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EFFECTS OF FLYWHEEL RESISTANCE TRAINING ON MUSCLE FUNCTION AND SPORT-SPECIFIC PERFORMANCE IN COLLEGIATE CLUB WATER POLO PLAYERS

by

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ABSTRACT

Flywheel training has been shown to be beneficial for improving a multitude of muscle function and performance parameters, but its short-term training effects on athletic performance have yet to be established. PURPOSE: To investigate the effects of four weeks of flywheel squat training on lower body muscle function adaptations and sport-specific performance in collegiate club water polo players. METHODS: Thirteen men and women who participated in collegiate club water polo performed flywheel squat training twice a week for four weeks. Isokinetic knee extension peak power (PP) and peak torque (PT), flywheel squat peak power (FPP) and mean power (FMP), countermovement jump (CMJ), in-water jump height (WJH) and foot speed were assessed at Pre1 (0 weeks), Pre2 (4 weeks), and Post (8 weeks). Throughout the training period, muscle soreness was assessed with a visual analog scale every session, and FPP and FMP were assessed during sessions 2, 4, 6, and 8. RESULTS: Isokinetic PP (ES = .65) and PT (ES = .67) increased significantly from Pre1 to Post, and FPP and FMP increased between Pre2 and Post (ES = 1.1, 1.0 respectively), and Pre1 and Post (ES = .79, .82). CMJ and foot speed were not changed, and WJH displayed a significant change between Pre1 and Post (ES = 0.4). FPP increased 19% from session 2 to 4 and FMP increased 27% from session 2 to 6, and each remained elevated through session 8. Muscle soreness peaked at session 2 but tapered off by session 3. CONCLUSIONS: Four weeks of flywheel squat training in collegiate club water polo players elicited large gains (47-52%, Effect Size = ~1.0) in flywheel specific squat power, but did not influence sport-specific performance measures including CMJ, WJH, and foot speed. Water-based exercises and stretch-shortening cycle movements (plyometrics) in combination with effective resistance training programs, including flywheel-based training, are likely needed for marked sport skill improvements, along with longer-term training studies.

INTRODUCTION

Water polo is both a physiologically and technically demanding sport. Water polo athletes must be able to swim at high speeds and tread water for long periods of time (Smith, 1998). Further, athletes must wrestle with opponents and perform sport skills such as throwing, shooting, and boosting themselves out of the water (Botonis et al., 2018). These skills involve high levels of strength, power, agility, and a high degree of sport-specific techniques.

One of the most important skills for water polo players is the in-water boost maneuver because it is a key sport-specific movement that is linked to improved passing, shooting, blocking and other defensive abilities (McCluskey et al., 2010). Gobbi et al. (2013) reported that expert-level athletes have higher levels of power and resultant maximal jump heights out of the water compared to intermediate athletes, suggesting that lower-level athletes could focus on power improvements to increase jump height out of the water. A number of different training protocols have been examined for water polo players, including high intensity interval training (HIIT) (Botonis et al., 2016), plyometrics (Saez de Villarreal et al., 2015), power (Veliz et al., 2015), strength (Veliz et al., 2015), and combined water and land training (Saez de Villarreal et al., 2014). Previous studies have demonstrated that strength and power training can lead to an increased ability of the athlete to boost his/her body out of the water (Saez de Villarreal et al., 2014, 2015), and a concurrent training protocol of strength and sport-specific in-water training was effective at eliciting improvements in water polo-specific performance parameters during the season (Saez de Villarreal et al., 2015).

Fernandes et al. (2010) assessed muscle activity during the “egg-beater kick”, which is the water polo-specific method of treading water. During the kick, the legs alternate through an elliptical motion which involves three phases: outward, power (the propulsive downward phase of the kick), and recovery (Oliveira et al., 2010). They reported that the gastrocnemius and vastus medialis (VM) muscles showed peak muscle activation during the power phase where powerful knee extension and ankle plantarflexion occur, and the VM was shown to be the most active compared to other quadriceps muscles during knee extension (Oliveira et al., 2010). In-water boosts require the same motion of the eggbeater kick, but the legs move simultaneously instead of alternately in order to achieve substantial height out of the water. Given the requirement for high quadriceps power to successfully perform these sport-specific in-water kick and boost maneuvers (Oliveira et al., 2010; Platanou, 2005; Sanders, 1999a), further research is warranted that examines the influence of longitudinal training-induced increases of lower body strength and power on in-water boost performance.

Flywheel training is a relatively novel, non-traditional resistance training modality that has the potential to rapidly improve lower body muscle performance and, therefore, may augment the in-water boost ability in water polo athletes. Flywheel training is an iso-inertial modality of training that was initially developed to provide astronauts with a compact, efficient means of resistance training to maintain their bone mass density in a microgravity environment (Tesch et al., 2017). The mechanism of resistance in flywheel training comes from a strap that is initially wound around a flywheel and then unwound when the athlete performs the concentric phase of an exercise. The concentrically produced kinetic energy is returned (by rewinding the strap) in the eccentric portion where the athlete resists the load to bring the wheel to rest (Tesch et al., 2017). Recently, flywheel training has garnered attention as an effective method for enhancing muscle size, strength, and power in the general population as well as in athletes (de Hoyo et al., 2015; Maroto-Izquierdo, García-López, & de Paz, 2017; Norrbrand et al., 2007). For example, a recent meta-analysis reported (Maroto-Izquierdo, García-López, Fernandez-Gonzalo, et al., 2017) that flywheel resistance training led to significantly greater improvements in muscle power (standardized mean difference versus traditional training; effect size = .80), strength (.66), hypertrophy (.57) and jump height (.46) compared to conventional resistance training. Thus there is a documented potential for improved athletic performance with flywheel training.

One explanation for the superior results previously shown for flywheel training may be that it allows for maximal or near maximal levels of muscle activation throughout the entire range of motion due to the accommodating load, which is unlike traditional resistance training (Norrbrand et al., 2010; Vicens-Bordas et al., 2018). For example, an absolute load (dynamic constant external resistance) in traditional resistance training provides maximum muscle activation only during the last repetition (when performed to near failure) (Tesch et al., 2017) and/or at the “sticking point” directly prior to the concentric phase (Martinez-Aranda & Fernandez-Gonzalo, 2017), whereas the flywheel maximizes the load for all points during the range of motion (as long as the lifter gives maximal effort during the entire range). In addition, for the flywheel, the kinetic energy produced during the concentric phase must be entirely absorbed during the eccentric phase (Tesch et al., 2017). Therefore, an increased ability to produce more mechanical and muscular work from the concentric phase due to an accommodating load results in a greater eccentric load given the requirement to absorb the kinetic energy produced during the concentric phase. This combined high concentric muscle activation and enhanced eccentric loading pattern may lead to improved muscle gains in a time-effective manner compared with traditional weight training (Tesch et al., 2017). Because the resistance is produced from the inertia that is determined by the mass and diameter of the flywheel (Sabido et al., 2018) the load can be individually tailored in order to accommodate either maximum force or power production by the athlete across various points along the force-velocity curve (Sabido et al., 2018).

