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Original Article

Effects of Multi-joint Eccentric Training on Muscle Function When Combined With Aquatic Plyometric Training: A Minimal Dose, Mixed Training Study

Cassidy Weeks[1,2], Brennan J. Thompson[1,2], Steven B. Spencer[1,2], Cody Fisher[1,2], Dianne Althouse[1,2], Talin J. Louder[1,2], Eadric Bressel[1,2]

[1]Kinesiology and Health Science Department, Utah State University, Logan, USA;
[2]Movement Research Clinic, Sorenson Legacy Foundation Center for Clinical Excellence, Utah State University, Logan, USA

Abstract

Objectives: To examine the effects of a combined eccentric overload and aquatic-based plyometric training program on muscle function/performance measures and soreness versus an eccentric-only training protocol using a minimal dose training paradigm. **Methods**: Twenty-five participants were randomized into either an eccentric-only training group (ECC) or a combined eccentric and aquatic plyometric group (ECC + AQP). The ECC group performed eccentric training once per week for 6-weeks while the ECC + AQP group performed the same eccentric training but with an additional aquatic plyometric training session. **Results**: There was no group × trial interactions for any of the variables. However, the training elicited large improvements in eccentric strength in both ECC (27%; ES = 1.33) and ECC+AQP (17%; ES = .86) groups. Isometric strength improved moderately for ECC and ECC+AQP groups (17.2%, ES = .53;9%, ES = .45). A moderate increase was observed for depth jump height for both ECC and ECC+AQP groups (13.1%, ES = .48;8.8%, ES = .36). No changes were observed for countermovement jump or sprint time and muscle soreness did not differ between groups. **Conclusions**: Minimal dose multi-joint eccentric overload training improved strength and depth jump outcomes after 6-weeks regardless of the training condition but adding a minimal dose aquatic plyometric protocol does not improve muscle function-based outcomes.

Keywords: Muscle Soreness, Muscle Strength, Sprint Speed, Strength Training, Vertical Jump

Introduction

Eccentric-based resistance training has gained popularity in recent years with regard to a variety of populations, including athletic, recreational, and rehabilitation settings. This type of resistance training is characterized by an emphasis on the force generated during the muscle lengthening phase. Accumulating scientific data has shown eccentric exercise to elicit superior muscle strength and mass gains[1,2] with lower rates of perceived exertion and less metabolic demand[3,4] than traditional resistance training. These characteristics make eccentric exercise suitable for a range of settings from athletic to clinical populations because of the substantial gains that can be made in a relatively time and energy-efficient manner. For example, clinicians may find eccentric exercise especially desirable for clinical populations that may not tolerate traditional resistance exercise due to the elevated perceived exertion and metabolic demands.

Some evidence suggests that eccentric exercise is highly correlated to improvements in vertical jump (VJ) height indicating the possible ability of eccentric strength gains to transfer to explosive power movements[5]. Bridgeman et al.[5] found that eccentric force and power correlated with countermovement jump peak power and VJ height, whereas, for the concentric measures, only absolute concentric force was correlated with any of the jump measures. Another

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Corresponding author: Brennan J. Thompson, Ph.D., Associate Professor, Kinesiology and Health Science Department Utah State University, 6425 Old Main Hill, Logan, UT 84322, USA
E-mail: brennan.thompson@usu.edu

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study done by Papadopoulos et al.[6] found eccentric exercise performed on a custom-made isokinetic leg press resulted in significant increases in depth jump height (14%) and peak power (26%). These findings suggest the eccentric phase of the stretch shortening cycle (SSC) and eccentric strength may be important for SSC-based performance[5,6].

However, the aforementioned results appear to partially conflict with recent research from our lab. In one study, a 19% increase in lower body eccentric strength was observed following twice-weekly training on a multi-joint isokinetic ergometer (Eccentron) for 4 weeks but no improvements were shown for 40-m sprint or VJ height[7]. In a follow up study, Crane et al.[8] found that 4 weeks of eccentric training on the Eccentron increased eccentric strength by 32%. Interestingly, the VJ showed a statistical improvement in this study, but the gains of 7%, were much smaller than the eccentric strength gains. These findings suggest that in the relatively short term (i.e., < 6 weeks), the transfer of large lower body eccentric training-based gains are modest for VJ performance and not present for sprint speed, possibly indicating a limited use for using solely this modality in training the SSC.

A plausible reason for this discrepancy in the literature may be due to the training models used. For instance, training on the Eccentron only involves muscle recruitment during the eccentric phase, and thus, lacks a robust SSC component[7,8] despite the high overload imposed. Notably, both the training interventions used by Bridgeman et al.[5] and Papadopoulos et al.[6] used concentric muscle action with the eccentric training. This differs from the eccentric-only training on the Eccentron which lacks a concentric muscle action and this could be the reason for the discrepant findings between the studies. It is well known that the SSC component of dynamic movement is a critical contributor to functional and sport performance measures[9-11]. In a longitudinal study, Cormie et al.[12] found improvements in peak and average eccentric force and power as well as peak eccentric velocity following a ballistic training program that involved training the SSC. Thus, high eccentric load training that is combined with the use of the SSC may be the necessary combination to induce more pronounced performance-based improvements.

It is well established that plyometric training is highly effective for training the SSC[13,14] as it involves high velocity, explosive movements which utilize both eccentric and concentric actions that are specific to a particular sport or functional task. Plyometric training combined with resistance training may produce greater improvements in functional tasks than either training protocol alone indicating that plyometrics may be more effective when paired with some form of resistance training[15]. These two modalities may provide complimentary features, such that high velocity plyometrics and overload eccentric exercise are two different training models which could work synergistically because the short-comings of one model are the strengths of the other (i.e., plyometrics are not as effective at producing muscle size and strength gains and eccentric-only training largely lacks the functional SSC component). More research is needed to examine a mixed training model of plyometrics and eccentric over-load training to determine if greater improvements in functional performance tasks could occur.

