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Research article

Muscle Architectural and Force-Velocity Curve Adaptations following 10 Weeks of Training with Weightlifting Catching and Pulling Derivatives

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Abstract

The aims of this study were to examine the muscle architectural, rapid force production, and force-velocity curve adaptations following 10 weeks of resistance training with either submaximal weightlifting catching (CATCH) or pulling (PULL) derivatives or pulling derivatives with phase-specific loading (OL). 27 resistance-trained men were randomly assigned to the CATCH, PULL, or OL groups and completed pre- and post-intervention ultrasound, countermovement jump (CMJ), and isometric mid-thigh pull (IMTP). Vastus lateralis and biceps femoris muscle thickness, pennation angle, and fascicle length, CMJ force at peak power, velocity at peak power, and peak power, and IMTP peak force and force at 100-, 150-, 200-, and 250 ms were assessed. There were no significant or meaningful differences in muscle architecture measures for any group ($p > 0.05$). The PULL group displayed small-moderate ($g = 0.25 - 0.81$) improvements in all CMJ variables while the CATCH group displayed trivial effects ($g = 0.00 - 0.21$). In addition, the OL group displayed trivial and small effects for CMJ force ($g = -0.12 - 0.04$) and velocity variables ($g = 0.32 - 0.46$), respectively. The OL group displayed moderate ($g = 0.48 - 0.73$) improvements in all IMTP variables while to PULL group displayed small-moderate ($g = 0.47 - 0.55$) improvements. The CATCH group displayed trivial-small ($g = -0.39 - 0.15$) decreases in IMTP performance. The PULL and OL groups displayed visible shifts in their force-velocity curves; however, these changes were not significant ($p > 0.05$). Performing weightlifting pulling derivatives with either submaximal or phase-specific loading may enhance rapid and peak force production characteristics. Strength and conditioning practitioners should load pulling derivatives based on the goals of each specific phase, but also allow their athletes ample exposure to achieve each goal.

Key words: Weightlifting, Olympic weightlifting, countermovement jump, isometric-mid thigh pull, force-velocity profile, rate of force development.

Introduction

One of the most common movements in sports is the triple extension of the hip, knee, and ankle (plantar flexion) joints. This movement is frequently performed during general sport tasks such as jumping, the acceleration phase of sprinting, change of direction, striking, kicking, throwing, and tackling movements; key musculature that contributes to these movements includes the vastus lateralis (VL) and biceps femoris (BF). Due to the frequent contribution of these muscles to sport tasks, strength and conditioning practitioners may prescribe various training stimuli (e.g., high-volume training, eccentric training, etc.) to target muscle thickness (MT), pennation angle (PA), and/or fascicle length (FL) adaptations, which may enhance an athlete's force production characteristics (e.g., magnitude and rate). Researchers have shown that MT and cross-sectional area are moderately-largely (r = 0.32 - 0.85) correlated with force production magnitude (Bazyler et al., 2017; Cormie et al., 2011; Suchomel and Stone, 2017) while moderate relationships (r = 0.34 - 0.44) exist between PA and rapid force production characteristics (Gerstner et al., 2017; Maffiuletti et al., 2016; Zaras et al., 2016). Moreover, Kawakami and Fukunaga (2006) indicated that FL directly relates to the force-velocity characteristics of pennate muscles, with longer fascicles resulting in a higher velocity. A variety of training protocols have been used to examine the impact of resistance training on muscle architectural changes (Kawakami, 2005); however, many of them have programmed only single-joint exercises such as elbow flexion or extension to isolate individual muscles. While these training programs may provide insight into the individual muscles, complete resistance training programs typically are not comprised of single-joint exercises when training for sport (Duehring et al., 2009; Ebben et al., 2004; Ebben et al., 2005; Simenz et al., 2005). While some researchers have examined changes in muscle architecture and performance following training with large muscle, multi-joint exercises (Aagaard et al., 2001; Cormie et al., 2010; Hoffman et al., 2022), the training programs focused on either high volume training (Aagaard et al., 2001) or included either a single exercise (Cormie et al., 2010) or exercise type (e.g., ballistic) (Hoffman et al., 2022). Due to the mechanistic nature of muscle architecture and its potential impact on force production characteristics, additional research is needed to determine the effect of different training stimuli on MT, PA, and FL adaptations.

Weightlifting movements and their derivatives have been shown to induce positive strength-power adaptations when compared to other methods of training (Hoffman et al., 2004; Otto III et al., 2012; Teo et al., 2016; Tricoli et al., 2005). However, it is important to note that several of the previous studies programmed only weightlifting movements with a squatting variation as the only non-weightlifting exercise within the training programs instead of implementing them within a well-rounded resistance training program that includes more exercises (Otto III et al., 2012; Teo et al., 2016; Tricoli et al., 2005). While these studies may have sought to examine the specific training stimulus

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of weightlifting movements, their ecological validity may be lacking given that strength and conditioning practitioners often combine a variety of exercises within their training programs (Duehring et al., 2009; Ebben et al., 2004; Ebben et al., 2005; Simenz et al., 2005). Moreover, it is important from a practical standpoint to understand how the combined training effects of weightlifting movements and traditional exercises impact strength-power performance adaptations. While more recent studies have combined both weightlifting derivatives and traditional exercises within their training programs (Comfort et al., 2018; Suchomel et al., 2020a; Suchomel et al., 2020b), there is a lack of research that has examined the combined training effects on muscle architectural adaptations and how those changes may relate to changes in strength-power performance.

Researchers have indicated that weightlifting pulling derivatives (i.e., those that exclude the catch phase) may provide a similar (Comfort et al., 2011a; Comfort et al., 2011b; Comfort et al., 2018) or greater strength-power training stimulus (Kipp et al., 2021; Kipp et al., 2018; Suchomel et al., 2020a; Suchomel et al., 2020b; Suchomel and Sole, 2017a; Suchomel and Sole, 2017b; Suchomel et al., 2014d) when compared to catching derivatives (i.e., those that include the catch phase). The latter findings have been attributed to the ability of weightlifting pulling derivatives to provide a greater force or velocity overload stimulus by allowing athletes to use loads in excess of their one repetition maximum (1RM) or exercises that are more ballistic in nature (e.g., jump shrug and hang high pull) (Suchomel et al., 2017; Suchomel et al., 2015b). While weightlifting exercises are primarily programmed to elicit neural adaptations that benefit strength-power performance, it is possible that the training adaptations elicited by weightlifting pulling derivatives may also be attributed to alterations in muscle architecture. Furthermore, when combined with traditional exercises, it is possible that these adaptations may be magnified due to the recruitment of larger motor units that is typical with heavy and/or ballistic exercises (Aagaard et al., 2002; Andersen and Aagaard, 2006). Therefore, the purpose of this study was to examine the muscle architectural, rapid force production, and force-velocity curve adaptations following 10 weeks of resistance training that included traditional resistance training exercises and either submaximal weightlifting catching or pulling derivatives or pulling derivatives with phase-specific loading. It was hypothesized that MT, PA, and FL adaptations would be specific to each group based on the exercise and load combinations prescribed. The authors would like to acknowledge that the data from the present study and previous studies (Suchomel et al., 2020a; Suchomel et al., 2020b) are related and were collected as part of the same project. However, the authors felt that the muscle architecture, countermovement jump (CMJ), and isometric mid-thigh pull (IMTP) data needed to be presented separately to provide a more thorough analysis of underpinning physiological characteristics while also respecting word, figure, table, and reference limits of the previous journals, and not overwhelming readers with large datasets.

