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Changes in Drop and Repeated Jump Ground Reaction Forces After A 10-Week Offseason Strength and Conditioning Program in Division I American Football Players

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ABSTRACT

The purpose of this study was to examine changes in ground reaction forces during drop jumps (DJs) and repeated jumps (RJs) across a 10-week offseason strength and conditioning program in collegiate Division I American football players. Twenty-two NCAA Division I American football players were recruited for this study, however, a total of n = 19 subjects (mean ± 95% confidence interval, height=186.83±2.66 cm, body mass=102.73±8.79 cm) completed the study. Subjects visited the laboratory twice, once for pre- and once for post-offseason testing. Subjects performed DJs and RJs during each visit. The DJ was performed off a 30 cm box. The RJ protocol consisted of four consecutive jumps. Ground reaction forces were collected during all jumps. Dependent samples t-tests compared changes in DJ metrics, while repeated measures analyses of variance compared changes in RJ metrics. For the DJ, peak braking power, peak propulsive power, mean propulsive force, and jump height increased ($p \leq 0.027$, $d \geq 0.552$). For jump 1 of the RJ, peak braking power increased ($p=0.005$, $d=0.733$). For all jumps of the RJ, peak propulsive power, mean propulsive force, jump height, and reactive strength index increased ($p \leq 0.049$, $\eta^2 \geq 0.134$). This study demonstrated that DJ and RJ performance increased in 10-weeks of strength and conditioning training. Strength and conditioning coaches may benefit from including DJ and RJ assessments to monitor the effectiveness of the strength and conditioning program.

Keywords: vertical jump; force plate; collegiate football

INTRODUCTION

Arguably the most popular collegiate sport in America is American football, comprising a large part of the culture of an institution and the nation. Due to its popularity, many finances and resources have been invested in the growth and success of American football programs, particularly at the collegiate level. Thus, success of the American football program at a given institution tends to be a priority, particularly due to the revenue it tends to generate, demonstrating the need for coaches to maximize performance for their players at the highest level. Previous studies have suggested that vertical jump performance may be one of the largest differences between lower- and higher-level American football players (Fry & Kraemer, 1991; Gillen et al., 2019). Thus, assessments of vertical jump performance may provide practical, accurate methods by which coaches and practitioners may gauge athletic performance for American football athletes, allowing them to better develop their players for on-field success. Commonly, vertical jump performance in collegiate American football players has been assessed via ground reaction forces (GRFs) (Burch et al., 2020; Hoffman et al., 2009; Laffaye et al., 2014; Merrigan et al., 2022; Sha et al., 2021). In fact, in a study interviewing over 100 strength and conditioning professionals, it was concluded that many coaches believe GRF production to be arguably the most important indicator of athletic performance (Luczak et al., 2018). If indeed GRFs are deemed of value for monitoring athletic performance in a strength and conditioning setting, it is imperative to examine this through research studies of the populations commonly seen in these settings. This demonstrates the need for continued examination of GRF assessments in strength and conditioning. However, despite the believed importance of GRFs, there are limited data assessing changes in GRFs during vertical jumps in collegiate American football players.

One of the most common methods of assessing athletic performance from GRFs during vertical jumps is through the countermovement jump technique. Several previous studies have showed that improvements in countermovement jump performance likely reflect improvements in on-field performance, suggesting this method of assessing GRFs may be a useful assessment to determine the efficacy of a strength and conditioning program (Fry & Kraemer, 1991; McGuigan & Winchester, 2008; Merrigan et al., 2022; Petway et al., 2021; Thompson et al., 2013). Most recently, our previous study in Division I American football players showed significant improvements in countermovement jump performance after a 10-week offseason strength and conditioning program (Gillen et al., 2024), demonstrating the usefulness of monitoring vertical jump performance to examine the efficacy of a strength and conditioning program.

Previous studies have suggested that other vertical jump techniques, such as the drop jump (DJ) may provide further information regarding musculoskeletal adaptations to training programs (Barr & Nolte, 2011; Harper et al., 2022; You & Huang, 2022; Young et al., 2002). Specifically, these studies have suggested that DJ and RJ performance may have positive associations and impact on sports performance in soccer, basketball, Australian football, tennis, and rugby. The DJ involves dropping from a predetermined height, hitting the ground and then jumping as quickly as possible. Since American football is a sport that requires rapid storage and utilization of elastic energy during sprinting, change-of-direction, and jumping movements, it stands to reason that the DJ may be a valuable assessment of sport specific adaptations to a strength and conditioning program for this sport. However, although previous studies have examined DJ performance among various sports (Barr & Nolte, 2011; Harper et al., 2022; You & Huang, 2022; Young et al., 2002), we are unaware of any studies to quantify and compare changes in DJ performance in collegiate Division I American football players across a strength and conditioning program.

Beyond the DJ, it could be argued that assessing GRFs during repeated jumps (RJs) may provide further insight into sport specific adaptations for American football. For example, during any given play, most positions have to sprint, change direction, or jump, providing maximal effort repeatedly during the play (Fullagar et al., 2017; Iosia & Bishop, 2008; Jacobson et al., 2013; Wellman et al., 2017). In fact, Iosia and Bishop (2008) found that most plays in collegiate American football games last, on average, between 4.86-5.60 s. Therefore, since the DJ only involves one jump, it may be beneficial to utilize an RJ protocol which better mimics the sport-specific time demands, taking somewhere between 4.0-6.0 s to complete. However, no studies have examined GRFs during RJs in collegiate Division I American football players. Therefore, the purpose of this study was to examine changes in in GRFs during DJs and RJs across a 10-week offseason strength and conditioning program in collegiate Division I American football players.

METHODS

Experimental Approach to the Problem

A repeated-measures design was used to examine the effects of a 10-week strength and conditioning offseason program on DJ and RJ performance in collegiate Division I American football athletes. Each subject visited the laboratory twice, once for pre-offseason testing (last week of May/first week of June) and once for post-offseason testing (last week of July/first week of August). During each visit, subjects performed three attempts of the DJ and the RJ. Variables calculated for the DJ and RJ are presented in Tables 1 and 2, respectively.