It is plausible that an interference effect may exist if eccentric overload training and land-based plyometric training are performed parallel to each other due to the high loading of each modality. There is high potential for muscle damage and associated soreness levels from eccentric overload training. Consequently, the large ground reaction forces typical of land-based plyometric training may not be well suited for mixed training alongside eccentric exercise, given high soreness could make performing land-based plyometrics uncomfortable, difficult, and/or less effective (i.e., presenting too strong of a stimulus effect), but if done in an aquatic environment, soreness may likely be better tolerated and perhaps recovery increased while allowing for the simultaneous performance of high SSC movement velocity activities. In support of this concept, Robinson et al.[16] compared land- and aquatic-based plyometrics in college-aged volleyball players and found both groups had significant improvements in VJ, peak torque, and velocity but the land-based group reported significantly greater perception of pain with muscle soreness than the aquatic-based group. The presence of buoyancy in aquatic environments allows for decreased landing forces[17] and reduced pain and soreness[16], and warm water temperatures (> 88°F) and hydrostatic pressure are other factors which may be beneficial in decreasing soreness[17]. For these reasons, combining aquatic plyometric training with high load eccentric training would seem to be a complimentary, and potentially effective training approach.

The unloading effects from buoyancy in an aquatic environment would also provide more rapid velocity concentric movements of the plyometric exercises possibly leading to an increase in power output because with deeper immersion comes greater buoyant effects and greater resistance of upward motion[18]. Studies have found increases in VJ, torque, and sprinting speed following aquatic-based plyometric programs[19-21].

A feature of our prior eccentric-only training studies is the use of a minimal dose training model. Remarkable results have been achieved with only 6 minutes of eccentric exercise per week[7,8]. This approach is useful as a means to help achieve a more tolerable exercise program that would likely not be prohibitive to many populations, thus potentially increasing exercise adherence[3]. In line with this concept, a minimal dose plyometric training program would be useful to best complement such an eccentric routine in order to maintain the minimal dose feature of the program.

To our knowledge there is no research to date that investigates the effects of combining minimal dose aquatic-based plyometric training with multi-joint eccentric overload training on muscle function and soreness measures. The purpose of this study was to examine the effects of a combined eccentric overload and aquatic-based plyometric training program on muscle function, sport-specific performance measures, and soreness versus an eccentric-only training

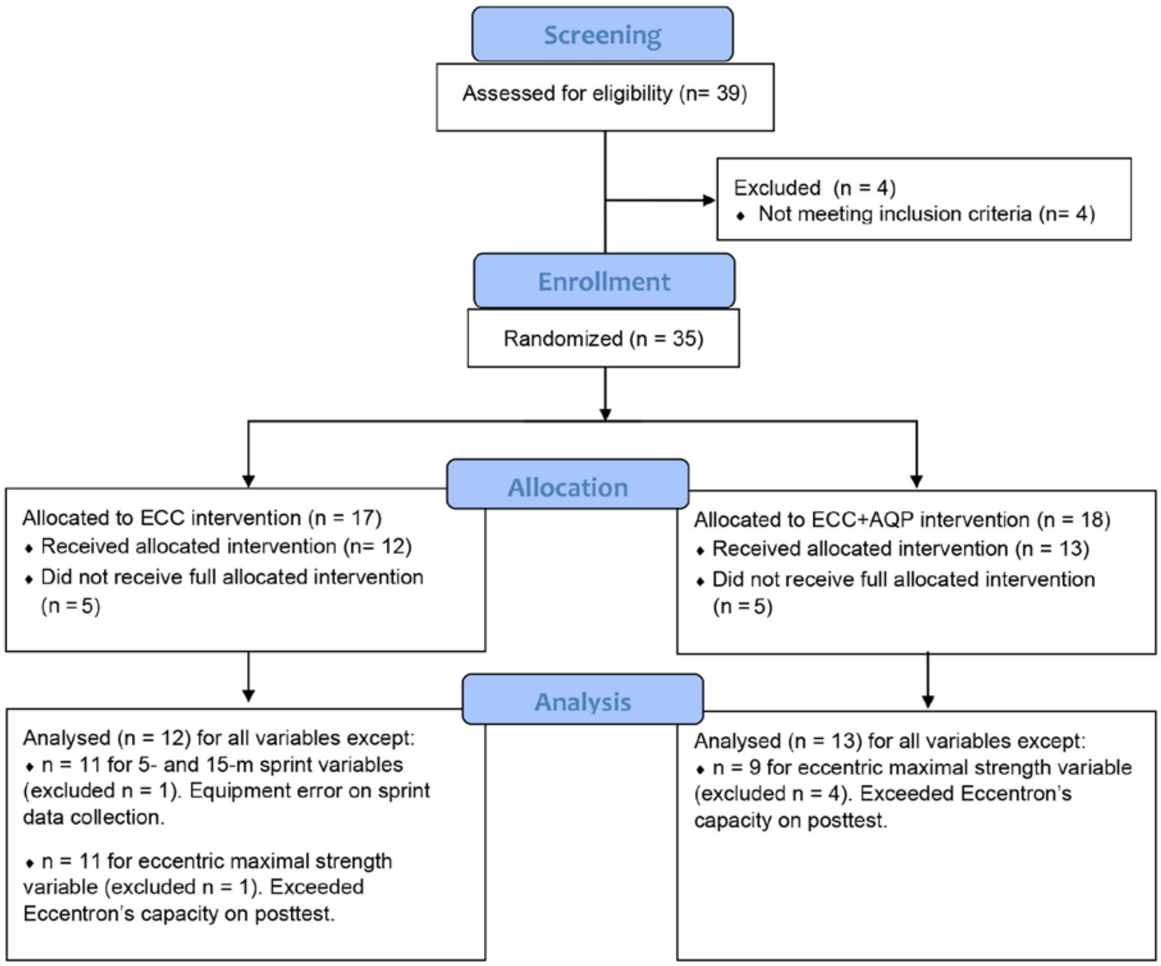

Figure 1. Flow diagram of participants in the study.

protocol. We hypothesized that the combination of aquatic-based plyometric training and multi-joint eccentric overload training would increase muscle function gains and reduce soreness levels, better than eccentric-only training.