Methods

Design

A repeated measure, between-group design was used to examine the differences in force-velocity characteristics and VL and BF muscle architecture following resistance training programs that used weightlifting catching or pulling derivatives. Participants trained three times per week for 10 weeks and were assessed prior to the training intervention and again after training was completed (Figure 1). Changes in MT, PA, and FL were assessed using a portable ultrasound device while CMJ force and velocity at peak power and IMTP force data were assessed using force plates.

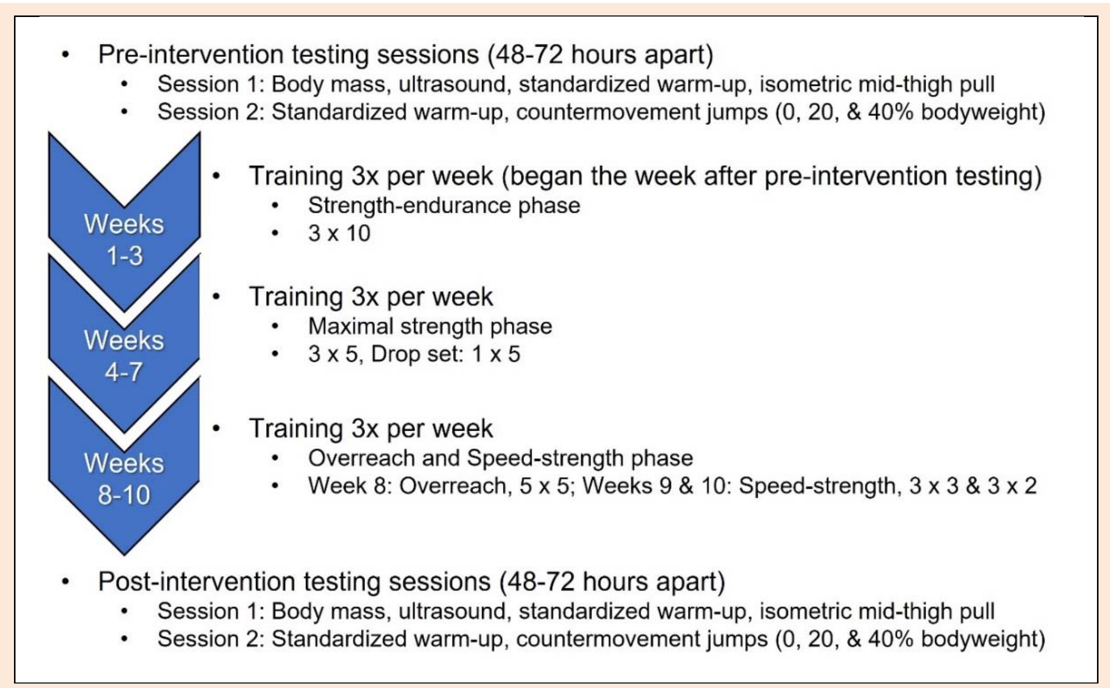

Figure 1. Pre- and post-intervention testing sequence. Modified from Suchomel et al. (2020b).

Participants

Twenty-nine male NCAA Division III athletes and resistance-trained men with previous power clean experience were recruited to participate in this study. Each participant was randomly assigned to one of three groups that included either weightlifting catching derivatives ([CATCH], n = 9, age = 22.8 ± 3.6 years, body mass: 85.8 ± 13.4 kg, height: 1.81 ± 0.06 m, power clean [PC] experience: 7.2 ± 3.7 years, relative one repetition maximum [1RM] PC: 1.20 ± 0.16 $kg \cdot kg^{-1}$, relative 1RM back squat: 1.75 ± 0.40 $kg \cdot kg^{-1}$), pulling derivatives ([PULL], n = 9, age = 22.2 ± 2.3 years, body mass: 84.3 ± 17.3 kg, height: 179.6 ± 3.7, PC experience: 6.4 ± 2.4 years, relative 1RM PC: 1.19 ± 0.18 $kg \cdot kg^{-1}$, relative 1RM back squat: 1.73 ± 0.17 $kg \cdot kg^{-1}$), or pulling derivatives that used phase-specific loading ([OL], n = 9, age = 22.3 ± 1.2 years, body mass: 83.0 ± 13.6 kg, height: 173.4 ± 9.3, PC experience: 6.4 ± 1.8 years, relative 1RM PC: 1.25 ± 0.15 $kg \cdot kg^{-1}$, relative 1RM back squat: 1.76 ± 0.32 $kg \cdot kg^{-1}$). It should be noted that two participants voluntarily withdrew from the study, one because of an injury sustained outside of the study, and the other due to a desire to train more than three days per week. Each participant completed 100% of the training sessions. In addition, each participant read and signed a written informed consent form, in accordance with the university's institutional review board (#17-017) prior to any participation in the study.

G*Power (version 3.1.9.2) (Faul et al., 2007) was used to perform an *a priori* power analysis to determine the necessary number of participants needed to display moderate effect sizes (Hedge's $g \geq 0.50$) between groups. Based on a previous study (Cormie et al., 2010), it was determined that at least 24 participants were needed at a power level of 0.90 and an *a priori* alpha level of ≤ 0.05.

Procedures

Pre- and post-intervention testing was completed over two testing sessions separated by 48 - 72 hours as discussed in a previous study (Suchomel et al., 2020a). This was done to decrease the volume of tests completed each day and to accommodate the schedules of the participants. An overview of the testing and training is displayed in Figure 1. The participants completed the post-intervention testing sessions with the same time between sessions as the two pre-intervention testing sessions (e.g., 48 hours between sessions). The participants were required to have a minimum of 48 hours of recovery prior to their testing sessions and all testing sessions took place within two hours of the participants' pre-intervention testing sessions to account for changes in Circadian rhythm. The time between the final training session and first post-intervention testing session was chosen based on taper recommendations (Bazyler et al., 2018; Bosquet et al., 2007). For consistency, the participants performed the same standardized warm-up prior to each testing session (Suchomel et al., 2019).