Subjects

Previous studies have used samples sizes ranging from n = 9 to n = 29 to examine differences in GRF metrics from vertical jumps (Barr & Nolte, 2011; Gillen et al., 2024; Harper et al., 2022; Neyroud et al., 2017; You & Huang, 2022; Young et al., 2002). Therefore, this study used a convenience sample of twenty-two NCAA Division I American football players were recruited for this study, however, a total of n = 19 subjects (mean ± 95% confidence interval, height = 186.83 ± 2.66 cm, body mass = 102.73 ± 8.79 cm) completed all DJ and RJ assessments before and after the strength and conditioning program. Three subjects did not complete the DJ and RJ assessments at the post-training program assessments. To be included in the present study, subjects must have been on the current academic year's roster, be 18-30-years of age, and had no recent musculoskeletal injuries of the lower extremities. Exclusion criteria included the following: previously diagnosed with a musculoskeletal and/or neurological disease, history of lower extremity musculoskeletal injuries, surgery of the lower extremities during the six months preceding the study, or lower extremity injury within the six months preceding the study. The present study was approved by the Mississippi State University Institutional Review Board. Prior to any data collection, each subject signed the approved consent form.

Procedures

All participants routinely completed the DJ and RJ during their normal training regimen. Prior to data collection, all participants walked on a treadmill for 5-minutes, then completed body weight squats, lunges, and submaximal jumps. Ground reaction forces for all vertical jumps were collected using one force plate (AMTI, AccuGait, Watertown, MA, USA). To perform the DJ, subjects began by standing upright on a 30 cm box (actual drop heights calculated by touchdown velocity ranged from 30.00 – 32.43 cm). Subjects were instructed to drop off the box, land with their feet on the force plate, and perform a maximal vertical jump as fast as possible upon landing. To perform the RJ, subjects began in an upright position with their legs and hips extended. Subjects then performed a rapid countermovement of self-selected depth followed by a maximal vertical jump, and then performed a maximal vertical jump as fast as possible upon landing until a series of four consecutive jumps had been performed. Subjects completed three attempts of each jump type and were instructed to keep their hands on their hips during all attempts. Trials for the DJ and RJ were considered successful as long as participants kept their hands on their hips, they did not flex at the knees during the flight phase, and the feet contacted the force plates for each jump.

During all jumps, the z-axis, vertical ground reaction forces were sampled at 1 kHz using The Motion-Monitor (Innovative Sports Training, Inc., Chicago, IL, USA). All signals were stored on a personal computer and processed off-line with custom written software (LabVIEW v. 2021, National Instruments, Austin, TX, USA). For each DJ attempt, the investigator manually identified a) the initial positive deflection after the subject's free fall, b) the point at which the subject's feet left the force plate (toe off, zero force), and c) the point at which the feet contacted the force plate after the jump (positive deflection above zero force). The following equation was used to calculate the end of the braking phase for each attempt (Bobbert et al., 1987):

$$p_{downward} = \sqrt{\frac{m \cdot g \cdot h}{1/2 \cdot m}} \cdot m$$

Where $p_{downward}$ is the vertical force at the end of the braking phase, m is body mass (kg), g is the acceleration due to gravity ($m \cdot s^{-2}$), and h is drop height (m). The point at which the force signal crossed $p_{downward}$, after the initial peak braking impact force, was considered the start of the propulsive phase ((b) above) (Bobbert et al., 1987). For all jumps, velocity-time tracings were calculated by taking the integral of the force-time curve divided by mass. For each RJ attempt, for the first jump the investigator manually identified (a) the initial onset of movement (always downward, negative force),

(b) the point at which the velocity signal was equal to zero, (c) the point at which the feet left the force plate (toe off, zero force), and (d) the point at which the feet contacted the force plate after the jump (positive deflection above zero force). The second, third, and fourth jumps of the RJs were analyzed identically to the DJs. Power-time tracings were calculated by multiplying the force-time tracing by the velocity-time tracing. Position-time tracings were calculated by taking the integral of the velocity-time tracing. Metrics taken during each phase of the DJ, as well as the second, third, and fourth jumps of the RJ, are presented in Table 1. Metrics taken during the first jump of the RJ are presented in Table 2. Example force tracings for a DJ and RJ can be found in Figures 1 and 2, respectively. For the DJ, the attempt with the highest jump height was used for all comparisons, while for the RJ, the attempt with the highest average jump height across all four jumps was used for all comparisons.

The strength and conditioning program was a rigorous 10-week program, designed and implemented by the Director of Strength and Conditioning for the football program who was a Certified Strength and Conditioning Specialist through the National Strength and Conditioning Association, and Strength and Conditioning Coach Certified through the Collegiate Strength and Conditioning Coaches Association. Pre-offseason testing was performed at the beginning of week 1 and post-offseason testing was performed at the end of week 10. Week 1 only included two days of training and week 10 included only one day of training, which may be considered an introductory week and final testing/recovery week, respectively. Week 6 was considered a recovery week and included a drastic reduction in overall training load and volume. All other weeks included four workouts, with a Monday, Tuesday, Thursday, Friday split. Our previous study provided the strength and conditioning program in detail (Gillen et al., 2024), however, below is a general description of the program.

Table 1. Metrics for the drop jumps and jumps 2, 3, and 4 of the repeated jumps.