Methods

Participants

Thirty-five college-aged men and women volunteered to participate in this study. Inclusion criteria included being between the ages of 18 and 35 years old and informally classified as recreationally active which was defined as participating in recreational activities or moderate dose physical activity. Exclusion criteria included regularly engaging in resistance training (>3 times in the previous month), doing aerobic exercise more than 30 minutes per day five days a week, having any lower limb injuries or surgeries within a year before the study or any musculoskeletal/neurological disorders that may affect the lower limbs, and having an eccentric isokinetic baseline strength level of > 3225 N (more on this below). Participants were required to complete at least 80% of the training sessions and if unable to they were withdrawn from the study. Figure 1 depicts the flow of participants through the phases of the study.

Experimental Procedures

This study utilized a randomized, parallel-group design with repeated measures to test the hypotheses following the 6-week training intervention. Upon enrollment, participants were randomly assigned (via drawing a number out of a hat) to one of two groups: 1) eccentric-only exercise (ECC) (n = 12; mean ± SD: age = 21.0 ± 3.0 years, mass = 76.2 ± 13.3 kg, height = 173.9 ± 8.1 cm), or 2) eccentric and aquatic plyometric exercises (ECC+AQP) (n = 13, age = 22.8 ± 2.6 years, mass = 74.1 ± 8.7 kg, height = 173.9 ± 8.7 cm). The design aimed, at minimum, to match groups for sex and baseline eccentric strength. Prior to the pretest, participants underwent a separate familiarization session 3-4 days before the pretest to become acclimated to the testing routine. All testing occurred at the same time of day (± 2 hours) and occurred in the following order: depth jump, countermovement jump, dominant leg isometric maximal strength, Eccentron isokinetic maximal eccentric strength, and 15-m sprint. Posttesting occurred 4-6 days following the last training session to allow for full recovery as per previous procedures[8]. All training was closely supervised by experienced research investigators and occurred in a private research lab.

Training Interventions

Eccentric Training

All eccentric training was completed using the Eccentron (BTE Technologies Inc., Hanover, MD) once per week for both groups for 6 weeks[8]. A brief warm-up was performed prior to each training session and involved cycling at 50 watts for 2 minutes on a cycle ergometer followed by two sets of 10 bodyweight squats separated by a 1-minute rest period. The Eccentron's protocol consisted of both a 1-minute warm-up and 1-minute cool down performed at half the session's target workload. The training consisted of a 3-minute workout period at the specified workload so that the total workout lasted 5-minutes including warm-up and cool down. The Eccentron velocity was set at 23 cycles per minute (a medium speed) which matched the velocity used in our previous studies that elicited large gains in strength[7,8]. The training progression was based on previous work completed in our lab[7,8] as well as additional pilot work. Progression was derived from a percentage of the baseline maximal eccentric strength recorded during pretesting. The progression was as follows: week 1 = 50%, week 2 = 55%, week 3 = 60%, week 4 = 60%. After week 4, the intensity was individually adjusted based on the participant's ability to meet the target force. If they were able to meet the target force with 85% or more accuracy the force was increased by 5% in the next session. If less than 85% accuracy was achieved the target force remained the same in the next session until 85% accuracy was achieved.

Aquatic Plyometric Training

The combined eccentric and aquatic plyometric group completed one additional training session per week consisting of plyometrics performed on an aquatic treadmill (Hydroworx 2000; Middletown, PA, USA) at a water temperature of 32°C. The training program was based on recommendations by Miller et al.[17] on how to implement aquatic plyometric programs as well as our own additional pilot work. The aquatic session occurred 96 hours after the Eccentron training to promote recovery. The aquatic training program warm-up consisted of a 3-minute, 5 mph aquatic treadmill jog at 20% jet resistance at a depth consistent with the participant's anterior superior iliac spine. A 2-minute rest then occurred between the warm-up and the plyometric program. The aquatic plyometric exercises and progressions are found in Table 1 and were all performed at a depth consistent with the participant's xiphoid process to allow for greater resistance to upward motion and potentially greater power development[18]. Each session concluded with three, 15 second sprints at a depth consistent with the participant's anterior superior iliac spine. All sprints were performed at 100% jet resistance and separated by a 1-minute rest period. For the first two weeks, the sprints were set at 6 mph and at week three, the sprints were set at 7 mph. Following week three, the sprints would move up by 0.5 mph if the participant ran above the halfway mark of the pool and would go down 0.5 mph if they finished below the halfway mark whereas it would stay the same if they maintained the halfway mark. The last 15-second set was used to determine the speed change. This program consisted of about 80-100 touches per session as recommended by NSCA guidelines for beginner plyometric volume and increased to 100-120 touches per session indicated as intermediate. Strong verbal encouragement was provided through the training sessions to encourage maximal effort.

Outcome Measures

Depth Jump

Participants performed three maximal effort depth jumps from a height of 0.3 meters onto a force plate (AMTI Model OR6-WP; Columbus, OH, USA). The participants were instructed to place their hands on their hips, to step straight off the box without lowering themselves, then land and quickly jump as high as they could with minimal ground contact time. A successful jump attempt required landing on the force plate with both feet after the drop and the rebound jump. A 1-minute rest period was provided between each jump attempt.