Ultrasonography

Prior to performing the warm-up and subsequent performance tests, linear measurements of the participant's right VL and BF muscles were assessed using a linear probe scanning head with a 4 - 15 MHz bandwidth range (uSmart 15L4, 3200T, Terason, Burlington, MA, USA) at an image depth of 5 cm and the gain set to 50 dB. The probe was coated with a water-soluble transmission gel (Aquasonic 100 ultrasound transmission gel, Parker Laboratories, Inc., Fairfield, NJ, USA) and positioned on the surface of the skin to provide acoustic contact without depressing the dermal layer to collect an image. For the VL measurements, participants laid on an athletic training table on their left side with their legs together and relaxed with 15° of knee flexion as measured by a manual goniometer (Reardon et al., 2014). For the BF measurements, participants laid in a prone position with their feet hanging off the end of the athletic training table. The anatomical location for all ultrasound measurements was standardized for all participants. VL measurements were taken at 50% of the distance between the greater trochanter and the lateral condyle of the tibia. BF measurements were taken at 50% of the distance between the ischial tuberosity and the posterior aspect of the fibular head. Three images were captured at each site during both the pre- and post-intervention testing sessions. The images were exported to and analyzed using ImageJ software (Wayne Rasband National Institute of Health, Bethesda, MD, USA). MT was measured as the vertical distance between the superficial and deep aponeuroses at the center of each image (Nimphius et al., 2012). The PA was measured as the angle between the fascicle and the deep aponeurosis (McMahon et al., 2015). Finally, FL was calculated by dividing the MT by the Sin of the PA. (Kawakami et al., 1995). The average measurements between the three images were used for statistical comparison. To account for differences in body and muscle size, and allow for normal data distribution, all muscle architectural data were log transformed (Nevill and Holder, 1995).

Countermovement jump assessment

Each participant performed unloaded (polyvinyl chloride [PVC] pipe weighing <1 kg) and loaded (20 and 40% of body mass) CMJ trials on dual force plates (PASPORT, PASCO Scientific, California, USA) sampling at 1000 Hz. The PVC pipe or barbell was positioned across their upper back during each CMJ. Prior to performing maximal effort CMJ trials, each participant performed warm-up CMJ trials at 50 and 75% of their perceived maximum effort with both a PVC and 20 kg barbell. Following the warm-up jumps, the participants performed two maximal effort jumps each with the PVC pipe and with 20 and 40% of their body mass, which was measured at the beginning of each testing session. The loads were performed in a randomized order and the order was kept consistent for each participant during the pre- and post-intervention testing sessions. The participants were cued to jump as fast and as high as possible. After a quiet standing period on the force plates of at least one second, the participants received the same countdown of "3, 2, 1, Jump!" Following the countdown, the participants performed a countermovement to a self-selected squat depth and without pausing, jumped as high as possible. One minute of rest was provided between jumps and between loads. The average performance of both jumps was used for statistical analysis.

Isometric mid-thigh pull assessment

Pre- and post-intervention IMTP testing was completed using methodology previously described by Beckham et al. (2013). Participants were positioned within an adjustable IMTP rig (Kairos Strength, Murphy, NC, USA) and an immovable barbell (Werksan Olympic Bar, Werksan, Moorestown, NJ, USA) was positioned at a height that replicated the beginning of the second pull phase of the clean. Based on previous recommendations, the knee and hip angles ranged between 125 - 135° and 140 - 150°, respectively (Comfort et al., 2019). The knee and hip angles for each participant were recorded during the pre-intervention testing session and replication post-intervention testing session. The hands of each participant were strapped and taped to the barbell to prevent grip from being a limiting factor, in line with previous research (Beckham et al., 2013). After receiving countdown instructions, each participant performed two submaximal IMTP efforts, with the first being performed at 50% of their perceived maximal effort and the second at 75% one minute later. After two minutes of rest, each participant performed two maximal effort IMTPs separated by two minutes. The participants were cued to pull "as fast and as hard as possible" and "push through the floor." Prior to the IMTP trials, the participants positioned their feet on the dual force plates (PASPORT force plate, PASCO Scientific, CA, USA) located under the stationary barbell. The participants were then cued to get into their previously measured starting position and remove any slack from their arms. After the proper body position was achieved and force was stable (verified by visual inspection), the participant received the countdown "3, 2, 1, Pull!" IMTP trials lasted for approximately five seconds while strong verbal encouragement was provided. Two maximal effort IMTP trials were performed with two minutes of rest between trials. An additional trial was performed if a difference of more than 250 N existed between trials, or a visible countermovement was performed prior to the pull (Beckham et al., 2013; Comfort et al., 2019). Vertical ground reaction forces were sampled at 1000 Hz and the average performance between IMTP trials was used for statistical analysis.

Training intervention

Each group trained three days per week for 10 weeks under the supervision of a certified strength and conditioning coach using a program outlined in the related studies mentioned above (Suchomel et al., 2020a; Suchomel et al., 2020b). Like previous studies (Suchomel et al., 2013; Suchomel et al., 2015a; Suchomel et al., 2014d) the weightlifting catching and pulling derivatives performed within each training program were programmed based on the 1RM power clean achieved during the pre-intervention testing session. Furthermore, the participants were coached throughout the training intervention using the technique described in previous literature (DeWeese and Scruggs, 2012; DeWeese et al., 2013; DeWeese et al., 2012; Suchomel et al., 2014a; Suchomel et al., 2014b; Suchomel et al., 2014c). The non-weightlifting derivative exercises (e.g., back squat, bench press, bent-over row, etc.) were programmed based on the heaviest loads lifted, sets, and repetitions performed prior to the study, as reported by the participants. Using this information, the 1RM and relative loads of each non-weightlifting derivative were determined using set-repetition best as previously outlined (DeWeese et al., 2015; DeWeese et al., 2014; Suchomel et al., 2021). The 1RM for each non-weightlifting derivative was recalculated throughout the study using the loads performed within the participants' training program. Finally, cluster sets of five repetitions with 30-40 seconds of intra-set rest were used based on previous recommendations (Hardee et al., 2013) when weightlifting derivatives were prescribed within the strength-endurance phase of training (3 sets of 10 repetitions). As noted in the previous studies (Suchomel et al., 2020a; Suchomel et al., 2020b), the CATCH group performed a weightlifting catching derivative during each session that a weightlifting derivative was prescribed, while the PULL and OL groups performed weightlifting pulling derivatives that were biomechanically similar (e.g., CATCH = hang power clean; PULL and OL = hang high pull). The CATCH and PULL groups used the same relative intensity (i.e., percentage of 1RM power clean) throughout the study while the OL group performed their derivatives with either a force or velocity overload stimulus, using either heavier (e.g., CATCH = mid-thigh power clean at 50% 1RM; OL = mid-thigh pull at 120% 1RM) or lighter loads (e.g. CATCH = hang power clean at 60% 1RM; OL = jump shrug at 20% 1RM), respectively. Weightlifting pulling derivatives that are more ballistic in nature (e.g., jump shrug) were also used to provide a velocity overload stimulus (Suchomel and Sole, 2017a; Suchomel and Sole, 2017b; Suchomel et al., 2014d).