Metric	Definition
Braking Phase	
Duration (s)	Time from landing to the bottom of countermovement.
Countermovement Depth (m)	Nadir of the position signal.
Braking Impulse ($N \cdot s \cdot kg^{-1}$)	The integrated area under the braking force-time curve, expressed relative to body mass.
Peak Braking Power ($W \cdot kg^{-1}$)	Peak value of the product of the force and velocity signals from landing to the bottom of countermovement, expressed relative to body mass.
Force at Bottom of Countermovement ($N \cdot kg^{-1}$)	Force at the nadir of the position signal, expressed relative to body mass.
Braking RFD ($N \cdot s^{-1} \cdot kg^{-1}$)	The change in force from landing to the bottom of countermovement divided by duration, expressed relative to body mass.
Mean Braking Force ($N \cdot kg^{-1}$)	The average of the force signal from landing to bottom of countermovement, expressed relative to body mass.
Braking Stiffness ($N \cdot m^{-1}$)	Absolute peak braking force divided by countermovement depth.
Propulsive Phase	
Duration (s)	Time from bottom of countermovement to take-off.
Propulsive Impulse	The integrated area under the propulsive force-time curve.
Peak Propulsive Power ($W \cdot kg^{-1}$)	Peak value of the product of the force and velocity signals from the bottom of countermovement to take-off, expressed relative to body mass.
Mean Propulsive Force ($N \cdot kg^{-1}$)	The average of the force signal from the bottom of countermovement to take-off, expressed relative to body mass.
Performance Metrics	
Jump Height (m)	Calculated using the impulse-momentum method, where jump height equals the velocity at take-off (calculated as net propulsive impulse divided by body mass) squared, divided by the constant acceleration of gravity multiplied by 2.
RSI	Flight time divided by the duration from landing to take-off.

BW = body weight (N), RFD = rate of force development, RSI = reactive strength index

Table 2. Metrics for the jump 1 of the RJ.

Metric	Definition
Unweighting Phase	
Duration (s)	Time from initiation of unweighting to low velocity.
Low Force ($N \cdot kg^{-1}$)	Nadir of the force signal, expressed relative to body mass.
Braking Phase	
Duration (s)	Time from low velocity to bottom of countermovement.
Countermovement Depth (m)	Nadir of the position signal.
Peak Braking Power ($W \cdot kg^{-1}$)	Peak value of the product of the force and velocity signals from low velocity to the bottom of countermovement, expressed relative to body mass.
Force at Bottom of Countermovement ($N \cdot kg^{-1}$)	Force at the nadir of the position signal, expressed relative to body mass.
Braking RFD ($N \cdot s\text{-}1 \cdot kg^{-1}$)	The change in force from low velocity to the bottom of countermovement divided by duration, expressed relative to body mass.
Braking Force ($N \cdot kg^{-1}$)	The change in force from low force to bottom of countermovement, expressed relative to body mass.
Braking Stiffness ($N \cdot m^{-1}$)	Absolute braking force divided by countermovement depth.
Propulsive Phase	
Duration (s)	Time from bottom of countermovement to take-off.
Peak Propulsive Power ($W \cdot kg^{-1}$)	Peak value of the product of the force and velocity signals from the bottom of countermovement to take-off, expressed relative to body mass.
Mean Propulsive Force ($N \cdot kg^{-1}$)	The average of the force signal from the bottom of countermovement to take-off, expressed relative to body mass.
Performance Metrics	
Jump Height (m)	Calculated using the impulse-momentum method, where jump height equals the velocity at take-off (calculated as net propulsive impulse divided by body mass) squared, divided by the constant acceleration of gravity multiplied by 2.
RSI	Flight time divided by the duration from initiation of unweighting to take-off.

BW = body weight (N), RFD = rate of force development, RSI = reactive strength index

For the resistance training portion of the program, all players on the roster, including those subjects who agreed to be a part of the study, warmed up together, focusing on mobility, upper- and lower-body warmups using band exercises, medicine ball throws and slams, as well as plank holds, shrugs, and neck work. After the warmup and mobility training period, all personnel split into two groups: (a) linemen (offensive and defensive) and (b) skill and big skill (all other positions including quarterbacks and specialists) and performed position-specific resistance training routines. Monday and Thursday were primarily lower-body workouts, and included various squat exercises, including variable resistance training methods such as chains, plyometric and step-up exercises, leg presses and curls, lunges, back extensions, and other single-leg, isometric holds, lifts, and balance exercises. Tuesday and Friday were primarily upper-body workouts and included various barbell and dumbbell bench press and overhead press exercises, loaded and unloaded pull-ups, pull downs and rows with various grip techniques, TRX® exercises, and various elbow flexion and extension exercises.

For the speed, acceleration, agility, and conditioning portion of the program, at the beginning of all training sessions all players warmed up together and performed traditional dynamic warm-up exercises. After the warmup, all personnel split into their respective position training groups listed above and performed position-specific speed, acceleration, agility, and conditioning routines. For weeks 1-5, the emphasis of the Monday workout was speed and acceleration, while the emphasis of the Tuesday, Thursday, and Friday workouts was tempo runs and general anaerobic conditioning. For weeks 7-10, the emphasis of the Monday and Thursday workouts was speed and acceleration, while the emphasis of the Tuesday and Friday workouts was general anaerobic conditioning.

Statistical Analysis

Means and 95% confidence intervals for all DJ and RJ metrics were calculated. Dependent samples t-tests were used to compare body mass and