Countermovement Jump

Participants performed three maximal countermovement vertical jumps on a force platform. The participants were instructed to stand on the platform with their feet shoulder-width apart and their hands on their hips. They were instructed to quickly lower themselves to a comfortable depth then immediately jump as high as possible while landing with their legs relatively straight[8]. A successful countermovement jump was counted if the participant landed on the platform with both feet and did not take a step before jumping. A 1-minute rest was provided between each jump attempt.

Isometric Strength

Participants performed three isometric maximal voluntary contractions (MVCs) with their dominant leg on the Eccentron. They were instructed to place both feet on the pedals with their heel positioned at the bottom of the pedal. The seat position was adjusted such that their knee angle was set at 45°. A block was placed under the appropriate pedal to

Table 1. Aquatic plyometric program progressions.

Training Week	Training Volume	Plyometric Drill	Sets x Reps	Training Intensity
1	84	Double leg hops	2 x 9	Low
		Side to side hops	2 x 9	Low
		Tuck jump	2 x 8	Med
		Alternating split squats	2 x 8	Med
		Countermovement jump	2 x 8	Med
		Sprint	3 x 15 s	6 mph, 100% jet
2	94	Double leg hops	2 x 10	Low
		Side to side hops	2 x 10	Low
		Tuck jump	3 x 6	Med
		Alternating split squats	3 x 6	Med
		Countermovement jump	3 x 6	Med
		Sprint	3 x 15 s	6 mph, 100 % jet
3	96	Single leg hops	2 x 8	Low
		Side to side hops	2 x 12	Low
		Tuck jump	2 x 10	Med
		Alternating split squats	2 x 10	Med
		CMJ repeated	2 x 8	High
		Sprint	3 x 15 s	7 mph, 100% jet
4	118	Single leg hops	2 x 10	Low
		Side to side hops	3 x 10	Low
		Tuck jump	2 x 12	Med
		Alternating split squats	2 x 12	Med
		CMJ repeated	2 x 10	High
		Sprint	3 x 15 s	**, 100% jet
5	114	Single leg hops	2 x 10	Med
		Side to side hops	3 x 10	Low
		Tuck jump	2 x 12	Med
		Alternating split squats	2 x 12	Med
		Single leg CMJ	2 x 8	High
		Sprint	3 x 15 s	**, 100% jet
6	110	Single leg hops	3 x 10	Med
		Tuck jump	3 x 10	Med
		Alternating split squats	3 x 10	Med
		Single leg CMJ	2 x 10	High
		Sprint	3 x 15 s	**, 100% jet

*A rest period of 30 s was given between sets and 1 minute between reps. A 1 minute rest was given between each set of sprints. ** Move up 0.5 mph if: above ½ mark, Move down 0.5 mph if: below ½ mark, Keep same if: at ½ mark (during last set).*

prevent the pedal from moving and the participants were instructed to push into their dominant foot pedal as fast and as hard as they could and to hold that for approximately 3 seconds until the researcher told them to let off. A 1-minute rest was provided between each MVC.

Eccentric Strength

Participants were tested for maximal isokinetic eccentric strength on the Eccentron. The testing procedures were in accordance with our previous studies[7,8]. Participants were instructed to sit in the seat and place their feet in the middle of the pedals with their heel positioned at the bottom. The seat position was adjusted so that the knee joint angle was set to 30° at the most extended position, per the manufacturer's recommendation. The pedals moved towards the participant in an alternating motion so that each leg worked isolaterally in a repetitive manner. A total of 12 MVC repetitions, six per leg were performed. The testing speed was set at 23 cycles per minute[7]. Participants were instructed to maximally resist the motion of the pedal as it moves towards them and relax as it moves away.

15-m Sprint

Lastly, participants performed three maximal effort 15-m sprints. Sprint time (s) was measured using timing gates (Dashr Motion Performance Systems, Dashr LLC, Lincoln, NE, USA) positioned at the start, 5-m mark, and endpoint of the distance. Participants were instructed to start in a 3-point stance with their feet staggered and one hand on the ground. They were also instructed to place the front of their lead foot on a line 30 cm behind the start line and to place the opposite hand on the starting line[21]. The sprint started with the covering of the laser on the timing gate and the sound that followed. Participants were instructed to run through the last timing gate to ensure full effort throughout the entire distance. A rest period of 2 minutes was given between each trial. The participants were instructed to wear shoes appropriate for sprinting and to wear the same shoes for both the pre- and post-test. Both 5-m and 15-m sprint time data was analyzed. During all testing, participants were given verbal encouragement to emphasize maximal effort.

Muscle Soreness

During the training period, soreness levels were assessed using a visual analog scale (VAS) per our previous procedures[8]. For both groups, the VAS was administered at baseline before the pretest, for five consecutive days following the pretest, and then three consecutive days per week following the eccentric training session for the remaining six weeks[8]. To assess their soreness, the subjects were instructed to perform three air squats to parallel at the same time of day and mark their perceived soreness of the lower limbs on a 100 mm line with the left and right ends corresponding to “no soreness” and “most soreness ever experienced.” Participants were not allowed to use nonsteroidal anti-inflammatory drugs (NSAIDS) during the study to prevent any effects it may have had on soreness or muscle damage responses.

Data Analysis

A data acquisition system (Biopac MP150WSW, Biopac System Inc., Santa Barbara, CA) was used to sample the raw force signals from the Eccentron. Data were sampled at 2 KHz and processed offline with custom written software (LabVIEW 2018, National Instruments, Austin, TX). The signal was scaled to N and filtered with a fourth-order, zero phase shift, Butterworth filter with a 50 Hz cutoff[22]. For the isometric peak force, the highest 500 ms epoch was computed and the highest repetition was used for subsequent analysis. For isokinetic eccentric peak force, the single highest data point for the highest repetition was used for subsequent analysis. Note the baseline value used to determine the training intensity was taken from the Eccentron’s software output, and not from the extracted signals.