Data analyses

Unfiltered force-time data during the CMJ and IMTP tests were measured using a laptop computer and specialist software (PASCO Capstone, PASCO Scientific, CA, USA). Unfiltered data were used for analysis since low-pass filters may not be required for accurate CMJ analyses (Harry et al., 2020) or may underestimate IMTP kinetics (Dos' Santos et al., 2018). CMJ and IMTP force-time data were exported and analyzed within customized spreadsheets in Microsoft Excel (Microsoft Corp., Redmond, WA, USA). The force-time data were integrated to generate velocity-time curves and power-time curves were calculated using the product of force and velocity data at each time point. The propulsion phase of each CMJ trial was identified as the instant where velocity first exceeded 0.01 $m \cdot s^{-1}$ following the onset of the jump. Peak power was then identified as the greatest power output value produced during the propulsion phase of each CMJ trial. The corresponding force and velocity magnitudes produced at peak power were recorded and used for force-velocity curve analyses. After subtracting each participant's body mass in Newtons, IMTP peak force was identified as the greatest force recorded using the force-time data (i.e., net force). IMTP peak force and a velocity magnitude of zero were used within the force-velocity curve analyses. Rapid force production characteristics produced during the IMTP were assessed by recording the net force produced at 100-, 150-, 200-, and 250 ms following the onset of each IMTP attempt. The onset of each IMTP was determined by using a threshold of five times the standard deviation of the participant's body weight recorded over one second during the countdown to start the IMTP test (Dos' Santos et al., 2017). Relative CMJ force at peak power and peak power output at each load and IMTP force at 100-, 150-, 200-, and 250 ms and peak force were calculated by dividing each value by each participant's body mass that was recorded during each testing session.

Statistical analyses

The Shapiro-Wilk test was used to assess data normality while Levene's test was used to assess the heterogeneity of variance between groups. Relative and absolute test-retest reliability for all dependent variables were assessed using two-way mixed intraclass correlation coefficients (ICC) and typical error expressed as a coefficient of variation percentages (CV%) with 95% confidence intervals, respectively. Relative reliability coefficients were interpreted as poor (< 0.50), moderate (0.50 - 0.74), good (0.75 - 0.90), and excellent (> 0.90) (Koo and Li, 2016). Within-session variability was deemed acceptable when CV% was <10% (Cormack et al., 2008). A series of 2 (time) x 3 (group) repeated measures ANOVA with Bonferroni *post hoc* tests were used to examine the MT, PA, and FL, CMJ force at peak power, velocity at peak power, and peak power, and IMTP force at 100-, 150-, 200-, and 250 ms and peak force differences within and between the CATCH, PULL, and OL groups. Statistical significance was identified when the p-value was ≤0.05. Hedge's *g* effect sizes were calculated to determine the magnitude of any differences within and between each group. Because the current participants qualified as 'highly trained' status (i.e., individuals training for at least five years) (Rhea, 2004), effect sizes were interpreted as trivial, small, moderate, and large when magnitudes were < 0.25, 0.25 - 0.49, 0.50 - 1.0 and >1.0, respectively. SPSS (Version 26, IBM, New York, NY, USA) was used to perform all statistical tests.

Results

All muscle architecture, CMJ, and IMTP data were normally distributed and demonstrated similar variance within each group. Good to excellent (ICC = 0.78 -0.99) reliability with acceptable variability (CV% = 0.3 - 9.3%) was shown for each testing session for each group.

Muscle architecture

Pre- and post-intervention VL and BF muscle architecture data are displayed in Table 1. There were no significant or meaningful time, group, or time x group interaction effects for VL MT (p = 0.223, p = 0.318, p = 0.140), FL (p = 0.838, p = 0.285, p = 0.515), or PA (p = 0.646, p = 0.881, p = 0.545). Similarly, there were no significant time, group, or time x group interaction effects for BF MT (p = 0.165, p = 0.167, p = 0.641), FL (p = 0.332, p = 0.166, p = 0.804), or PA (p = 0.644, p = 0.636, p = 0.611).

Countermovement jump

Pre- and post-intervention CMJ data are displayed in Table 2. There were no significant time (p = 0.172, p = 0.479, p = 0.217), group (p = 0.728, p = 0.757, p = 0.799), or time x group interaction (p = 0.116, p = 0.183, p = 0.408) effects for F_{PP} during the 0, 20, or 40% bodyweight CMJ conditions, respectively. There were however significant time effects for V_{PP} at 0, 20, and 40% bodyweight (p = 0.008, p = 0.011, p = 0.006); although, there were no significant group (p = 0.995, p = 0.988, p = 0.957) or time x group interaction (p = 0.701, 0.129, 0.401) effects. *Post hoc* analysis indicated that post-intervention group-averaged V_{PP} was significantly greater than pre-intervention V_{PP} at 0 (p = 0.008), 20 (p = 0.011), and 40% (p = 0.006) bodyweight. There were significant time effects for PP at 0, 20, and 40% bodyweight (p = 0.004, p = 0.009, p = 0.003), respectively. In addition, there was a significant time x group interaction effect at 20% bodyweight (p = 0.042). However, there were no significant group (p = 0.905, p = 0.988, p = 0.963) effects across all loads or time x group interaction effects at 0 (p = 0.279) or 40% (p = 0.167) bodyweight. *Post hoc* analysis indicated that post-intervention group-averaged PP was significantly greater than pre-intervention PP at 0 (p = 0.004), 20 (p = 0.009), and 40% (p = 0.003) bodyweight; however, there were no significant differences in PP between groups (p = 1.000).

Table 1. Vastus lateralis (VL) and biceps femoris (BF) muscle architecture descriptive data.