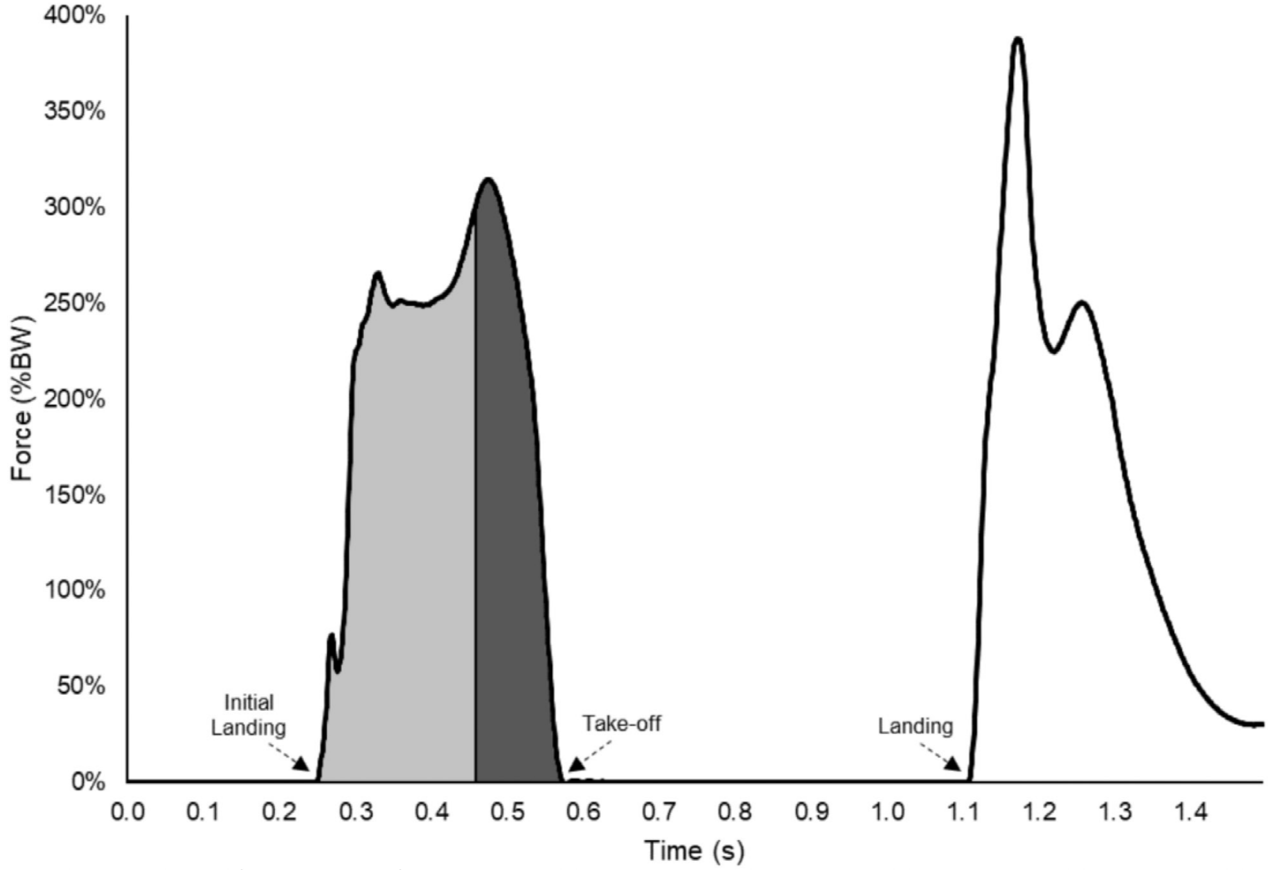

Figure 1. A sample force tracing for a drop jump. The light gray shaded area represents the braking phase and the dark gray shaded area represents the propulsive phase.

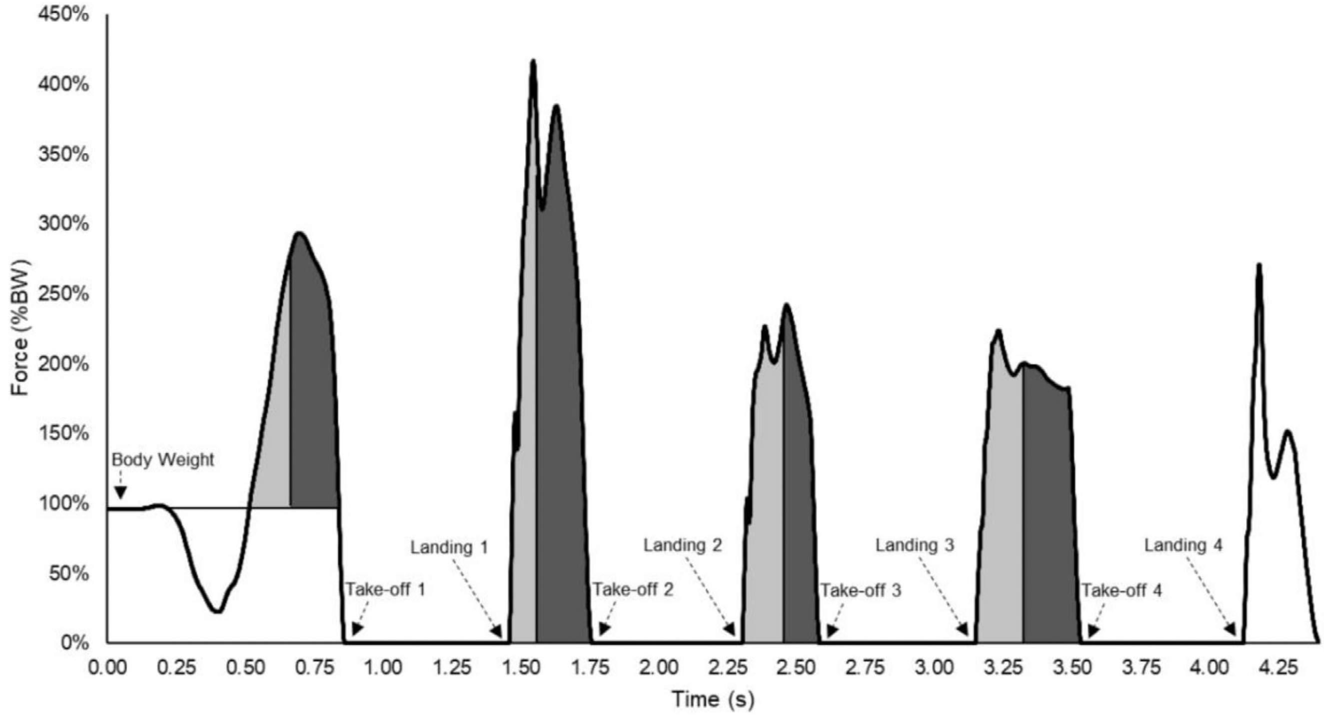

Figure 2. A sample force tracing for a repeated jump. The unshaded area below body weight for the first jump represents the unweighting phase. The light gray shaded area represents the braking phase. The dark gray shaded area represents the propulsive phase for all jumps.