An average VAS score was determined for each group and each week by taking the average of three days each week for each participant including the last three days of the five days recorded after the pretest. Then an average was calculated for each week and each group so that both groups had seven VAS scores (Baseline to Week 6). Note that baseline here refers to the week after the pretest and before training began.

Statistical Analyses

Independent t-tests were used to compare group baseline demographics and baseline eccentric strength. A chi-squared test was used to assess group differences in sex. Mixed factorial ANOVAs (trial [pretest vs. posttest] × training condition [ECC vs. ECC + AQP]) were used to examine the effects of the training conditions for each of the dependent variables. When appropriate, significant effects were further decomposed with t-tests. Cohen’s effect size (ES; d) statistic was used to evaluate meaningfulness of the differences with values of 0.2, 0.5, and 0.8 representing small, medium, and large ES, respectively. An alpha level of 0.05 was used to determine statistical significance and all statistical analyses were performed in R Studio (RStudio Team (2020). RStudio: Integrated Development for R. RStudio, PBC, Boston, MA URL http://www.rstudio.com).

Results

A total of 25 participants completed the study due to 10 participants (of the original 35) not completing at least 80% of the training sessions and were therefore withdrawn. Five participants, one from the ECC group and four from the ECC + AQP group, exceeded the Eccentron’s load tolerance (set at 3336) levels at the posttest making the sample size for eccentric maximal strength n = 11 in the ECC group and n = 9 in the ECC+AQP group (note these participants’ data were included for all other measures). The ECC and ECC + AQP groups were not significantly different at baseline for age (p = .13), mass (p = .68), height (p = .99), or sex (p = .32). Baseline isokinetic eccentric strength was also found to not be significantly different (p = .15) although the isometric MVC variable was significantly different between the groups at baseline (p = .009).

The means and SDs are presented in Table 2 and Figure 2 shows the individual scores. For the isokinetic eccentric strength variable, there was no significant group × trial interaction (p = .23), however, a significant main effect was observed for trial (p < .001) such that the posttest was higher than the pretest with the Cohen’s ES showing a large effect for both the ECC (1.33) and ECC + AQP (.86) groups. For depth jump height there was no significant group × trial interaction (p = .65), however, a significant

Table 2. Means (SD) and Cohen's d effect sizes for the Eccentron strength, depth jump height, and isometric peak force for the eccentric-only (ECC) and eccentric plus aquatic plyometric (ECC+AQP) training conditions at pretest (Pre) and posttest (Post).

Action	Variable	ECC			ECC+AQP		
		Pre	Post	Cohen's d	Pre	Post	Cohen's d
Eccentron	Peak Force (N)	1919.3 (446.4)	2482.4 (397.8) ***	1.33	2345 (506.5)	2732.2 (392.4)***	.86
Depth Jump	Height (m)	.28 (.07)	.32 (.10) **	.47	.32 (.08)	.35 (.08) **	.38
CMJ	Height (m)	.29 (.07)	.31 (.09)	.17	.33 (.09)	.33 (.08)	.01
Isometric MVC	Peak Force (N)	1884.2 (569.6)	2208.9 (648.6) *	.53	2518.8 (553.5)	2753.4 (488.9) *	.45
5-m Sprint	Time (s)	1.43 (.26)	1.41 (.16)	.09	1.30 (.25)	1.23 (.28)	.26
15-m Sprint	Time (s)	2.94(.35)	3.05(.32)	-.33	2.86(.38)	2.80(.46)	.14

*Cohen's d values only compare the pretest and posttest differences in this table. Note: n = 11 for ECC sprint variable, and n = 9 and n = 11 for Eccentron strength variable for ECC and ECC+AQP groups, respectively. *p < .05, **p ≤ .01, ***p ≤ .001. Statistical symbols denote significant differences between trials, collapsed across group. There were no trial x group interactions for any variables.*