Variable		CATCH		PULL		OL	
		Pre	Post	Pre	Post	Pre	Post
VL MT	Mean	1.22	1.24	1.23	1.30	1.18	1.16
	SD	0.09	0.12	0.12	0.09	0.17	0.24
	g	0.18		0.63		-0.09	
VL FL	Mean	2.31	2.26	2.26	2.32	2.17	2.18
	SD	0.19	0.23	0.16	0.19	0.19	0.25
	g	-0.23		0.33		0.04	
VL PA	Mean	2.98	3.04	3.04	3.05	3.08	3.06
	SD	0.26	0.26	0.17	0.19	0.28	0.36
	g	0.22		0.05		-0.06	
BF MT	Mean	1.33	1.27	1.18	1.18	1.20	1.13
	SD	0.15	0.15	0.19	0.21	0.16	0.22
	g	-0.38		0.00		-0.35	
BF FL	Mean	2.92	2.77	2.72	2.65	2.62	2.60
	SD	0.28	0.39	0.36	0.42	0.30	0.19
	g	-0.42		-0.17		-0.08	
BF PA	Mean	2.47	2.56	2.52	2.58	2.64	2.58
	SD	0.23	0.36	0.30	0.26	0.24	0.22
	g	0.28		0.20		-0.25	

Muscle thickness (MT), fascicle length (FL), and pennation angle (PA) measurements were log transformed. SD = standard deviation; *g* = Hedge's *g* effect size magnitudes.

Isometric mid-thigh pull

Pre- and post-intervention IMTP data are displayed in Table 3. There was a significant time effect for IMTP F_{100} (p = 0.024), F_{150} (p = 0.045), and PF (p = 0.002), but not for F_{200} (p = 0.065) or F_{250} (p = 0.119). There were no significant group effects for IMTP F_{100} (p = 0.717), F_{150} (p = 0.832), F_{200} (p = 0.883), F_{250} (p = 0.820), or PF (p = 0.268). Finally, there was a significant time x group interaction effect for IMTP F_{250} (p = 0.020) and PF (p = 0.005), but not for F_{100} (p = 0.383), F_{150} (p = 0.177), F_{200} (p = 0.052). *Post hoc* analysis indicated that post-intervention group-averaged F_{100} (p = 0.024), F_{150} (p = 0.045), and PF (p = 0.002) were greater compared to pre-intervention values. Additional *post hoc* analyses indicated that there were no significant differences in IMTP F_{250} or PF between groups during the pre-intervention (p = 0.848, p = 0.775) or post-intervention (p = 0.271, p = 0.065) testing sessions.

Table 2. Descriptive countermovement jump data for each group.

Variable		CATCH		PULL		OL	
		Pre	Post	Pre	Post	Pre	Post
FPP0 ($N \cdot kg^{-1}$)	Mean	21.8	22.1	21.9	22.7	22.8	22.6
	SD	1.6	1.4	2.3	2.4	1.9	2.6
	g	0.19		0.32		-0.08	
VPP0 ($m \cdot s^{-1}$)	Mean	2.47	2.52	2.43	2.54	2.43	2.54
	SD	0.30	0.25	0.17	0.12	0.25	0.20
	g	0.17		0.71		0.46	
PP0 ($W \cdot kg^{-1}$)	Mean	54.0	55.7	53.3	58.0	55.6	57.4
	SD	8.7	6.8	8.1	8.4	7.7	8.4
	g	0.21		0.54		0.21	
FPP20 ($N \cdot kg^{-1}$)	Mean	24.0	24.0	23.6	24.2	24.7	24.4
	SD	1.7	1.4	2.6	2.0	2.1	2.6
	g	0.00		0.25		-0.12	
VPP20 ($m \cdot s^{-1}$)	Mean	2.33	2.34	2.26	2.40	2.31	2.38
	SD	0.22	0.25	0.20	0.12	0.21	0.19
	g	0.04		0.81		0.33	
PP20 ($W \cdot kg^{-1}$)	Mean	56.0	56.2	53.5	58.3	57.1	58.2
	SD	7.2	7.6	9.7	7.4	7.9	8.9
	g	0.03		0.53		0.12	
FPP40 ($N \cdot kg^{-1}$)	Mean	25.7	25.8	25.2	26.0	26.2	26.3
	SD	1.8	1.6	2.3	2.2	2.2	2.9
	g	0.06		0.34		0.04	
VPP40 ($m \cdot s^{-1}$)	Mean	2.14	2.18	2.09	2.21	2.11	2.17
	SD	0.19	0.22	0.17	0.12	0.19	0.17
	g	0.19		0.78		0.32	
PP40 ($W \cdot kg^{-1}$)	Mean	55.2	56.4	52.8	57.6	55.3	57.1
	SD	7.3	7.4	8.5	7.8	7.3	8.9
	g	0.16		0.56		0.21	

SD = standard deviation; F_{PP} = force at peak power; V_{PP} = velocity at peak power; PP = peak power; Pre = pre-intervention; Post = post-intervention; *g* = Hedge's *g* effect size magnitude

Table 3. Descriptive isometric mid-thigh pull data for each group.

Variable		CATCH		PULL		OL	
		Pre	Post	Pre	Post	Pre	Post
F100 ($N \cdot kg^{-1}$)	Mean	18.2	19.1	17.1	19.9	17.8	22.8
	SD	5.8	5.6	5.0	4.8	6.9	8.0
	g	0.15		0.54		0.64	
F150 ($N \cdot kg^{-1}$)	Mean	23.0	22.5	21.8	24.7	22.0	26.7
	SD	5.8	5.5	6.0	5.2	7.6	7.7
	g	-0.08		0.49		0.59	
F200 ($N \cdot kg^{-1}$)	Mean	26.0	24.5	24.8	27.9	24.6	28.4
	SD	5.5	4.9	5.2	5.7	7.8	7.3
	g	-0.27		0.54		0.48	
F250 ($N \cdot kg^{-1}$)	Mean	27.4	25.2	26.3	28.8	25.8	29.7
	SD	5.4	5.3	4.5	5.6	7.0	7.3
	g	-0.39		0.47		0.52	
PF ($N \cdot kg^{-1}$)	Mean	36.7	35.6	38.5	42.0	37.3	42.2
	SD	5.2	5.7	5.1	6.9	6.2	6.6
	g	-0.19		0.55		0.73	

All values are net relative force (ratio scaled by body mass). SD = standard deviation; F_{100} = force at 100 ms; F_{150} = force at 150 ms; F_{200} = force at 200 ms; F_{250} = force at 250 ms; PF = peak force; *g* = Hedge's *g* effect size magnitude

Force-velocity curves

The pre- and post-intervention force-velocity curves of the CATCH, PULL, and OL groups are displayed in Figure 2, Figure 3, and Figure 4, respectively. Despite visible shifts in force and velocity characteristics for both the PULL and OL groups, there were no significant or meaningful differences in force-velocity curves for either group based on the overlap of the 95% confidence intervals.