all DJ metrics before and after the strength and conditioning program, as well as unweighting phase and braking phase metrics for jump 1 of the RJ. Time (pre vs. post) x jump (2 vs. 3 vs. 4) repeated measures analyses of variance (ANOVAs) were used to compare all braking metrics for jumps 2, 3, and 4 of the RJ. Time (pre vs. post) x jump (1 vs. 2 vs. 3 vs. 4) repeated measures analyses of variance (ANOVAs) were used to compare all propulsive and performance metrics for all jumps of the RJ with Bonferroni corrections. Calculations of effect sizes were performed using partial η^2 such that an effect size of ≥ 0.14 was considered a large effect, an effect size of ≥ 0.06 and < 0.14 was considered a moderate effect, and an effect size of ≥ 0.01 and < 0.06 was considered a small effect, and an effect size of < 0.01 was considered a negligible effect, as well as Hedge's *g* such that an effect size ≤0.19 = trivial, 0.20-0.59 = small, 0.60-1.19 = moderate, 1.20-1.99 = large, ≥ 2.0 = very large. All statistical analyses were performed in IBM SPSS v. 28 (Chicago, IL, USA). An alpha level of $p \leq 0.05$ was considered statistically significant.

RESULTS

Normality as assessed via the Shapiro-Wilk test revealed data from the DJ and RJ were normally distributed ($p \geq 0.055$). Within-session reliability was calculated from the data from the first visit. Using intraclass correlation coefficient (ICC) model 2,1 (Weir, 2005), metrics from the DJs exhibited ICCs ≥ 0.757 and coefficients of variation (CVs) ≤ 12.23%, while metrics from the RJs exhibited ICCs ≥ 0.625 and coefficients of variation (CVs) ≤ 16.47%.

Comparisons of body mass and DJ metrics are presented in Table 3. Body mass increased significantly with a moderate effect size ($p = 0.015$, $g = 0.607$, Table 3). Peak braking power, peak propulsive power, mean propulsive force, and jump height increased with small to moderate effect sizes ($p \leq 0.027$, $g \geq 0.540$, Table 3). There were no other significant changes after the training program ($p \geq 0.059$, $g \leq 0.453$).

Comparisons of RJ metrics are presented in Table 4. There were no differences before and after training for unweighting phase metrics during the first jump of the RJ with a small effect size ($p \geq 0.157$, $g \leq 0.362$), while peak braking power increased after training with a moderate effect size ($p = 0.005$, $g = 0.718$) with no other significant differences for braking phase metrics ($p \geq 0.199$, $g \leq 0.299$). For the braking phase of jumps 2-4, there were jump-related main effects with a large effect size ($p \leq 0.015$, $\eta^2 \geq 0.288$) such that braking impulse, peak braking power, and mean braking force decreased from 2 to 3 with small to moderate effect sizes ($p \leq 0.023$, $g \geq 0.533$) then remained the same from jumps 3 to 4 ($p \geq 0.220$, $g \leq 0.174$), with no other jump-related differences for braking metrics ($p \geq 0.072$, $\eta^2 \leq 0.173$). For the propulsive phase of jumps 1-4, there were time-related main effects for peak propulsive power and mean propulsive force such that both variables increased after training with a large effect size ($p \leq 0.049$, $\eta^2 \geq 0.199$). Additionally, for the propulsive phase of jumps 1-4 there were jump-related main effects with moderate to large effect sizes ($p \leq 0.049$, $\eta^2 \geq 0.134$) such that propulsive phase duration decreased from jumps 1-3 with a moderate effect size ($p \leq 0.007$, $g \geq 0.822$) and remained the same for jumps 3-4 ($p = 0.480$, $g = 0.400$), propulsive impulse decreased from jumps 2-3 with a moderate effect size ($p < 0.001$, $g = 0.660$) and remained the same for jumps 3-4 ($p = 1.000$, $g = 0.062$), peak propulsive power increased from jumps 1-2 with a very large effect size ($p < 0.001$, $g = 3.131$), decreased from jumps 2-3 with a moderate effect size ($p = 0.016$, $g = 0.671$), and remained lower from jumps 3-4 ($p = 1.000$, $g = 0.184$), and mean propulsive force was higher for jump 2 than 4 with a moderate effect size ($p = 0.003$, $g = 0.641$). For the performance metrics, there were time- and jump-related main effects for jump height such that jump height increased after training for all jumps with a large effect size ($p = 0.010$, $\eta^2 = 0.316$) and was greater for jump 1 than jumps 2-4 with moderate to large effect sizes ($p < 0.001$, $g \geq 1.064$). For RSI, there was a significant time x jump interaction with a large effect size (p = 0.006, $\eta^2 = 0.205$) such that RSI increased after training for jumps 3-4 with small effect sizes ($p \leq 0.003$, $g \geq 0.413$), while before training, RSI for jumps 2-4 was greater than jump 1 with very large effect sizes ($p < 0.001$, $g \geq 2.512$), and after training RSI for jumps 2-4 were greater than jump 1 with large effect sizes ($p < 0.001$, $g \geq 2.883$) and RSI for jump 3 was greater than jump 2 with a small effect size ($p = 0.023$, $g = 0.486$).

Table 3. Means ± 95% confidence intervals for jump metrics before and after 10-weeks of strength and conditioning training for the drop jump.