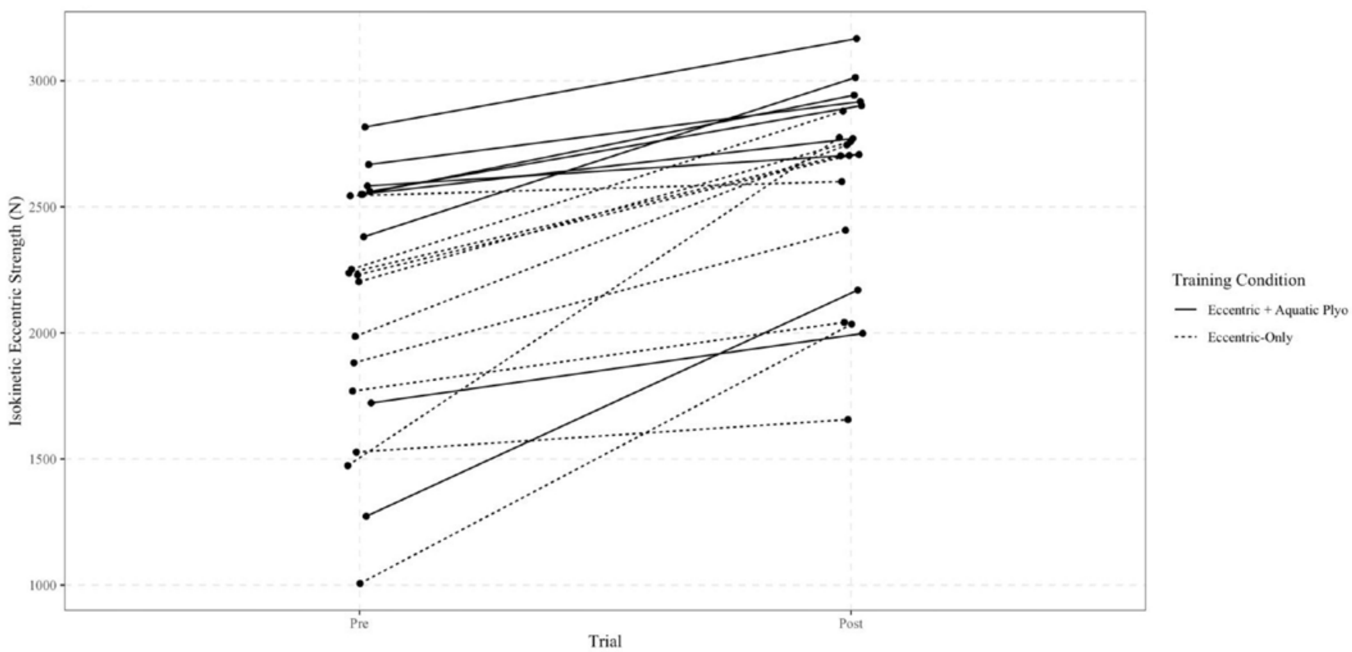

Figure 2. Spaghetti plot of individual participant isokinetic eccentric strength pre and post exercise training.

main effect was observed for trial (p = .001) such that the posttest was higher than the pretest with the Cohen's ES showing a medium effect for the ECC (.47) but small-medium for the ECC+AQP (.38) (Figure 3). For isometric strength there was no significant group × trial interaction (p = .73), however, a significant main effect was observed for trial (p = .04) such that the posttest was higher than the pretest with Cohen's ES showing a medium effect for both the ECC (.53) and ECC + AQP (.45) groups. There was no significant group × trial or significant main effect for trial in either 5-m sprint time (p=.48, p=.29 for the ECC and ECC+AQP groups, respectively), 15-m sprint time, (p = .34; p = .77) or countermovement jump height (p = .46; p = .49).

Only the VAS muscle soreness data violated Mauchly's test for sphericity (p < .001), therefore a Greenhouse-Geisser correction was utilized. For the VAS scores, there was no significant group × trial interaction for the muscle soreness data (p = .65) but a significant main effect was observed for trial (p < .001) when collapsed across the ECC and ECC + AQP groups (see Figure 4). Baseline was lower than weeks 1 (p < 0.01), 2 (p < .01), and 3 (p = .04).

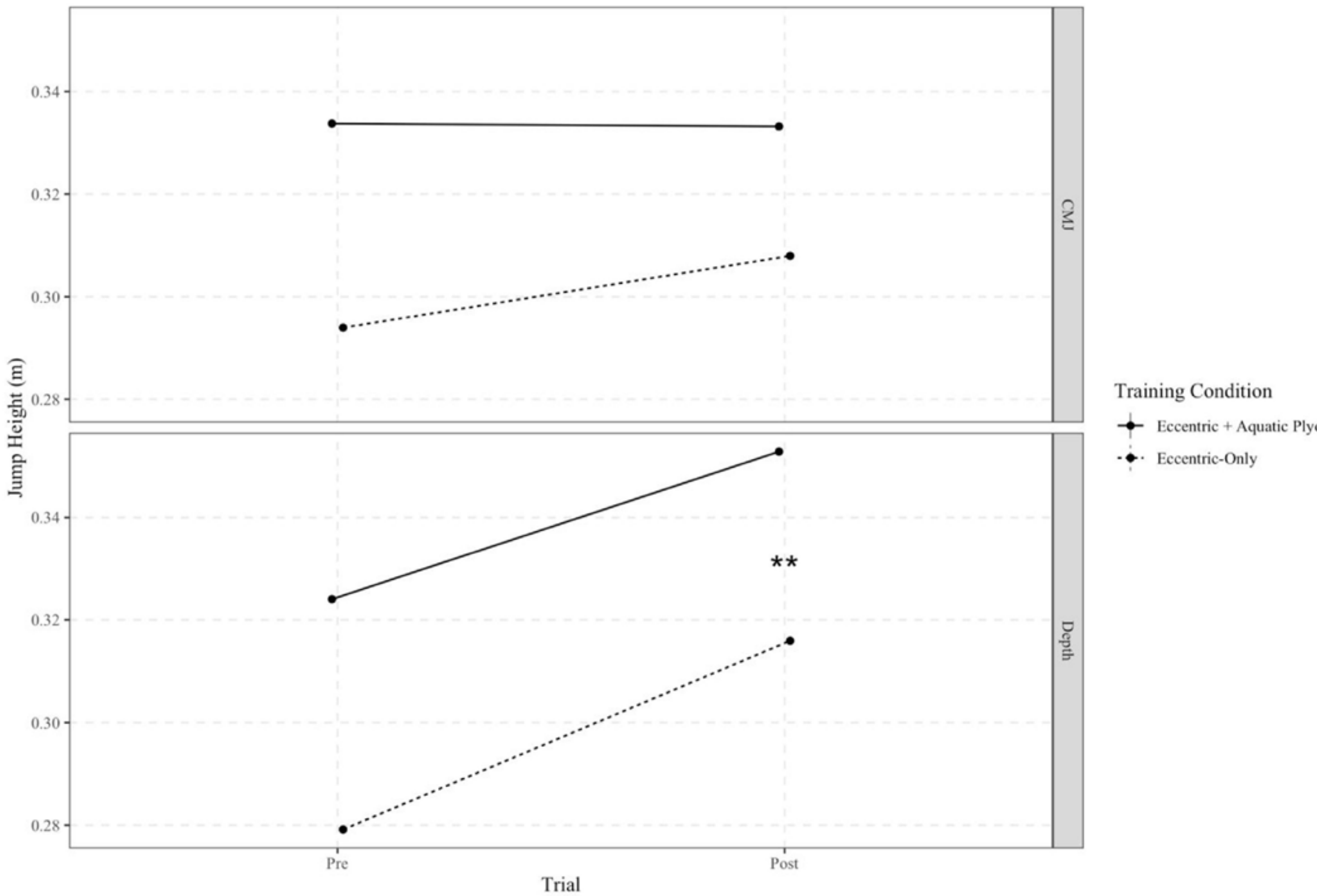

Figure 3. Pre to post exercise training changes in jump height for countermovement (top panel) and depth (bottom panel) jump measures. ** denotes a significant trial effect, collapsed across groups.