Although results from previous studies suggest there may be a strong conceptual basis for using flywheel training in water polo players, to the best of our knowledge, no previous work has examined flywheel training as a means to improve muscle function and sport-specific (in-water boost maneuver) parameters in water polo players. Due to the maximum muscle activation that can be achieved in the concentric phase of flywheel exercise, there may be a strong relationship between flywheel squat training adaptations and the vertical propulsion achievable in-water. Gains in squat strength and power may transfer to the sport-specific actions that have a high concentric demand such as treading, the in-water boost, and swimming (Smith, 1998). Also, the possibility of enhanced eccentric loading may further elicit muscle adaptations (size and strength) to a greater extent than traditional training methods or concentric-only training (Kelly, 2015; Vicens-Bordas et al., 2018). Given the ability of the squat exercise to increase lower body muscle performance and to transfer to other lower body-based sport tasks (Maroto-Izquierdo, García-López, & de Paz, 2017), we reasoned that the flywheel squat exercise could be effective in increasing the strength, power, and leg speed, specifically in the quadriceps muscles that are important for the eggbeater kick and in-water boost in water polo athletes.

Due to its unique physiological training characteristics, flywheel-based training may be a useful means to improve a variety of muscle performance abilities in a short amount of time (Fernandez-Gonzalo et al., 2014; Maroto-Izquierdo, García-López, & de Paz, 2017; Norrbrand et al., 2007). Therefore, the purpose of this study was to examine the effectiveness of a four-week lower body flywheel resistance training program on muscle function adaptations and sport-specific performance parameters of collegiate club water polo players.

We hypothesized that flywheel training would induce improvements in muscle function (power) and favorable changes on sport-specific skills such as a countermovement jump (CMJ), water jump height (WJH), and foot speed during WJH. The short-term (four-week) training intervention focused on early-phase muscle function adaptations to flywheel training which is valuable for numerous entities (athletic trainers, physical therapists, coaches, and/or athletes) who often depend on rapid improvements or restoration of muscle function capabilities (Gordon et al., 2018).

METHODS

Subjects

Thirteen players from a women's (n = 5) and a men's (n = 8) collegiate club water polo team volunteered to participate in the study (mean ± SD: age = 19.54 ± 1.51, height = 175.11 ± 5.06 cm, mass = 78.93 ± 12.71 kg). Subjects had to be current members of the collegiate water polo team with at least one season of collegiate water polo experience (through the offseason or competition season prior to study enrollment) and between 18-30 years of age. Subjects filled out a questionnaire ascertaining their medical history, age, rank in school, training characteristics, injury history, and playing experience prior to study enrollment. This information was used to further determine study exclusion, including history of lower body injury (e.g. ACL tear, hamstring strain etc.) or surgery within six months of the start of the study, or any neuromuscular diseases (e.g. Muscular Dystrophy). There were no exclusions. Further, subjects confirmed that they would not perform any structured lower body resistance training outside of the study's training intervention during the four-week training period. The study was approved by the University's Institutional Review Board, and all subjects were fully informed about the study procedures. They read and signed an informed consent document prior to the start of the study.

Experimental procedures

The study used a prospective cohort design with a control period that involved testing sessions at weeks 0 (Pre1), 4 (Pre2) and 8 (Post) of the study. The first four-week block served as a control period for which the subjects did not undergo any experimental intervention and did not perform any extra lower body training outside of the study. The second four-week block was the experimental period where the subjects performed a flywheel-based resistance training program. During both the control and experimental periods, subjects attended practice 2-3 times a week for an hour each. Practices consisted of a 200 yard swimming warmup, skill drills, and live action scrimmaging. Both the men and women participated in the study during the competition season. Each testing session assessed isokinetic knee extensor strength and power, maximum power during the flywheel squat exercise, maximum jump height on land and in water, and foot speed during the in-water jump. The testing order followed performance testing principles as recommended by the National Strength and Conditioning Association (Haff & Triplett, 2016). Specifically, assessments were performed in the following order: anthropometry measurements, jump height on land, flywheel squat power, isokinetic knee extensor muscle strength, and the in-water jump height and foot speed assessments, both of which were performed last to make the testing routine convenient for the subjects. Testing took 60-75 minutes total, and the testing order and procedures remained the same across all testing sessions and the tests were performed in a private lab and private pool setting.

Outcome Measures

Anthropometry

Subjects were assessed for height, weight, and arm length using calibrated equipment. Height and arm length were only measured at the first session, but weight was assessed each time as it can vary over an 8 week period. Arm length was measured from the acromion process to the longest fingertip with the arm abducted at 90° in order to obtain raw values of height achieved by the torso while adjusting for the effect of arm length.

Vertical Jump (land)

Prior to the performance testing, subjects performed a standardized 5-min warm up on a cycle ergometer at 50 W. Subjects were provided with one warm-up or practice countermovement jump repetition, then they performed three countermovement jumps (CMJ) on a jump mat (Just Jump Technologies, Huntsville, AL) using standardized procedures that have been reported previously (Crane et al., 2020), which calculates jump height based on flight time during the jump. Subjects started with their feet shoulder-width apart and their hands on their hips. They were instructed to jump as high as possible without using their arms to help increase reliability of the test, and 1-min of rest was provided between jump trials.

Flywheel Squat Power

Subjects performed a maximum squat power test (FSP) on a flywheel training device (kBox4 Pro, Exxentric, Bromma, Sweden) using standardized procedures described previously. The device consisted of a box platform with a drive belt attached to a flywheel directly underneath the box, with the load determined by the inertia level of the flywheel. For the squat movement, subjects wore a vest that attached to the drive belt that ran directly below (and between) the subjects' feet. The drive belt length was set at full extension (knees and hips extended) for each subject to maximize their individual range of motion with feet shoulder-width apart. For the test, subjects performed four maximum squat repetitions as hard and fast as they could at a standardized flywheel inertia of 0.05 $k \cdot gm^2$, with two pre-repetitions provided to initiate the inertial load. Flywheel concentric peak power (FPP) and flywheel mean power (FMP) were both calculated from a rotational sensor on the flywheel (kMeter II) as the maximum value over the four repetitions. The kMeter II collected the rotational data at 10,000 Hz and transmitted the data to a mobile device via Bluetooth. On the first day of testing, two familiarization sets were performed with 2-min rest in-between, and on the Mid and Post days, two warm-up sets of 5 reps at 50% and 75% effort respectively were performed separated by 2-min rest. These were followed by three separate FSP trials of 4 reps, each separated by 2-min rest. In addition, FPP and FMP were recorded for the second training session of each week (e.g., session 2, 4, 6, 8) using the maximum value of the four training sets.

Strength Assessments

Strength testing was performed on an isokinetic dynamometer (Biodex System 3, Biodex Medical Systems, Shirley, NY). Participants were seated on the dynamometer and secured to the seat of the machine via straps placed over their thigh, chest, and waist. The center of the knee joint was aligned with the input axis of the dynamometer and the lower leg was secured to a padded lever arm at ~ 5 cm above the medial malleolus. Subjects performed a localized submaximal warm-up of the knee extensors and flexors consisting of 10 extension/flexion repetitions at approximately 75% of their perceived maximum at a velocity of $150°\cdot s^{-1}$. Following the warm-up, subjects performed three maximum effort isokinetic contractions, where they extended and contracted their lower leg through 80° of total movement (90° – 10° knee joint angle from the initial, to final position, respectively) at a velocity of $240°\cdot s^{-1}$.