Metric	Pre-training	Post-training	*p*-value	Hedge's *g*
Body Mass (kg)	102.73 ± 8.79	104.35 ± 9.33	0.015	0.607
Braking Phase				
Duration (s)	0.21 ± 0.05	0.21 ± 0.03	0.830	0.049
Countermovement Depth (m)	0.31 ± 0.04	0.32 ± 0.04	0.641	0.106
Braking Impulse (N·s·kg^{-1})	4.52 ± 0.51	4.46 ± 0.34	0.753	0.046
Peak Braking Power (W·kg^{-1})	***132.94 ± 9.82***	***139.67 ± 10.16***	***0.025***	***0.548***
Force at Bottom of Countermovement (N·kg^{-1})	30.32 ± 2.79	31.27 ± 2.73	0.327	0.226
Braking RFD (N·s^{-1}·kg^{-1})	176.15 ± 37.13	182.23 ± 42.98	0.537	0.142
Mean Braking Force (N·kg^{-1})	22.78 ± 2.05	23.32 ± 2.03	0.299	0.240
Braking Stiffness (N·m^{-1})	11695.31 ± 2392.66	10871.35 ± 2514.77	0.341	0.220
Propulsive Phase				
Duration (s)	0.16 ± 0.03	0.17 ± 0.02	0.375	0.204
Propulsive Impulse (N·s·kg^{-1})	3.36 ± 0.72	3.48 ±0.51	0.629	0.215
Peak Propulsive Power (W·kg^{-1})	***175.33 ± 17.41***	***188.33 ±14.64***	***0.027***	***0.540***
Mean Propulsive Force (N·kg^{-1})	***21.17 ± 1.59***	***22.54 ±1.57***	***0.001***	***0.886***
Performance Metrics				
Jump Height (m)	***0.30 ± 0.04***	***0.32 ±0.04***	***0.015***	***0.603***
RSI	1.60 ± 0.21	1.69 ±0.25	0.059	0.453

BW = body weight (N), RFD = rate of force development, RSI = reactive strength index. Bold and italicized metrics indicate a significant difference for pre- vs. post-training.

Table 4. Means ± 95% confidence intervals for jump metrics before and after 8 weeks of strength and conditioning training for the repeated jumps.

Jump No.	Metric	Pre-training	Post-training	Pre vs. Post *p*-value	Pre vs. Post Hedge's *g*
	Unweighting Phase				
	Duration (s)	0.37 ± 0.04	0.36 ±0.04	0.605	0.118
	Unweighting Impulse (N·s·kg^{-1})	5.14 ±0.53	5.79 ±0.58	0.157	0.332
	Low Force (N·kg^{-1})	4.34 ±0.99	4.33 ±0.87	0.966	0.010
	Braking Phase				
	Duration (s)	0.15 ± 0.01	0.15 ± 0.01	0.352	0.214
	Braking Impulse (N·s·kg^{-1})	2.58 ±0.25	2.80 ± 0.40	0.444	0.176
	Countermovement Depth (m)	0.28 ± 0.04	0.29 ± 0.03	0.745	0.074
	Peak Braking Power (W·kg^{-1})	***17.11 ± 2.94***	***18.21 ± 2.77***	***0.005***	***0.718***
	Force at Bottom of Countermovement (N·kg^{-1})	24.46 ±2.01	24.86 ± 2.07	0.368	0.207
1	Braking RFD (N·s^{-1}·kg^{-1})	103.32 ±20.63	107.14 ± 16.62	0.485	0.160
	Braking Force (N·kg^{-1})	20.12 ± 2.63	20.89 ± 2.59	0.199	0.299
	Braking Stiffness (N·m^{-1})	7290.59 ±1059.46	7595.28 ± 119.78	0.403	0.193
	Propulsive Phase				
	Duration (s)	0.24 ± 0.01	0.24 ± 0.02	0.371	0.206
	Propulsive Impulse (N·s·kg^{-1})	5.12 ± 0.20	5.30 ± 0.27	0.053	0.925
	Peak Propulsive Power (W·kg^{-1})	***57.30 ± 4.58***	***59.91 ± 4.21***	***0.031***	***0.526***
	Mean Propulsive Force (N·kg^{-1})	***21.13 ± 0.80***	***21.88 ± 0.87***	***< 0.001***	***0.950***
	Performance Metrics				
	Jump Height (m)	***0.38 ± 0.04***	***0.40 ± 0.03***	***0.049***	***0.453***
	RSI	0.75 ± 0.06	0.76 ± 0.04	0.664	0.101