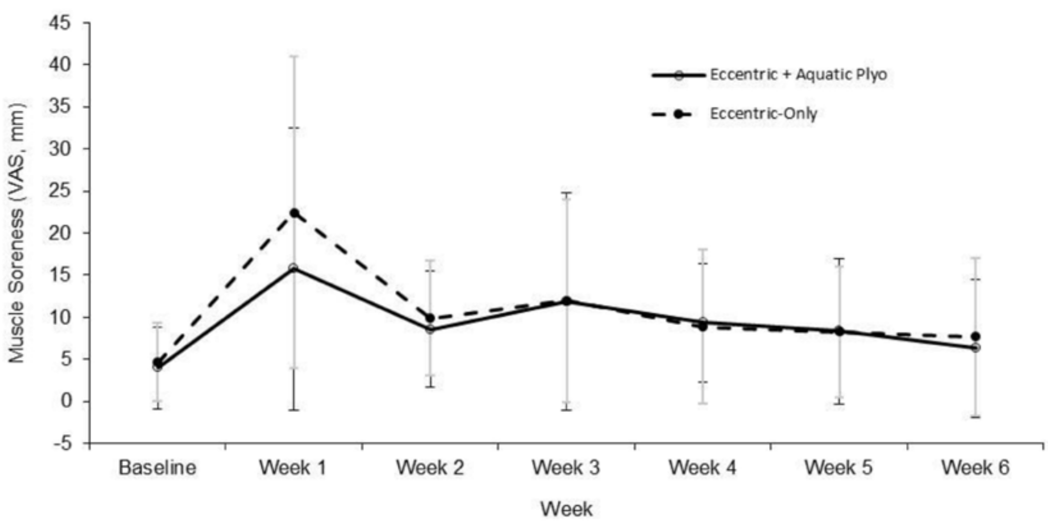

Figure 4. Mean visual analog scale (mm) muscle soreness values across the duration of the study for the eccentric + aquatic plyometric (solid line) and eccentric-only (dashed line) groups. Note, the grey error bars represent the eccentric-only group and the black error bars represent the eccentric + aquatic plyometric group.

Discussion

The primary findings of this investigation were: 1) low dose multi-joint isokinetic eccentric overload training is highly effective for increasing muscular strength, 2) depth jump is the only SSC performance that increased with training, but the combined aquatic plyometric training and multi-joint isokinetic eccentric overload training did not increase depth jump performance more than eccentric training alone, 3) muscle soreness did not differ between the two training conditions.

The eccentric training protocol used in both training groups significantly improved muscular strength after 6 weeks (Figure 2). Although there was no significant interaction, further analysis shows that the ECC training condition had an ES of 1.33 (27% gain) and the ECC + AQP group had an ES of .86 (17% gain) with an overall strength improvement of 23% across both groups. This finding is significant and potentially impactful. The volume of eccentric training in this investigation was only 3 minutes, once a week resulting in a total of just 18 minutes of total eccentric training in the study. This is significant because the dose of training in this study was half as much as some previous studies done on the Eccentron in our lab[7,8]. Although the eccentric training was only half the dose the strength gains were similarly large as compared to Crane et al.[8] which showed strength gains of 27% and Gordon et al.[7] with gains of 19.2% following a training volume of 6 minutes per week for 4 weeks (a total training amount of 24 minutes). These results indicate that multi-joint isokinetic eccentric overload training can be exceptionally low dose and still be highly effective at increasing muscular strength providing further evidence that this type of eccentric training is time and energy efficient making it desirable for populations that may not well tolerate traditional resistance training or those with severe time restraints.

There were no significant group × trial interactions observed for any of the outcome measures indicating that the addition of aquatic plyometric training to eccentric overload training did not increase muscle function measures, including muscular strength and SSC performance, more than eccentric training alone. This is likely due to the low dose nature of the aquatic training program. Compared to other studies where aquatic plyometric training was successful at increasing vertical jump height and sprint speed[16,17,19] this investigation had lower volume. Robinson et al.[16] utilized a similar training protocol; however, they implemented their program twice a week for 45 minutes as opposed to this study's 20 minute program once a week. Miller et al.[17] also utilized a twice weekly training volume. It is also important to note that Robinson et al.[16] and Miller et al.[17] participants were college athletes and had significant plyometric training experience. It is possible that aquatic plyometric training could still act complementary to eccentric overload training if the aquatic training protocol was a higher dose such as with twice weekly training instead of a single weekly session. However, one important thing that may be gleaned from this study is that due to the extremely short duration required for substantial gains with the present study's eccentric training protocol, more time could be dedicated to the plyometric training while still keeping the weekly total training time relatively low. Moreover, this study demonstrates that a minimal dose training model appears to work well for eccentric training, but does not work as well for plyometrics. It would thus appear that more training volume is needed to induce SSC-based, sport specific adaptations, than is required for simply increase muscle strength.