The raw torque and velocity signals were sampled at 2000 Hz from the Biodex dynamometer with a Biopac data acquisition system (MP150, Biopac Systems Inc., Santa Barbara, Calif., USA) and processed offline using custom written software (LabVIEW 2018, National Instruments, Austin, TX). The voltage signal was scaled to appropriate units (torque = Nm, velocity = $°\cdot s^{-1}$) and filtered using a zero-phase shift, fourth-order Butterworth filter with a 150-Hz (torque) (Thompson, 2019) or 10-Hz (velocity) (Thompson et al., 2014) low-pass cut-off frequency. The isokinetic torque signal was corrected for the effect of gravity in accordance with the procedures of Aagaard and colleagues (Aagaard et al., 1995). The isokinetic peak torque (PT) was calculated as the mean value of the highest 25-ms epoch of the torque-time signal. The power signal was generated from the product of the torque and velocity signals, and peak power (PP) was calculated as the highest 25-ms epoch of the power curve.

Vertical Jump (water)

The water jump height (WJH) was assessed using the HydroWorx 2000, a private therapy pool (Hydroworx, Middletown, PA) in a university laboratory with subjects wearing their swimsuits. The measurement protocol was based on the procedures as previously described by Platanou (2006) and Saez de Villarreal et al. (2014). Subjects performed a standard warm-up of 2-min of treading water and one in-water jump. Then three jumps were performed for maximum jump height, with an extra trial performed if the jump heights of the three trials varied by more than +/- 10%. For the jump protocol subjects treaded water underneath a modified Vertec jump tester (Sports Imports, Hilliard, OH) placed on the edge of the pool (Figure 1). The subjects were required to start in the standard preparation position in water polo, sculling with their hands with the water surface at acromion height, with their hips positioned behind them at surface level and their legs performing the "eggbeater kick" to stay afloat. Whenever the subject was ready (unprompted), they performed one large kick to propel themselves upward (a specific learned skill in water polo players) and attempted to reach as high as they could with their dominant arm and displace the Vertec vanes. A 1-min rest was provided between the jump trials and the maximum WJH per test session and change scores between maximum values were analyzed.

In addition, vertical foot speed was assessed during the water vertical jump because it has been shown to be a strong determinant of one's ability to boost their body mass out of the water (Sanders, 1999a). The protocol for data collection followed that of Bressel et al. (2017), where the kinematic data were assessed using an underwater camera (Eyes Series HD Gen2: Ocean Camera, FL; NTSC; 1080p) and NightOwl software (Night Owl Security Products, FL). The camera comes standard with the HydroWorx pool and was fixed perpendicular to the plane of motion at a distance of about 1.5 meters from the object point. The heel served as the object point of interest, which was contrasted using permanent marker ink applied to the heel (Figure 2). Foot speed was then calculated from the digitization of the scaled marker using a motion analysis program (Logger Pro 3.8.4; Vernier Software & Technology, Beaverton, OR). A second reviewer analyzed 30% of the video data, and an inter-reviewer reliability analysis showed that reviewers were in agreement 83% of the time while assessing foot speed throughout downward foot movement. When comparing means between reviewers, they only differed by 1.4%.

Muscle Soreness

Soreness was assessed using a visual analog scale (VAS scale), which was administered prior to the start of each training session (8 assessments, including a baseline prior to the first session). Subjects performed their warm-up (described below in the training protocol) and recorded their perceived soreness of the lower body on a 100-mm line with the left and right ends of the line corresponding to “no soreness” and “most soreness ever experienced,” respectively, ranging from 0-100.

Training protocol

For the flywheel training intervention, subjects were instructed on the proper number of sets and reps and provided with one familiarization set at the intended training inertia (note, they had already been familiarized with the flywheel squat movement during the two prior testing sessions). The flywheel training was performed two times per week for four weeks for 8 total training sessions (Crane et al., 2020; Gordon et al., 2018). The training sessions took place at least twenty-four hours following a practice or competition and the sessions were separated by ≥ 48 hours. Subjects warmed-up with 2 sets of 10 repetitions of body weight squats with 1-min rest between each set. For training specifically, subjects then performed 4 sets of 7 repetitions of the flywheel squat at their maximum effort in accordance with the procedures of previous flywheel training studies (Norrbrand et. al., 2010; Tesch et al., 2017).

The inertial loads were selected based on the findings of Sabido et al. (2018) which showed that work increased with increasing inertial loads, with 0.075 kg·m^2 being the highest. Additionally, Martinez-Aranda et al. (2017) found that women experienced increases in both eccentric mean force and work with increasing inertia levels up to 0.075 kg·m^2, while men experienced an increase in force up to 0.100 kg·m^2. In a separate study, Norrbrand et al. (2010) utilized an inertial load of 0.110 kg·m^2 for their subjects. Accordingly, the women in the present study used an inertial load of 0.075, and the men used a load of 0.11 kg·m^2. At the club sport level, athletes are less resistance trained compared to varsity or professional athletes, and thus, a good base of strength is important to have prior to attempting to develop power. However, because club sport athletes are less experienced with resistance training, they used lower inertias compared to those with greater experience with resistance training who used inertias between .145 – .440 kg·m^2 (de Hoyo et al., 2015; Maroto-Izquierdo, García-López, & de Paz, 2017). Cormie et al. (2010) observed that both ballistic power training and heavy strength training in relatively weak individuals resulted in similar increases of athletic performance. Thus, somewhat heavier inertial loads as described by Martinez-Aranda & Fernandez-Gonzalo (2017) and Sabido et al. (2018), were chosen for this study’s training aspect. This allowed the training load would be slightly tilted to the strength side of the strength-power continuum.

Each squat repetition was performed at a maximum effort with subjects instructed to “drive your body up as hard and explosively as you possibly can.” In addition, they were instructed to strongly resist the downward pull of the drive belt following the concentric phase to a squat depth position at the point where the thighs were parallel to the ground. During all training sessions, subjects were provided feedback on their squat technique and verbal encouragement was provided to help ensure a high level of exertion was applied throughout all repetitions. Each set was separated by a two-minute rest period. Throughout the course of the study, the investigator verbally confirmed with the subjects that they were not performing any lower body strength training outside of the study. Post testing occurred 2-5 days following the final training session to help prevent any residual training-induced muscle damage from influencing the test results.

Statistical Analyses

Repeated measures analyses of variance (ANOVAs) were used to examine differences across test trials (Pre1 vs. Pre2 vs. Post) and training sessions (session 2 vs. 4 vs. 6 vs. 8) in the dependent variables. Bonferroni adjusted pairwise comparisons were used for post hoc comparisons. The Cohen's *d* statistic was calculated to examine the effect size for mean differences between test trials with values of 0.20, 0.50, and 0.80 being considered as small, medium, and large, respectively. Pearson product-moment correlations were used to evaluate the relationships among selected performance variables. Statistical analyses were performed using SPSS software (Version 25, IBM Corp., Armonk, NY, USA), and an alpha level of $P < 0.05$ was used to determine statistical significance for all comparisons. Univariate scatterplots displaying individual participant data were created from templates provided by Weissgerber et al. (2015).