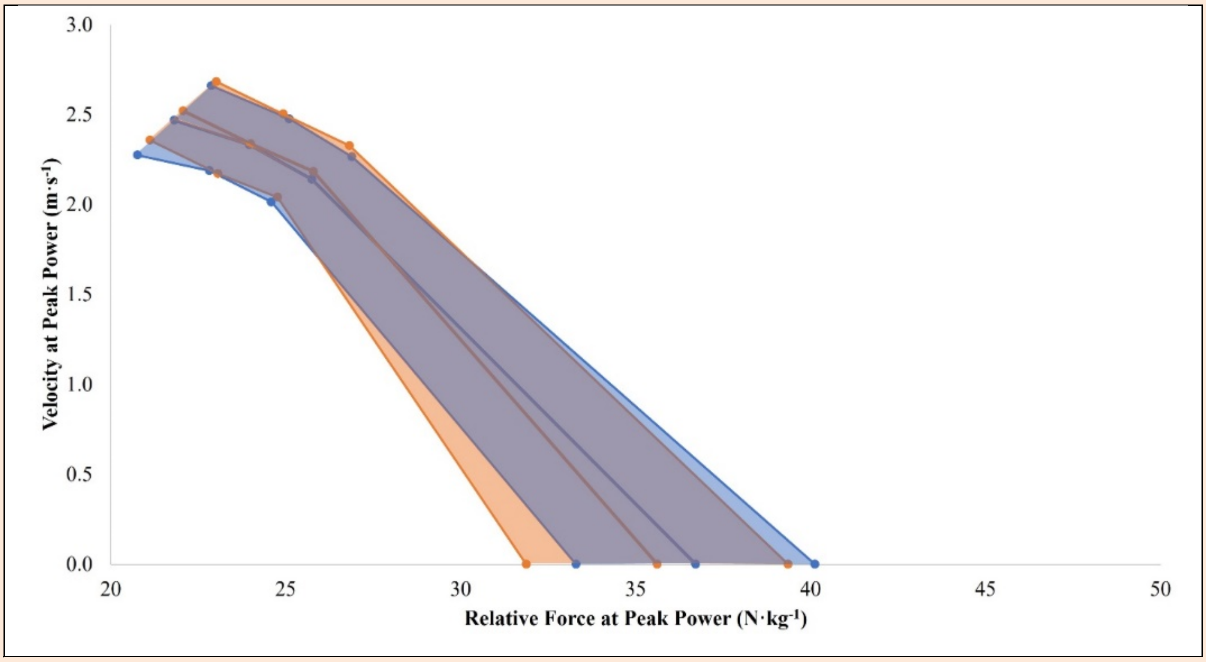

Figure 2. CATCH group pre- (Blue) and post-intervention (Orange) force-velocity curves with 95% confidence intervals.

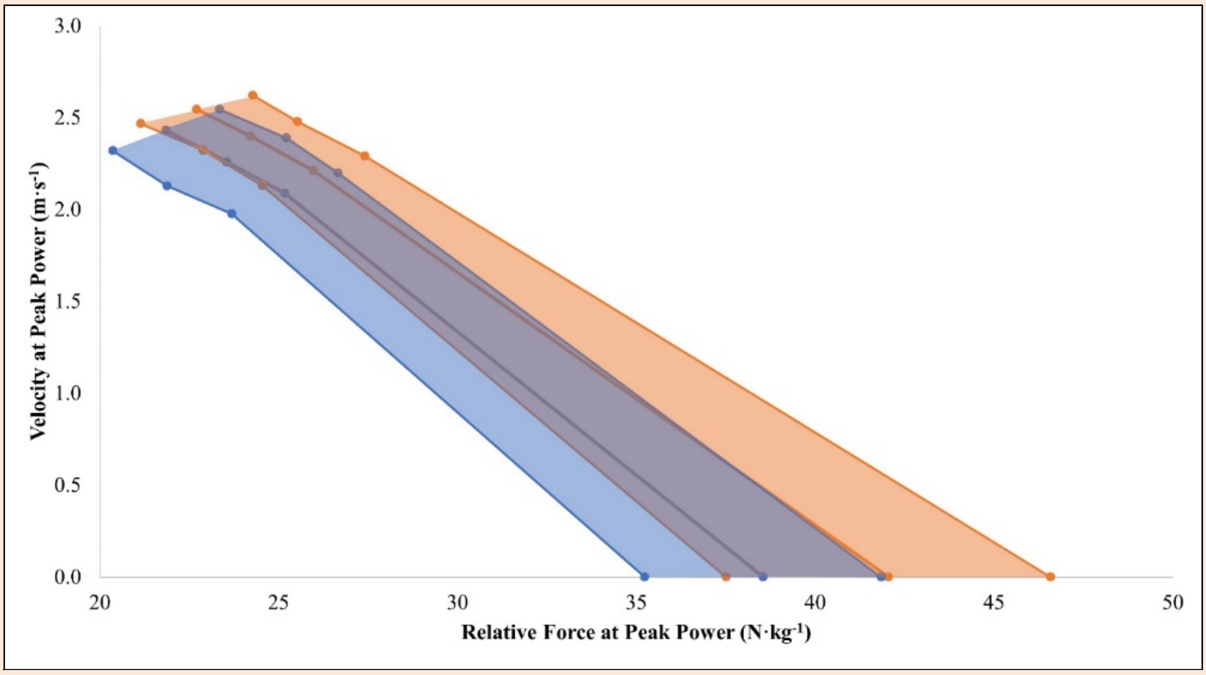

Figure 3. PULL group pre- (Blue) and post-intervention (Orange) force-velocity curves with 95% confidence intervals.