Another possible reason this study's particular aquatic training protocol did not cause increased SSC performance more than the eccentric only group is the depth of the water used. All plyometric exercises, with the exception of the sprints, were performed at chest depth (xiphoid process). The reasoning behind this was to further decrease the large ground reaction forces that may cause excessive muscle soreness and risk of injury as well as to allow for more rapid upward velocity movements as observed by Louder et al.[18] It is possible that performing plyometrics in water too deep decreases SSC reaction time and subsequently diminishes the effect of the concentric portion of the SSC[17], thereby working in a counterproductive way.

Interestingly, depth jump height significantly increased at posttest in both ECC and ECC + AQP groups ($p = .001$), however, countermovement jump height did not significantly increase posttest for either group ($p = .49$). This indicates that the eccentric portion, which is more prominent in executing a depth jump, was trained more effectively than the concentric portion of the SSC, which would reflect test-to-training specificity and so illustrates the importance of specificity of training in creating training programs. It is possible that the immersion level used in this study impacted these findings, such that it was set at a rather deep (xiphoid) level, which could have impacted the kinetics of both the concentric and eccentric movements more so than it would at shallower depths. Further research is needed to determine if performing higher dose plyometrics in a water depth consistent with the anterior superior iliac spine (waist deep) would elicit more increases in SSC performance than eccentric training alone and allow for more effective training of the concentric portion.

Even though depth jump height increased significantly in both groups, the ECC group did show a modestly larger improvement with a percent change of 13.1% and effect size of .47 compared to the ECC+AQP group with a change and effect size of 8.8% and .38, respectively. These results further show the importance of eccentric training on depth jump performance and subsequently SSC performance in a specificity context. Isometric peak force also significantly increased in both groups at posttest ($p = .04$) with the ECC group showing non-significantly larger increased peak force with a 17.2% (ES = .53) change versus the ECC + AQP percent change of 9% (ES = .45) (Figure 3). These results further indicate the effectiveness of the eccentric training protocol to increase muscular strength. They also indicate that although the aquatic program did not augment SSC performance it also did not completely inhibit strength gains even though the two different training conditions were performed concurrently.

The overall lower volume of training in this study could also explain the lack of a difference in soreness scores between the ECC and ECC + AQP groups (Figure 4). With double the volume, muscle soreness averaged around 20-30 mm on the VAS (Crane et al., 2020) compared to an average of 8-10 mm found in the current study. In essence, the present protocol resulted in similar strength-based gains, but with less soreness than our prior studies using an identical eccentric exercise. Interestingly, a close inspection of the soreness data (Figure 4) indicates a non statistically significant lower soreness value for week 1 for the ECC + AQP group vs. the ECC group. Perhaps there is some slight benefit to the mixed training that was not directly determined statistically in this study. At the minimum, the combined aquatic plyometric protocol did not hinder the training effect. The lack of a decrease in performance from this mixed protocol may indicate it as a potential means to train without inducing detrimental effects, which may have implications for overtraining or other lower stimulus needs that do not diminish gains, but allow for a range of lower intensity plyometric-based activities in practice. This finding is promising for practitioners, clinicians, or trainers who work with populations who have difficulty adhering to physical activity protocols or that may not tolerate high levels of soreness or exercise volume.

A limitation to this study was the lack of a true control group which does not allow for comparison against a non-training condition. Another limitation was the mode of obtaining muscle soreness measures. Participants were coached on how to properly assess and record their soreness as well as reminded at each lab appointment. It is assumed that each participant correctly performed air squats to an appropriate depth and recorded their responses at the same time of day. Also, it is possible that the rather deep immersion level (xiphoid) used in this study for the aquatic plyometric training was not ideal for maximizing the velocity of the movements, and thus further work is needed which uses shallower immersion depths to determine the effect of immersion level on aquatic-based plyometric training outcomes. Finally, a rather large attrition occurred where 10 of the 35 participants that started the study were withdrawn due to them failing to attend at least 80% of the training sessions. The reason for this relatively high dropout is largely due to the data collection coinciding with COVID-19 prevalence in Fall 2021 and the university's restrictions (quarantine requirements). Thus, it was not due in large part to the training routines as conducted in this study.

In conclusion, multi-joint eccentric overload training significantly improved eccentric and isometric strength and depth jump height after 6 weeks regardless of the training condition (ECC vs. ECC + AQP). The addition of aquatic plyometric training to the eccentric training did not enhance SSC performance but also did not inhibit the aforementioned improvements. A novel finding of this study is the divergent outcome of minimal dose training for the two types of training, whereby minimal dose eccentric training is highly effective at inducing muscle strength gains, whereas minimal dose plyometric training does not appear to attain the training threshold needed for achieving functional gains. It is likely a higher dose of aquatic plyometric training is needed to improve SSC-related performances, specifically when combined with eccentric training. The demonstrable benefits of low dose eccentric training could allow for proportionally more time devoted to other forms of training, such as plyometrics, where a greater training dose may be necessary, but when combined, could still be collectively performed in a relatively minimal dose training program. Muscle soreness was not significantly different between the two training conditions, but was overall less than reported in similar previous work[8] likely because of the lowered training volume, which is a potential marked advantage of this type of training program that could help improve exercise adherence and tolerability. Low dose multi-joint isokinetic eccentric overload training may be an effective resistance training modality that could be practical for clinicians or trainers who work with sedentary, diseased, or older populations who may not tolerate traditional resistance training. However, further research is needed to examine if a higher volume of aquatic plyometric training, or different water immersion levels, would augment the low dose eccentric overload training and produce improvements in functional sport specific tasks such as sprint speed and countermovement jump height.

Ethics approval

The study was approved by the Utah State University Institutional Review Board (protocol #11903).

Consent to participate

All participants read and signed an informed consent before participating.

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