RESULTS

All subjects fully completed all 8 training sessions and there were no reported injuries. There was a significant main effect for isokinetic PT ($P < .01$) and PP ($P < .01$) at 240°·s^{-1}. There was no difference between Pre1 and Pre2 for PT ($P = .19$) or PP ($P = .14$), but there was a significant increase from Pre1 to Post for PT ($P = .03$) and PP ($P = .03$) with medium effect sizes for both. However, between Pre2 and Post, PT ($P = .09$) and PP ($P = .13$) showed no significant differences with small effect sizes. Table 1 shows the mean (SD) and Cohen's d effect sizes for these variables.

Flywheel Power

For the FSP test, the FPP had a significant main effect ($P < .01$) and the post-hoc analysis showed significant increases between Pre2 and Post ($P < .01$) and Pre1 and Post ($P < .01$) with large effect sizes (ES = 1.1 and .79, respectively). There was no difference between Pre1 and Pre2 ($P = .10$). For the FMP, there was a significant main effect ($P < .01$) and post-hoc analysis revealed there was a significant increase between Pre2 and Post ($P < .01$), as well as between Pre1 and Post ($P < .01$). There was no difference between Pre1 and Pre2 ($P = .69$). Table 1 shows the mean (SD) and Cohen's d effect sizes for these variables.

Training Variables

For the flywheel training sessions, data recordings were unavailable for two subjects for two of the training sessions so these subjects were omitted from these analyses (N = 11 for training FPP and FMP variables). During training sessions, the FPP had a significant main effect ($P < .01$). Training sessions 4 ($P < .01$), 6 ($P < .01$), and 8 ($P < .01$) were all significantly greater than session 2. There were no other differences between all other sessions ($P = .18$ – 1.0). A significant main effect was observed for FMP across the flywheel training sessions ($P < .01$).

Training sessions 6 ($P = .02$) and 8 ($P = .05$) were significantly greater than training session 2. There were no other differences between all other sessions ($P = .11$ – 1.0). Figure 3 shows the progression of both variables during the course of the training. Mean VAS soreness scores for the total combined sample as well as separately for the men and women are reported in Figure 4. There was a distinction made between the men and women for this variable because they had different inertial loads for training sessions.

Performance Variables

There was a significant main effect ($P < .01$) for WJH. There was no difference between Pre1 and Pre2 ($P = .21$; 47.8 ± 3.7 and 48.7 cm ± 3.8, respectively) however, there was an increase between Pre1 and Post ($P < .01$; 47.8 ± 3.7 and 49.3 ± 4.0 cm) and a small-medium effect size (ES = 0.4). There was no difference between Pre2 and Post ($P = .26$) and a trivial effect size (ES = .17). Figure 4 presents a scatterplot of the individual change scores across test trials for WJH. There was no significant main effect for CMJ ($P = .14$), and thus, no differences ($P = .09$ – 1.0) between test trials (17.7 ± 3.7, 17.2 ± 3.3, and 17.6 ± 3.6 cm for Pre1, Pre 2, and Post, respectively) and trivial effect sizes between all trials (ES = .01 – .15).

Foot Speed

There was no significant main effect for peak ($P = .36$) or average ($P = .26$) foot speed with small effect sizes (ES = .08-.28) between all test trials. Mean ± SD values for peak foot speed across trials (Pre1, Pre2, Post) were 3.28 ± 1.01, 3.36 ± 1.05, and 3.51 ±.77 m/s, and values for average foot speed were 1.96 ± 0.65, 2.04 ± 0.58, and 2.15 ± 0.72 m/s. Figure 6a shows a scatterplot of the absolute change scores in peak foot speed and Figure 6b shows the peak foot speed raw values across testing trials. However, a different inspection of the data reveal there are specific determinants on WJH that seem prudent to further consideration, such as foot speed and years of experience. Figure 7 shows a significant correlation ($P < .01$, $r = .69$) between peak foot speed and maximum WJH, and Figure 8 shows there was a significant correlation ($P < .01$, $r =.66$) between years of experience and maximum WJH, both adjusted to control for the effect of arm length on the WJH parameter.

DISCUSSION

The primary findings were that four weeks of flywheel training elicited significant improvements in lower body muscle function parameters (e.g., isokinetic PT and PP, and FSP) but these muscle function gains did not translate to sport-specific tasks (land jump height and foot speed), and it was unclear if water jump height improved due to training or familiarization. There was evidence of increased isokinetic PT and PP (~9% each between Pre2 and Post), and FMP (52%) and FPP (47%) for the FSP test (Table 1). Also, the FMP and FPP parameters increased during the first 2-3 weeks of the training sessions (Figure 3). The relatively greater gains in the FSP measurements vs. the isokinetic (seated knee extension) variables reflects the high specificity of the FSP test to the training modality. These findings align with the outcome of a meta-analysis that determined that maximal concentric muscle power experienced the greatest increase out of all outcomes after a period of flywheel training (Maroto-Izquierdo, García-López, Fernandez-Gonzalo, et al., 2017). Further, the substantial increases in peak and mean muscle power are supported by the findings of Fernandez-Gonzalo et al. (2014), which showed a similar increase (to the present results) in concentric power using an inclined leg press test for men and women (46 – 56%) in untrained students who performed 4 sets of 7 reps of seated squat training on a Multi-Gym flywheel device for six weeks (inertia 0.140 $kg \cdot m^2$). The collegiate club water polo population in this study achieved equally as large of gains in concentric power in only four weeks as the untrained population in the Fernandez-Gonzalo et al. (2014) study did in six weeks. This demonstrates the high reserve of potential for muscle function gains in the collegiate club water polo population in a short time period (accomplished in only 8 training sessions).

In a separate RCT with professional handball players highly experienced with resistance training, the experimental group trained with 4 sets of 7 reps on a flywheel leg press at an inertia of 0.145 kg·m^2, and the control group trained with a leg press on a traditional weight-stack machine for six weeks (Maroto-Izquierdo, García-López, & de Paz, 2017). Utilizing a 45 degree leg press device to measure maximal power, their findings revealed that only the flywheel group showed significant increases in power ranging from 10 – 21.6% at different loads (from 50%-90% of 1RM). The smaller improvements in their study compared to the current study of 47% and 52% for the FPP and FMP could be due to their study population's higher level of experience with resistance training, but these findings add to the accumulating evidence that short duration flywheel training is effective at increasing muscle power across different populations and levels of training.

In contrast, Norrbrand et al. (2007) compared flywheel training to gravity-dependent weight stack training over a five week period in untrained men and found that power only increased in the weight stack group with no changes in the flywheel group. Notably, their study used a single-joint leg extension exercise for the flywheel training (at an inertial load of .11 kg·m^2) as compared to multiple-joint training modes used in the present and aforementioned studies (de Hoyo et al., 2015; Fernandez-Gonzalo et al., 2014; Maroto-Izquierdo, García-López, & de Paz, 2017; Norrbrand et al., 2011). Therefore, the discrepancy of the Norrbrand et al. (2007) findings compared to the present study and other studies (de Hoyo et al., 2015; Fernandez-Gonzalo et al., 2014; Maroto-Izquierdo, García-López, & de Paz, 2017; Norrbrand et al., 2011) could be due to training mode-specific differences in flywheel-induced gains, such that multiple-joint, complex training movements for the flywheel appear to produce enhanced gains relative to single-joint isolation movements for the lower body. However, as flywheel training studies are still limited, more work is needed to substantiate this conclusion.

