycle exercise. Med Sci Sports Exerc 30:415–420
17. Hikida RS, Staron RS, Hagerman FC, Sherman WM, Costill DL (1983) Muscle fiber necrosis associated with human marathon runners. J Neurol Sci 59:185–203. https://doi.org/10.1016/0022-510X(83)90037-0
18. Kyrolainen H, Pullinen T, Candau R, Avela J, Huttunen P, Komi PV (200) Effects of marathon running on running economy and kinematics. Eur J Appl Physiol 82:297–304
19. Petersen K, Hansen CB, Aagaard P, Madsen K (2007) Muscle mechanical characteristics in fatigue and recovery from a marathon race in highly trained runners. Eur J Appl Physiol 101:385–396. https://doi.org/10.1007/s00421-007-0504-x
20. Kim HJ, Lee YH, Kim CK (2009) Changes in serum cartilage oligomeric matrix protein (COMP), plasma CPK and plasma hs-CRP in relation to running distance in a marathon (42.195 km) and an ultra-marathon (200 km) race. Eur J Appl Physiol 105:765–770. https://doi.org/10.1007/s00421-008-0961-x
21. Jones DA, Newham DJ, Round JM, Tolfree SE (1986) Experimental human muscle damage: morphological changes in relation to other indices of damage. J Physiol 375:435–448. https://doi.org/10.1113/jphysiol.1986.sp016126
22. Kim HJ, Lee YH, Kim CK (2007) Biomarkers of muscle and cartilage damage and inflammation during a 200 km run. Eur J Appl Physiol 99:443–447. https://doi.org/10.1007/s00421-006-0362-y
23. Riley WJ, Pyke FS, Roberts AD, England JF (1975) The effect of long-distance running on some biochemical variables. Clin Chim Acta 65:83–89. https://doi.org/10.1016/0009-8981(75)90338-1
24. Siegel AJ, Silverman LM, Lopez RE (1980) Creatine kinase elevations in marathon runners: relationship to training and competition. Yale J Biol Med 53:275–279
25. Nosaka K, Clarkson PM (1995) Muscle damage following repeated bouts of high force eccentric exercise. Med Sci Sports Exerc 27:1263–1269. https://doi.org/10.1249/00005768-199509000-00005
26. McHugh MP, Connolly DA, Eston RG, Gleim GW (1999) Exercise-induced muscle damage and potential mechanisms for the repeated bout effect. Sports Med 27:157–170. https://doi.org/10.2165/00007256-199927030-00002
27. Clarkson PM, Hubal MJ (2002) Exercise-induced muscle damage in humans. Am J Phys Med Rehabil 81:S52–S69. https://doi.org/10.1097/00002060-200211001-00007
28. Williardson J (2007) Core stability training: applications to sports conditioning programs. J Strength Cond Res 21:979–985. https://doi.org/10.1519/00124278-200708000-00054
29. McGill SM (2001) Low back stability: from formal description to issues for performance and rehabilitation. Exerc Sport Sci Rev 29:26–31
30. Chimera NJ, Swanik KA, Swanik CB, Straub SJ (2004) Effects of plyometric training on muscle-activation strategies and performance in female athletes. J Athl Train 39:24–31
31. Marti B, Vader JP, Minder CE, Abelin T (1988) On the epidemiology of running injuries. Am J Sports Med 16:285–294. https://doi.org/10.1177/036354658801600316
32. Chorley JN, Cianca JC, Divine JG, Hew TD (2002) Baseline injury risk factors for runners starting a marathon training program. Clin J Sport Med 12:18–23. https://doi.org/10.1097/00042752-200201000-00007
33. Lundstrom CL, Betker MR, Ingraham SJ. Effects of plyometric and explosive speed training on recreational marathoners (2017) J Sports Sci 5:1–13. https://doi.org/10.17265/2332-7839/2017.01.001
34. Aliverti A, Kayser B, Mauro AL, Quaranta M, Pompilio P, Dellaca RL et al (2011) Respiratory and leg muscles perceived exertion during exercise at altitude. Respir Physiol Neurobiol 177:162–168. https://doi.org/10.1016/j.resp.2011.03.014
35. Grant S, Aitchison T, Henderson E, Christie J, Zare S, McMurray J et al (1999) A comparison of the reproducibility and the sensitivity to change of visual analogue scales, borg scales, and likert scales in normal subjects during submaximal exercise. Chest 116:1208–1217. https://doi.org/10.1378/chest.116.5.1208
36. Andersen LL, Jay H, Andersen DC, Jakobsen GM, Sundstrup E, Topp R, Behm DG (2013) Acute effects of massage or active exercise in relieving muscle soreness: Randomized controlled trial. J Strength Cond Res 27:3352–3359. https://doi.org/10.1519/JSC.0b013e3182908610
37. Laurent MC, Green MJ, Bishop AP, Sjokvist EJ, Schumacker TR, Richardson T et al (2011) A practical approach to monitoring recovery: development of a perceived recovery status scale. J Strength Cond Res 25:620–628. https://doi.org/10.1519/JSC.0b013e3181c69ec6
38. Borg G (1998) Borg's perceived exertion and pain scales. Human Kinetics, Champaign
39. Hildebrand DK. In Laing JD, Rosenthal H (eds) (1977) Analysis of ordinal data. Sage Publications, Beverly Hills
40. Jamurtas AZ, Fatouros IG, Buckenmeyer P, Kokkinidis E, Taxildaris K, Kambas A et al (2000) Effects of plyometric exercise on muscle soreness and plasma creatine kinase levels and its comparison with eccentric and concentric exercise. J Strength Cond Res 14:68–74. https://doi.org/10.1519/00124278-200002000-00012