Discussion

The aim of this study was to examine the effect of training with weightlifting catching and pulling derivatives on the muscle architecture, rapid force production, and force-velocity curves of resistance-trained men. The findings of the study are fourfold. First, apart from VL MT for the PULL group (moderate effect), only trivial-small effects existed for all other VL and BF muscle architecture measures and the changes were not unique to each training group. Second, the most notable changes in CMJ performance were displayed by the PULL group who displayed small-moderate improvements in F_{PP}, V_{PP}, and PP across all loads examined (0, 20, 40% bodyweight) while the CATCH and

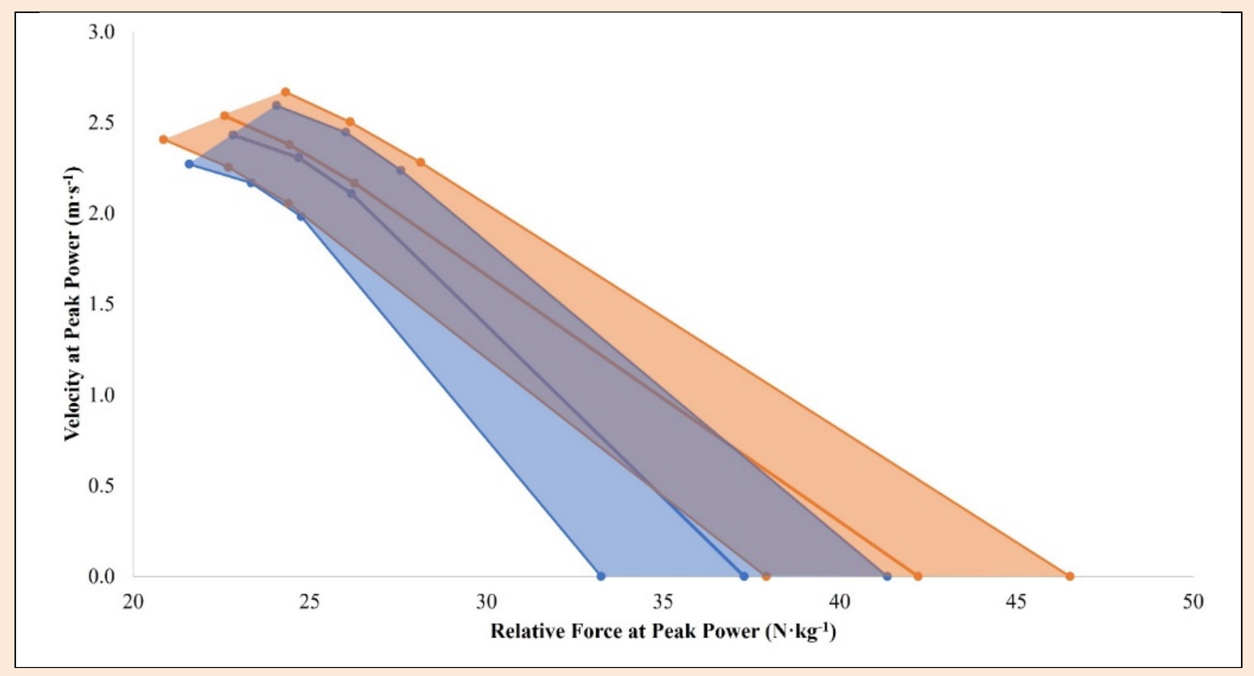

Figure 4. **OL group pre- (Blue) and post-intervention (Orange) force-velocity curves with 95% confidence intervals.**

OL groups displayed trivial and trivial-small changes, respectively. Third, the OL group displayed the greatest increases in rapid force production and peak force during the IMTP (moderate effects). This was followed by the PULL (small-moderate) and CATCH (trivial-small) groups. Finally, despite visible shifts in the force-velocity curves of the PULL and OL groups, the changes were not significant or meaningful.

The training groups in the current study displayed primarily trivial-small changes in VL and BF MT, PA, and FL. As a result, it is reasonable to conclude that the pre- to post-intervention muscle architectural changes (or lack thereof) did not contribute to the CMJ and IMTP performance adaptations shown by each group. The findings of the current study contrast with previous research that has shown positive changes in muscle architecture and strength-power performance adaptations (Aagaard et al., 2001; Cormie et al., 2010). However, it is important to note that the training programs and participants in the previous studies were much different than the current study. For example, Aagaard et al. (2001) included a minimum number of 30 repetitions per exercise within a single session. Moreover, 3 - 4 other exercises targeting similar muscle groups were also performed within each session. Therefore, it could be argued that the previous training programs almost exclusively targeted muscle hypertrophy while the training program in the current study included different training emphases. For example, weeks 1-3, 4-8, and 9-10 emphasized strength-endurance, general strength, and strength-speed/speed-strength, respectively. In another study, Cormie et al. (2010) showed increases in VL MT and PA following a resistance training program that exclusively implemented heavy back squats for 10 weeks. These changes occurred concurrently with enhanced force, velocity, power, and force-velocity profile improvements. However, it should be mentioned that the participants in the previous study were relatively weak (relative back squat: 1.28 ± 0.17 $kg \cdot kg^{-1}$) compared to those within the current study and thus, direct comparisons cannot be made. Moreover, it is highly likely that weaker athletes will demonstrate much greater increases in strength compared to those who are already strong (James et al., 2018; Suchomel et al., 2016). To the authors' knowledge, this is the first study to compare muscle architectural changes between resistance training programs that included either weightlifting catching or pulling derivatives. Thus, future researchers should consider examining the impact of different weightlifting derivative programs on muscle architectural changes to make more direct comparisons.

Unique CMJ F_{PP}, V_{PP}, and PP adaptations were displayed by each of the training groups. The PULL group displayed the greatest increases across all variables, followed in order by the OL and CATCH groups. These results support our previous findings in relation to CMJ force-time characteristics (Suchomel et al., 2020b). Despite increases in F_{PP}, only trivial-small changes existed within each group, whereas larger changes occurred with V_{PP} and PP. The reason behind these benefits may be based on the loading used within the PULL group's training program. For example, many of the implemented pulling derivatives were submaximally-loaded throughout the duration of the study. That is, the prescribed exercises may be loaded with much heavier loads as evidenced by the OL group's training program and additional literature that has examined supramaximal loads with various pulling derivatives (Comfort et al., 2015; Comfort et al., 2012; Haff et al., 2003; Meechan et al., 2020a; Meechan et al., 2022; Meechan et al., 2020b). This is an important consideration as performing these exercises with lighter loads will not only allow athletes to mimic CMJ movement patterns (Kipp et al., 2019), but also allow them to perform movements at faster velocities. In contrast, the V_{PP} adaptations shown by the OL group may be the result of the consistent use of heavy (some supramaximal relative to their 1RM power clean) loads for much of their training program (8 weeks) whereas only two weeks (weeks 9-10) included the use of lighter loads with pulling derivatives. Despite moving heavy loads with ballistic intent, the velocities of the movements were likely much slower than the PULL group, which may have led to a slower propulsion phase of the CMJ. This is supported by our previous study that showed a small increase in propulsion phase time with the OL group (Suchomel et al., 2020b). It should be noted that the duration of the training program may have negatively impacted the ability to provide a greater velocity overload stimulus with the OL group. It is possible that an additional training block (3-4 weeks) focused on speed-strength may have allowed the exercise and load combinations prescribed to allow for greater velocity adaptations to occur. As evidenced by the exposure of the PULL group to higher velocity movements with submaximal pulling derivatives, further research on this topic is needed.