Despite the flywheel training-induced increases in peak torque and power, there were minimal to no improvements in the sport-specific parameters. The only time trial effect was seen for WJH between Pre1 and Post (ES = .4), however, this does not warrant concluding there were real training-induced changes given there was no change between the Pre2 vs. Post trials (because the Pre1 phase includes the non-training control period). There were also no improvements in peak foot speed or CMJ. The reason for this lack of change in the sport-specific performances despite large gains in lower body power is unknown. However, we postulate two potential explanations for this rather non-intuitive outcome.

First, the flywheel squat movement may not have optimally utilized or trained the stretch-shortening cycle. The amortization phase is an essential part of the stretch-shortening cycle and is dependent first on the ability of the subject to decelerate in the eccentric phase. With flywheel training exercises, the goal is to decelerate the load in a relatively narrow window so that the kinetic energy can be dissipated in a shorter period of time leading to greater muscular stretch and overload (Tesch et al., 2017). However, doing so may prolong and/or disrupt the natural and rapid execution of the amortization phase, which could be sub-optimal for training the stretch-shortening cycle particularly as it functions for unloaded sport-specific tasks (i.e., CMJ). This may help explain why the CMJ in the present study was unaffected by the flywheel training. In a systematic review, Vicens-Bordas et al. (2018) compared the effects of flywheel training and gravity-dependent resistance training on jumping performance and found that the flywheel group achieved relatively better gains on depth jumps that require a longer stretch-shortening cycle, whereas the non-flywheel group showed better gains on a 4-jump test that utilizes a faster stretch-shortening cycle. These data appear to suggest the principle of specificity is in operation with flywheel training in regards to stretch-shortening cycle tasks. Thus, the training-associated adaptations elicited gains for basic muscle function characteristics but may not have transferred either as quickly or directly to dynamic functional maneuvers that rely heavily on the stretch shortening cycle in the present type of training.

A second potential explanation for the lack of sport-specific performance improvements from flywheel training may be that a 4-week training period was not enough time to elicit gains in functional measures such as water and land jumping. Longer training periods may be needed to translate large gains in muscle power to more technical tasks, as there may be a delayed adaptive response for improvements of more technical movements.

A novel aspect of the current study was the assessment of sport-specific performance in the water. Sport-specific training for water polo players involves predominantly water-based activities, which has different demands on the body compared to the land-based CMJ (due to unloading, water resistance in all directions, etc). Thus, the club water polo players may have been more unfamiliar with performance demands on land compared to a different cohort of elite youth soccer players who showed a 7.6% improvement in their CMJ after 10 weeks of flywheel squat and leg curl training (de Hoyo et al., 2015). However, these youth soccer players were highly experienced with land-based training parameters, had a longer training period (10 weeks) and used greater inertial resistances (either .220 kg·m^2 or .440 kg·m^2, selecting the one that gave highest power output), so that may also explain their improvements versus the lack of improvements in the present study.

The WJH assessment may exhibit a lack of specificity to the flywheel squat, as the aquatic environment exhibits unique characteristics (hydrostatic pressure, temperature, and biomechanical differences) and there is no weight-bearing activity, and no eccentric or amortization phase as the need to stay afloat requires constant leg movement. The improvement from Pre1 to Post (Figure 5) may be due to the effects of learning as demonstrated by the slightly greater percent changes and effect sizes between Pre1 and Pre2 versus Pre2 and Post (1.9%, ES = .24; 1.2%, ES = .17 respectively). Although water polo athletes should, in theory, be accustomed to treading and jumping activities in water, the assessment of their jump height in water involving a modified Vertec tester with a jump and reach maneuver may have been a particularly unfamiliar water-based task. This method of testing has been used in a few previous studies (Platanou, 2006; Saez de Villarreal et al., 2014), but it appears that improvements in jump height from the Pre1 to Post test trials were not a consequence of training and the Pre1 and Pre2 trials likely served as practice for the subjects to learn to perform the test better. Thus, future studies may require further familiarization with the WJH testing protocol.

The present findings revealed a correlation between peak foot speed and maximum WJH with peak foot speed accounting for 48% of the variance in WJH (Figure 7). WJH also correlated with years of experience (44% of variance accounted for by years of experience), based on the idea that greater years of experience should yield better treading biomechanics. Sanders (1999a) analyzed potential determinants of WJH in water polo players and found that foot speed was modestly correlated with WJH ($r = .55$, $P < .05$) and accounted for 30% of the variance in height. Those with higher WJH maintained high maximum foot speeds over a longer period of time during the kick by emphasizing the anteroposterior and mediolateral directions. Sanders (1999a) found that in order to improve WJH, athletes should focus on more effective foot positions by improving plantar- and dorsi-flexion and moving the feet in more curved paths. The implication that optimal lower body mechanics should improve WJH was confirmed by Gobbi et al. (2013) who found that expert players (with at least 6 years of resistance training experience) produced significantly higher values of force, power, velocity, and WJH compared to intermediate players (with between one and 6 years of resistance training experience). The authors mentioned motor unit recruitment as a potential limit in the ability of intermediate players to produce power, postulating that expert players have greater motor control and thus recruit MUs more rapidly for propulsion due to their greater resistance training experience and neural adaptations. Although the peak foot speed and WJH measures did not improve from flywheel training, the correlation found between peak foot speed and WJH (Figure 7) and years of experience with WJH (Figure 8) may provide useful information for future water polo training studies. Perhaps training with more sport-specific exercises to directly improve foot speed and biomechanics in the water combined with resistance training to improve force and power production may more effectively improve WJH performance. Research studies examining mixed training models combining sport-specific aquatic-based exercises with flywheel resistance training are needed to help elucidate the most effective strategies to improve water polo sport skills.

The VAS scores demonstrated that soreness was greatest at the second session (due to the initial session), but largely tapered off by session 3 (Figure 4). It appears that once the athletes became accustomed to the exercise and training loads their soreness decreased, but their flywheel power production capabilities increased above baseline by session 4 and remained elevated for the rest of the training sessions. Even though the men tended to show relatively higher soreness than the women, the data demonstrates that neuromuscular adaptations were effectively achieved and that soreness likely only impacted the results to a small degree, if at all. However, it is still curious as to whether or not the inertial load in the present study was optimal. In all studies that used greater or equal inertias relative to the present study in seated or standing flywheel squats (de Hoyo et al., 2015; Fernandez-Gonzalo et al., 2014; Maroto-Izquierdo, García-López, & de Paz, 2017; Norrbrand et al., 2011), none examined soreness as an outcome measure. The literature is limited in regards to the effects of flywheel training loads on muscle soreness and the associated consequences on various muscle function and performance outcome measures. In fact, only three studies have investigated the effects of low, medium, and high inertial loads on lower extremity force, power, and work characteristics using flywheel leg extension (Martinez-Aranda & Fernandez-Gonzalo, 2017; Sabido et al., 2018) and flywheel squat (Carroll et al., 2018), yet they also did not report soreness. Thus future work is needed that is focused on elucidating optimal inertial loads for different parameters (power, force, velocity) with flywheel squat training and models of load progression throughout the course of a training period as well as how loads and progressions affect muscle soreness.