Jump No.	Metric	Pre-training	Post-training	Pre vs. Post *p*-value	Pre vs. Post Hedge's *g*
	Braking Phase				
	Duration (s)	0.13 ± 0.01	0.12 ± 0.01	0.350	0.216
	Countermovement Depth (m)	0.14 ± 0.02	0.12 ± 0.02	0.257	0.263
	Braking Impulse (N·s·kg^{-1})	2.75 ± 0.15	2.80 ± 0.16	0.118	0.369
	Peak Braking Power (W·kg^{-1})	80.52 ± 10.49	88.01 ± 14.34	0.251	0.266
	Force at Bottom of Countermovement (N·kg^{-1})	29.65 ± 3.52	33.20 ± 4.40	0.132	0.355
	Braking RFD (N·s^{-1}·kg^{-1})	253.52 ± 46.60	296.39 ± 63.42	0.201	0.298
	Mean Braking Force (N·kg^{-1})	22.66 ± 2.04	23.22 ± 2.49	0.563	0.132
2	Braking Stiffness (N·m^{-1})	28772.81 ± 4563.75	30845.53 ± 4640.34	0.527	0.145
	Propulsive Phase				
	Duration (s)	0.18 ± 0.03*	0.20 ± 0.40*	0.403	0.192
	Propulsive Impulse (N·s·kg-1)	4.02 ± 0.74	4.58 ± 0.75	0.088	0.405
	Peak Propulsive Power (W·kg-1)	*152.20 ± 22.19**	*181.23 ± 22.44**	*0.013*	*0.621*
	Mean Propulsive Force (N·kg-1)	*21.66 ± 2.20*	*24.03 ± 2.02*	*0.039*	*0.419*
	Performance Metrics				
	Jump Height (m)	*0.30 ± 0.40**	*0.33 ± 0.03**	*0.029*	*0.532*
	RSI	1.67 ± 0.23*	1.75 0.23*	0.166	0.325
	Braking Phase				
	Duration (s)	0.13 ± 0.02	0.14 ± 0.01	0.707	0.086
	Countermovement Depth (m)	0.12 ±0.02	0.11 ± 0.02	0.287	0.247
	Braking Impulse (N·s·kg^{-1})	2.42 ±0.18+	2.51 ± 0.14+	0.096	0.395
	Peak Braking Power (W·kg^{-1})	68.63 ± 13.12+	72.96 ± 10.64+	0.056	0.424
	Force at Bottom of Countermovement (N·kg^{-1})	28.69 ± 4.83	30.20 ± 4.09	0.158	0.331
	Braking RFD (N·s^{-1}·kg^{-1})	249.83 ± 66.04	267.02 ± 54.53	0.205	0.295
	Mean Braking Force (N·kg^{-1})	19.50 ± 2.64+	20.57 ± 2.24+	0.079	0.419
3	Braking Stiffness (N·m^{-1})	31126.16 ± 10073.62	33154.69 ± 6870.05	0.536	0.142
	Propulsive Phase				
	Duration (s)	0.15 ±0.02*+	0.13 ± 0.02*+	0.052	0.414
	Propulsive Impulse (N·s·kg^{-1})	3.16 ± 0.68*+	3.35 ± 0.89*+	0.669	0.098
	Peak Propulsive Power (W·kg^{-1})	*123.26 ± 25.59*+*	*143.65 ± 23.32*+*	*0.044*	*0.404*
	Mean Propulsive Force (N·kg^{-1})	*20.08 ± 3.37*	*22.48 ± 2.48*	*0.003*	*0.785*
	Performance Metrics				
	Jump Height (m)	*0.29 ± 0.04**	*0.33 ± 0.04**	*0.003*	*0.787*
	RSI	*1.77 ± 0.23*+*	*2.00 ± 0.26*+*	*< 0.001*	*0.956*

Jump No.	Metric	Pre-training	Post-training	Pre vs. Post *p*-value	Pre vs. Post Hedge's *g*
	Braking Phase				
	Duration (s)	0.13 ± 0.02	0.13 ± 0.02	0.838	0.047
	Countermovement Depth (m)	0.12 ± 0.02	0.13 ± 0.03	0.720	0.082
	Braking Impulse (N·s·kg^{-1})	2.38 ±0.17^{+}	2.42 ± 0.15+	0.519	0.418
	Peak Braking Power (W·kg^{-1})	62.96 ± 12.74^{+}	68.12 ± 11.94+	0.428	0.182
	Force at bottom of Countermovement (N·kg^{-1})	26.44 ± 4.30^{+}	28.05 ± 4.43+	0.540	0.140
	Braking RFD (N·s-1·kg^{-1})	224.82 ± 59.23	242.55 ± 59.74	0.631	0.110
	Mean Braking Force (N·kg^{-1})	18.92 ± 2.52^{+}	19.66 ± 2.54+	0.574	0.129
4	Braking Stiffness (N·m^{-1})	27523.68 ± 6333.06	28848.19 ± 7216.85	0.757	0.070
	Propulsive Phase				
	Duration (s)	0.17 ± 0.03*	0.15 ± 0.03*	0.170	0.321
	Propulsive Impulse (N·s·kg^{-1})	3.06 ±0.53*$^{+}$	3.62 ± 0.67*$^{+}$	0.163	0.327
	Peak Propulsive Power (W·kg^{-1})	***112.82 ± 21.55*$^{+}$***	***135.96 ± 23.28*$^{+}$***	***0.047***	***0.448***
	Mean Propulsive Force (N·kg^{-1})	***18.78 ±2.67^{+}***	***20.62 ± 2.40^{+}***	***0.048***	***0.441***
	Performance Metrics				
	Jump Height (m)	***0.28 ± 0.04****	***0.32 ± 0.03****	***0.043***	***0.444***
	RSI	***1.68 ± 0.25****	***1.90 ± 0.27****	***0.003***	***0.757***

*BW = body weight (N), RFD = rate of force development, RSI = reactive strength index. Bold and italicized metrics indicate a significant difference for pre- vs. post-training. * Indicates different from jump 1, $^{+}$ indicates different from jump 2.*

DISCUSSION

Although several studies have examined vertical jump performance in American football players (Fry & Kraemer, 1991; McGuigan & Winchester, 2008; Merrigan et al., 2022; Thompson et al., 2013), none we are aware of have examined the effects of a strength and conditioning program on DJ and RJ performance in collegiate American football players. The results of the present study demonstrated improvements for braking and propulsive metrics, as well as jump height for the DJ and RJ. Since these jump techniques necessarily require absorption and reapplication of relatively high braking forces above that of a traditional countermovement jump, it stands to reason that a 10-week offseason strength and conditioning program may be effective at improving elastic energy storage and utilization capabilities in American football players, leading to subsequent improvements in braking and propulsive force and power production.

The present study yielded significant increases in peak braking power, peak propulsive power, mean propulsive force, and jump height for the DJ. Although there is a dearth of literature examining DJ performance in American football players, it has been demonstrated that improvements in DJ performance are associated with improvements in athletic performance in various sports settings (Barr & Nolte, 2011; Harper et al., 2022; You & Huang, 2022; Young et al., 2002). In adult competitive athletes, Young et al. (2002) found that greater DJ performance was positively associated with greater change-of-direction ability in amateur to advanced soccer, basketball, Australian football, and tennis players, while in elite-level rugby players, Barr and Nolte (2011) reported that DJ performance was positively related to linear sprinting ability. Furthermore, You and Huang (2022) demonstrated that better DJ performance may reflect superior elastic energy utilization among elite-level lacrosse players. Most recently, Harper et al. (2022) found that greater DJ performance tended to be associated with horizontal deceleration ability, a vital component of athletic performance, in collegiate team sport athletes. Nevertheless, in conjunction with previous studies (Barr & Nolte, 2011; Harper et al., 2022; You & Huang, 2022; Young et al., 2002), it can be hypothesized that the improvements in DJ performance, in particular force and power production as well as jump height, in the present study likely also reflects improvements for sport-specific performance for American football players.