Based on effect sizes (Table 3), the OL group demonstrated the greatest IMTP force production adaptations with similar, but slightly smaller magnitudes shown by the PULL group. Given the consistent prescription of heavy and supramaximally-loaded (relative to the 1RM power clean) exercises within the OL training program, it should not be surprising that this group produced the greatest IMTP PF adaptations. However, it is interesting that this method of prescription also allowed this group to achieve the greatest increases in rapid force production. While all groups performed weightlifting derivatives within their respective training programs, which are ballistic/semi-ballistic exercises, the OL training program added the aspect of moving heavy loads with ballistic intent. These findings are supported by researchers that indicated that a high load phase of training led to greater increases in rapid force production (50-, 100-, 150-, 200-, and 250 ms) compared to a moderate load phase (Comfort et al., 2022). However, some researchers have shown that consistent light load training with ballistic exercises may also enhance rapid force production (Cormie et al., 2010; McBride et al., 2002; Winchester et al., 2008). In fact, similar effect size magnitudes (Cohen's d = 0.46 - 0.58) in IMTP rapid force production and peak force were displayed in another study that used submaximally-loaded pulling derivatives (Comfort et al., 2018). Despite the improvements in IMTP rapid force production and PF with the OL and PULL groups, it is important to discuss the lack of improvement by the CATCH group. While previous work has shown small improvements in dynamic strength (1RM PC), sprint, and change of direction performance within the CATCH group (Suchomel et al., 2020a), positive performance enhancements during the IMTP were not apparent in the current study. This may be explained by following: first, as shown in previous research (Suchomel and Sole, 2017a), it is possible that deceleration at the end of the triple extension phase of the catching derivatives diminished the rapid force production stimulus provided to the participants throughout the study; second, the baseline rapid force production characteristics of the CATCH group were highest amongst the training groups albeit with trivial differences; third, it is possible that changes in 1RM PC were due to changes in technique rather than force production characteristics.

Researchers have shown that an individual's force-velocity curve may shift based on the type of training performed (Cormie et al., 2010; James et al., 2022; James et al., 2018). For example, Cormie and colleagues (2010) displayed unique shifts in force-velocity curves for groups who completed 10 weeks of training using either heavy back squats (improved forces) or light jump squats (improved velocities) during three sessions per week. In addition, James et al. (2018) showed force-velocity curve shifts with stronger and weaker training groups following a 10 week training program that included weightlifting derivatives, plyometric movements, and ballistic exercises. While both previous studies noted shifts in their participants' force-velocity curves, neither of them included confidence intervals throughout the entire curve to indicate whether a portion or the whole curve shifted significantly. To the authors' knowledge, the current study is the first to include confidence intervals when examining group force-velocity curve characteristics. Although the force-velocity curves of each group did not shift to a significant extent, visual examination of the curves shows large increases in IMTP force likely contributed to unique shifts in both the PULL and OL groups, whereas little to no shifting occurred with the CATCH group. Weightlifting pulling derivatives allow individuals to use loads exceeding a 1RM catching derivative with certain exercises (e.g., mid-thigh pull, countermovement shrug, etc.) allowing them to achieve greater force production. As noted above, the OL group trained with heavier loads than both the CATCH and PULL groups for most of the study, which likely led to the greatest increases in IMTP PF and a shift in their force-velocity curve. In contrast, it is likely that the use of relatively light loads (based on the prescribed exercises) allowed the PULL group to attain greater velocity characteristics and thus, shift the velocity portion of the curve to the greatest extent.

A potential limitation of this study was the length of the training program. The OL training program was intended to provide both a force- and velocity- overload stimulus using unique exercise and load combinations to target a specific characteristic within each training phase. While this program has been shown to benefit sprint, change of direction, and jump performance (Suchomel et al., 2020a; Suchomel et al., 2020b), much of its focus during the strength-endurance or general strength phases was to provide a force overload via heavier loads. While the current study showed clear benefits in IMTP PF and rapid force production, an entire training phase dedicated to speed-strength – rather than a two-week taper – may have allowed this group to produce greater velocity adaptations. However, this study was restricted in its length based on the academic calendar and the availability of participants. Therefore, future researchers may consider examining the differences in force production characteristics with weightlifting derivatives after both general strength and speed-strength phases of sufficient duration. Although changes in relative 1RM PC strength were discussed in a previous study (Suchomel et al., 2020a), they were not included in the current analysis. If the previous data or another maximal strength test were included (e.g., 1RM squat strength), additional information regarding the changes in force production characteristics may be determined. Finally, the current study used static muscle architecture measures and related the subsequent changes to changes in CMJ performance. While static and dynamic performance characteristics may be related, researchers have indicated that muscle-tendon unit kinematic changes following ballistic training did not coincide with FL changes (Hoffman et al., 2022). This is an important consideration for researchers interested in examining muscle architectural changes in the future.

Conclusion

A 10-week resistance training program with weightlifting pulling derivatives performed with either submaximal (PULL) or phase-specific loading (OL) produced positive CMJ force, velocity, and power adaptations as well as IMTP rapid force production and peak force adaptations. In contrast, the CATCH displayed only trivial changes and trivial-small decreases in their CMJ and IMTP performance, respectively. In addition, despite visible shifts in the force-velocity curves of the PULL and OL groups, these changes were significant or meaningful. The CMJ, IMTP, and force-velocity curve adaptations appeared to occur independently from changes in VL and BF muscle architecture.

From a practical standpoint, pulling derivatives performed with either submaximal or phase-specific loading may allow athletes to enhance their force production characteristics (magnitude and rate). It is recommended that strength and conditioning practitioners load pulling derivatives based on the goals of each specific phase, but also allow their athletes ample exposure to achieve each goal. For example, pulling derivatives that allow for the use supramaximal loads (e.g., mid-thigh pull, countermovement shrug, and pull from the floor) may be used during general or absolute strength phases to enhance an athlete's peak force production (Suchomel, 2020). In addition, pulling derivatives may be implemented with much lighter loads during strength-speed and speed-strength phases that focus on the development of rapid force production and PP. Furthermore, by sequencing these phases of training appropriately, practitioners may allow for the optimal development of an athlete's force production characteristics (DeWeese et al., 2015; Suchomel et al., 2018).

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Key points

- There were no significant or practically meaningful changes in vastus lateralis or biceps femoris muscle thickness, pennation angle, or fascicle length for any group.
- The PULL group produced the greatest CMJ force at peak power, velocity at peak power, and peak power adaptations.
- The PULL and OL groups produced similar benefits in rapid force production; however, peak force adaptations favored the OL group.
- Despite visible shifts in the force-velocity curves of the PULL and OL groups, none of the changes were statistically significant.

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