CONCLUSION

This investigation revealed that four weeks of flywheel squat training in collegiate club water polo players elicited large gains in flywheel specific squat power (47%). However, these gains did not transfer to land- or water-based sport-specific performance measures including CMJ, WJH, or foot speed. It is likely that more time and/or sport-specific movements utilizing natural stretch-shortening cycle characteristics are needed to elicit greater gains in these sport-specific parameters. For water polo players, water-based specificity exercises are likely needed for marked sport skill improvements, and perhaps these could be combined with an effective resistance training program such as the flywheel model used in the present study. Further, examination of longer-term training effects using training studies longer than 6 weeks would be warranted to provide a better understanding of the potential adaptations and improvements when given a longer time frame. We conclude that flywheel training is effective for inducing basic muscle function improvements but more work is needed to determine how these gains may be incorporated into combination training programs for maximal efficacy in functional performances, especially for water-based athletes.

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Table 1. Mean (SD) and Cohen’s d effect size values for all strength and power tests.

Variables	Pre1	Pre2	Post	Cohen’s d Pre2-Post	Cohen’s d Pre1-Post
Quadriceps PT	84.8 (23.5)*	92.6 (21.8)	101.3 (26.1)	.36	.67
Quadriceps PP	338.2 (103.9)*	376.5 (98.7)	409.7 (114.5)	.31	.65
FPP	653.2 (216.6)*	586.5 (187.3)*	861.4 (312.1)	1.1	.79
FMP	276.4 (116.5)*	258.5 (99.9)*	392.8 (168.6)	1.0	.82

PT = isokinetic peak torque at 240 $°s\cdot^{-1}$; PP = isokinetic peak power at 240 $°s\cdot^{-1}$, FPP = flywheel peak concentric power, FMP = flywheel mean power. * denotes significantly different from post-test at $P < .05$

Figure Legends

Figure 1. Experimental setup for water jump height (WJH) test.

Figure 2. Camera view for the foot speed test.

Figure 3. Flywheel peak power (FPP) and flywheel mean power (FMP) values for sessions 2, 4, 6, and 8 of the training sessions. Values are means ± SEM. N = 11 for these variables. * denotes significantly different from Session 2.

Figure 4. Visual analog scores (VAS) soreness scores for the total combined values and men and women groups shown separately. There was a distinction made between the men and women for this variable because they had different inertial loads for training sessions. Soreness assessments of the lower body were taken after performing the warm-up air squats prior to the flywheel squats for each session. Error bars not included for clarity. (Note only 8 subjects are used for the session 1 soreness which was done before the start of the training program; N = 13 for sessions 2 – 8). Data values represent total combined VAS scores.

Figure 5. Scatterplot showing the absolute (cm) change scores for maximum water jump height (WJH) between the Pre1, Pre2 and Post test trials. The black horizontal bars represent the mean change scores, *denotes significant difference.

Figure 6. Scatterplots showing (a) absolute change scores in peak foot speed and (b) peak foot speed raw data values across testing trials. The black horizontal bars represent the mean values.

Figure 7. Correlation between peak foot speed (average of peak foot speeds across all 3 test sessions) and water jump height (average of maximum WJH across all 3 test sessions). $P < .01$

Figure 8. Correlation between years of experience and water jump height (WJH), calculated as the average of maximum WJH across all 3 test sessions. $P < .01$

Figure 1. WJH test

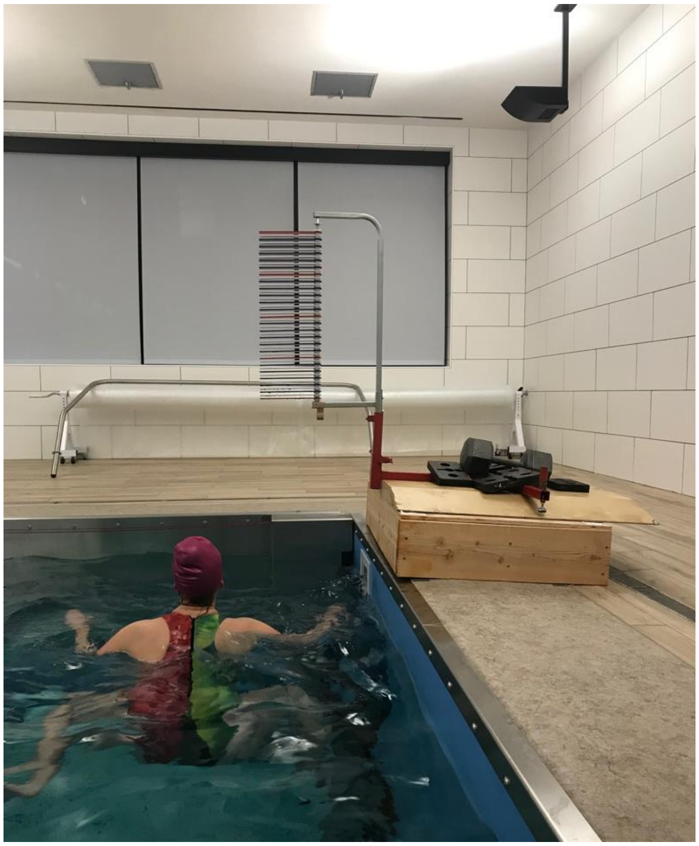

Figure 2. Foot speed testing

Figure 3. Power output during training sessions

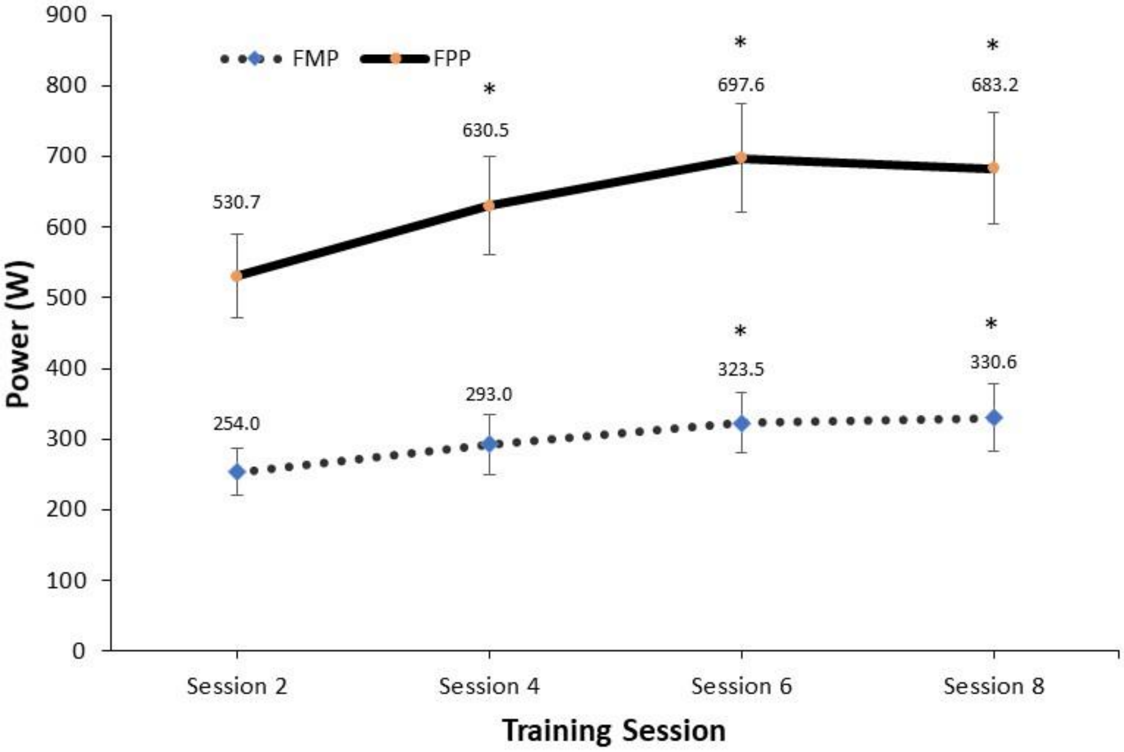

Figure 4. Soreness levels across training sessions

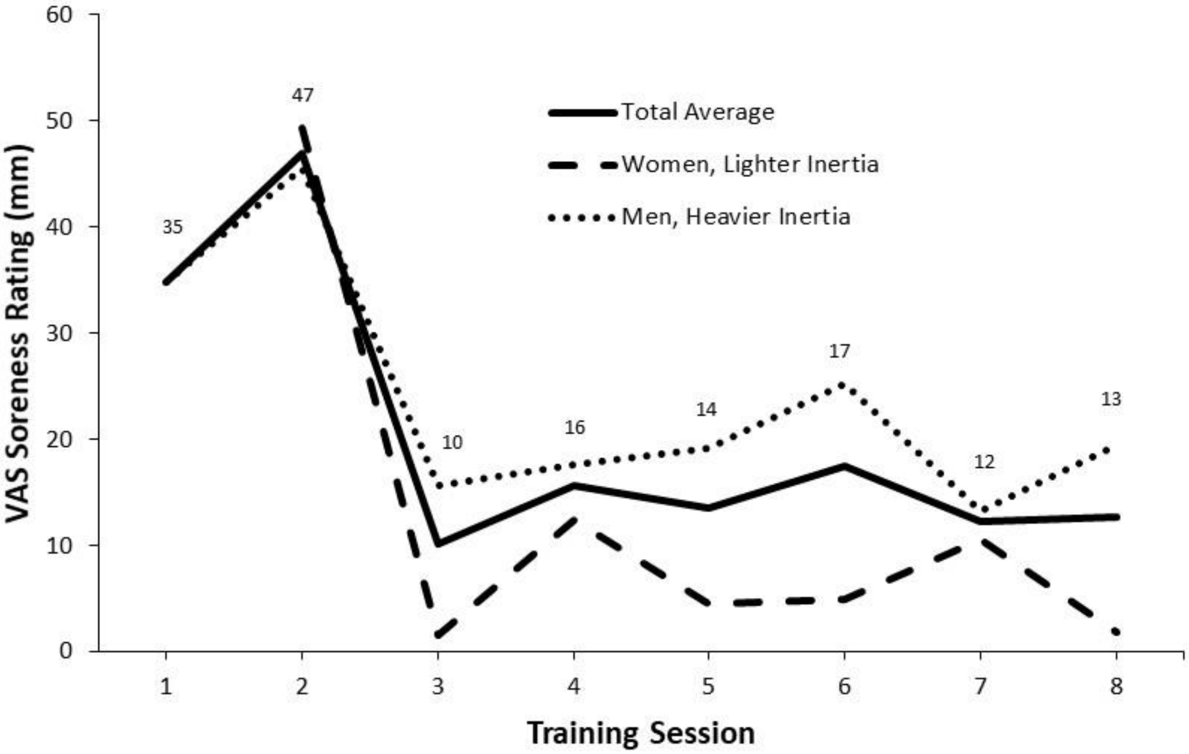

Figure 5. Change scores in WJH between testing sessions

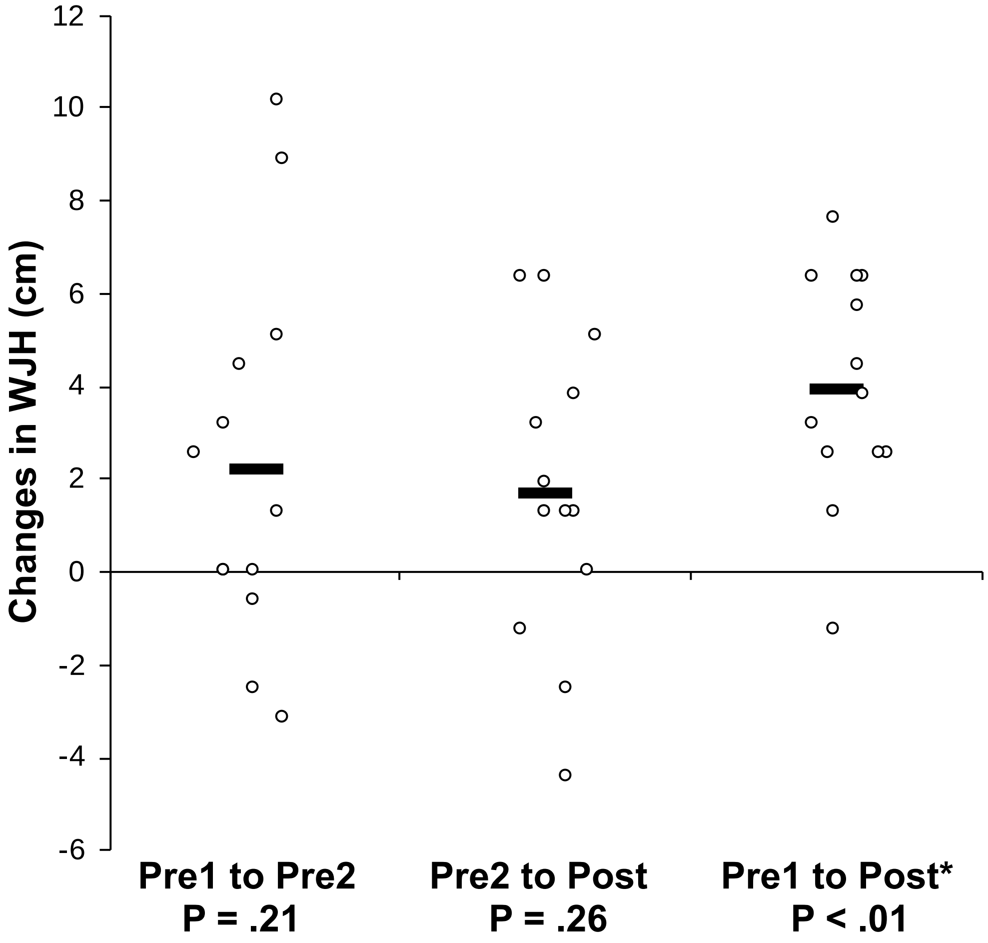

Figure 6. a. Change scores in peak foot speed, b. Peak foot speed values

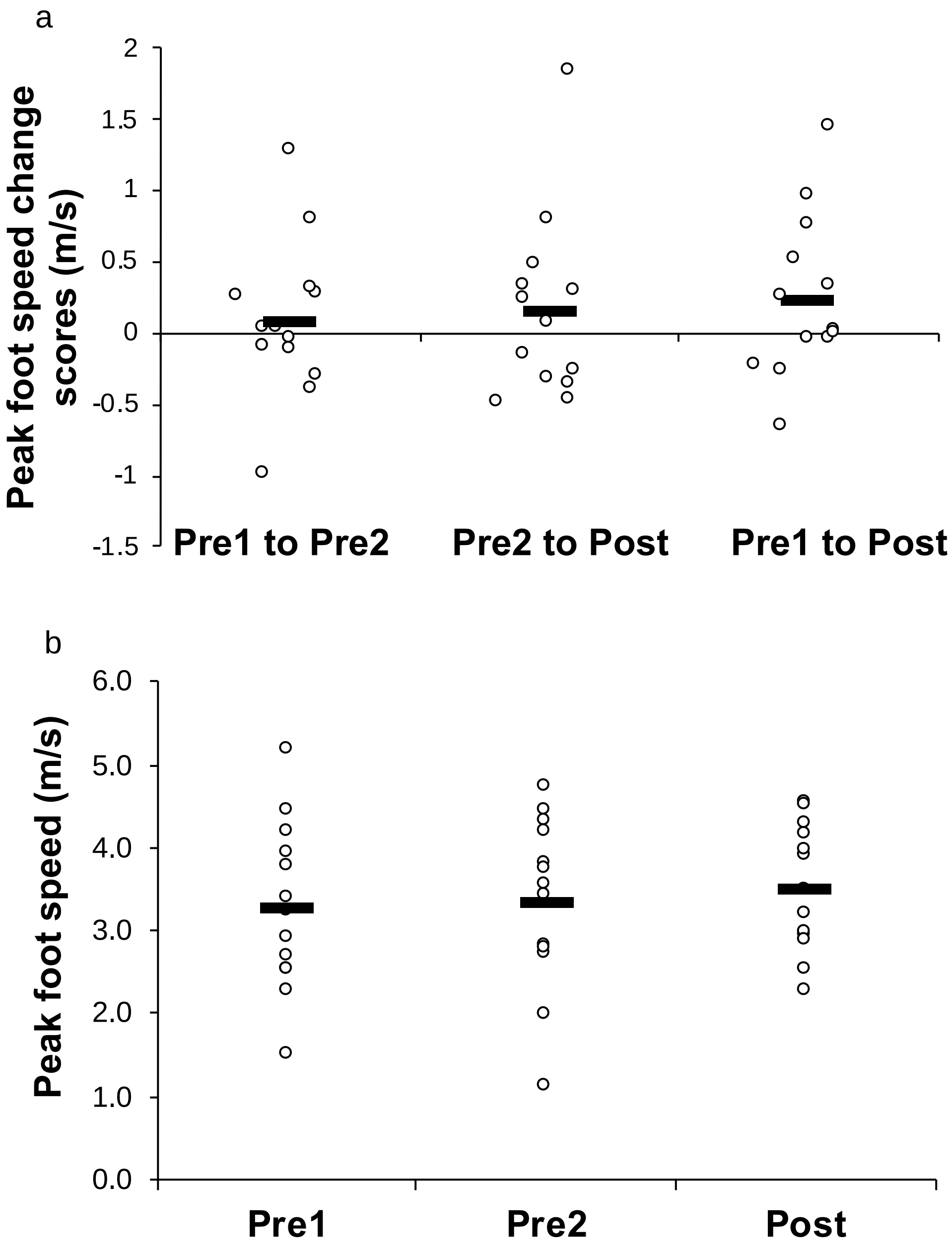

Figure 7. Correlation between peak foot speed and WJH

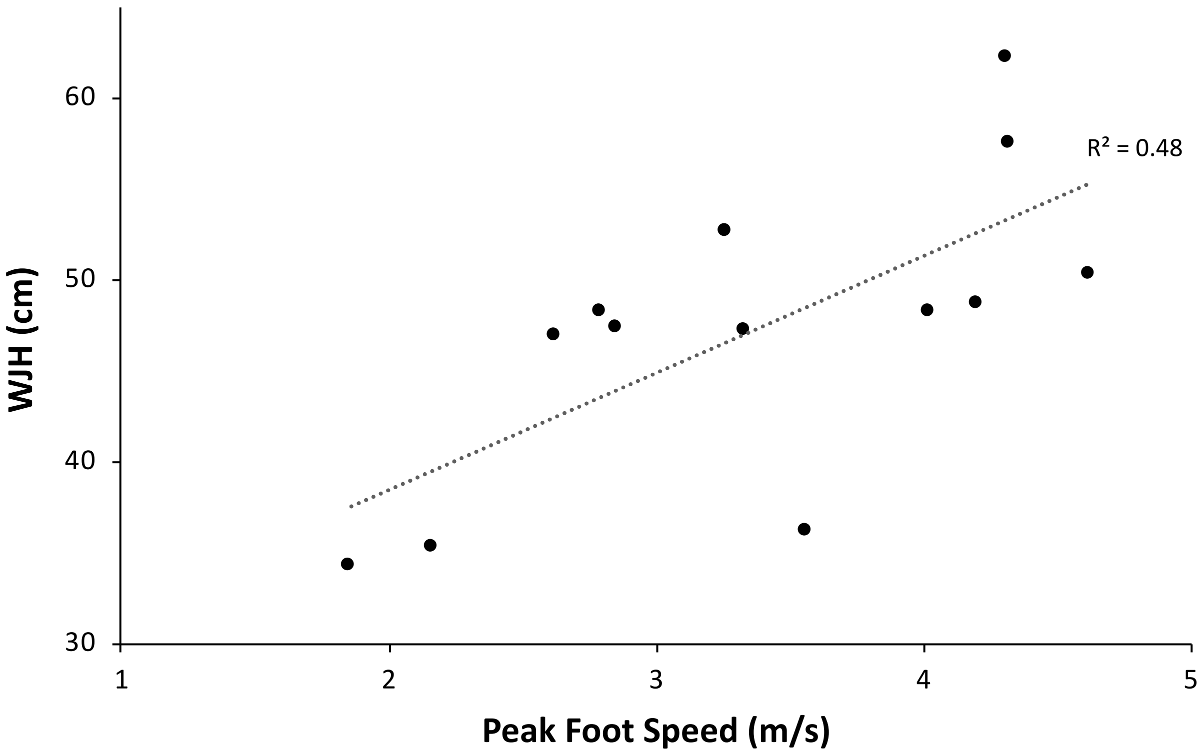

Figure 8. Correlation between years of experience and WJH