It has been previously hypothesized that increases in braking metrics during vertical jumps may improve subsequent propulsive performance (McHugh et al., 2021; Struzik & Zawadzki, 2013, 2019). This can be explained by thinking of the muscle as a spring, such that the downward forces applied during the landing and subsequent countermovement are analogous to compressing the spring (McHugh et al., 2021; Struzik & Zawadzki, 2013, 2019). Increasing the magnitude of tension on the spring (i.e., greater braking force and power) should theoretically lead to greater release of stored elastic energy during the subsequent recoil, or propulsive phase. This is further supported by the findings of our previous study (Gillen et al., 2024), which demonstrated improvements in braking and propulsive metrics during the CMJ before and after an offseason training program for collegiate Division I American football players. Although the present study only demonstrated increases in one braking metric (peak braking power), these findings did demonstrate improvements in peak propulsive power, mean propulsive force, and jump height, even with increases in body mass, a known confounding factor when examining increases in vertical jump performance (Khamoui et al., 2011; Nuzzo et al., 2008; Thompson et al., 2013; West et al., 2011). Of note, the contact times in the present study, which ranged from 234-624 ms, might suggest the program was more effective at improving slow stretch-shortening cycle performance, rather than fast stretch-shortening cycle performance. Although the DJ is commonly considered a fast stretch-shortening cycle movement (Held et al., 2020; Wadden et al., 2012), and the instructions given to subjects were to jump as fast as possible, it may be that the larger body masses, commonly seen in American football players, or increases in body mass inhibited them from achieving the faster contact times commonly seen in the DJ. Interestingly, despite the improvements in force production, there were no changes in impulse, which might suggest the concomitant increase in body mass and force production inhibited further improvements in contact times as greater body mass does require greater overall force generation to overcome the downward momentum of the DJ. This might suggest further implementation of fast stretch-shortening cycle movements, in conjunction with strength training, may yield further improvements in overall athletic capabilities in American football players. This may be worth expanding on in further research to determine if increases in body mass may yield a point of diminishing return with regards to improving the ability to change direction (downward trajectory of the DJ to the upward jump). However, one could argue this is position-specific in a sport like American football as some positions have few jumping movements, while others have more. Based on the present results it can be hypothesized that the increased braking power production may indeed be indicative of increases in utilization of stored elastic energy when taking into consideration increases in subsequent propulsive vertical jump performance. With American football being a sport requiring repeated usage of stored elastic energy (i.e., repeated sprints, jumping, change-of-direction), improvements in these abilities, which can be assessed from a simple DJ, should be prioritized. Thus, the present results suggest that a 10-week offseason strength and conditioning program does appear to yield improvements in DJ performance, which may act as a surrogate indicator of improvements for on-field performance.

Repeated utilization of the stretch-shortening cycle is an important component of American football that can be demonstrated during on-field movements such as sprinting or change-of-direction movements (Fullagar et al., 2017; Iosia & Bishop, 2008; Jacobson et al., 2013; Wellman et al., 2017). During these movements, players perform a maximal effort sprint, plant, or jump, followed by a brief period of deceleration, and then another maximal effort movement, demonstrating the need for efficient landing, braking, and reacceleration abilities. Iosia and Bishop (2008) reported that, on average, running plays lasted 4.86 s and passing plays lasted 5.60 s in Division IA collegiate American football games. With this in mind, it is pertinent to include simple assessments of repeated high-intensity movements that may reflect on-field demands and allow coaches to track performance changes. Furthermore, Wellman et al. (2017) demonstrated Division I collegiate American football players are repeatedly exposed to high impact forces during competitive games, indicating the need to maximize the ability to absorb and reapply these forces repeatedly during a play. However, worth noting is Wellman et al. (2017) did not examine GRFs directly due to the lack of feasibility of these types of measures during a game. Thus, the RJ used in the present study, which consisted of four consecutive maximal jumps, may be reflective of the ability to maximally accelerate, decelerate and absorb large braking forces, and then reaccelerate again for another maximal effort movement, though future research using wearable technology, such as socks with pressure sensors embedded may provide more clarity to actual impact forces during a game. In the present study, RJ performance increased after the training program, demonstrating that a traditional 10-week strength and conditioning offseason program may yield performance improvements for abilities that utilize repeated stretch-shortening cycle actions. Interestingly, regardless of pre- or post-training, propulsive power increased from jump 1-2, but decreased, along with all other propulsive metrics, from jump 2-3. Worth noting, propulsive phase duration did decrease from jump 1-2 and 2-3, demonstrating less ground contact time which, during repeated stretch-shortening cycle actions, may be advantageous. For example, the two factors that determine sprint speed are stride frequency and stride length (Haff & Triplett, 2016). Thus, if two athletes have the same stride length, while the other has greater stride frequency, then the athlete with the greater stride frequency will be faster. This is to say, the RJ may be an effective tool for strength and conditioning coaches to monitor not only power output, but force plate contact time, which may provide unique insight into on-field performance. Thus, not only may the DJ be used to monitor changes in athletic performance across a strength and conditioning offseason program, it appears that the RJ may provide unique insight beyond what tests involving one single vertical jump may provide, particularly since the RJ combines both the CMJ and multiple DJs consecutively.

In conclusion, the present study demonstrated that DJ and RJ performance significantly increased in as few as 10-weeks of strength and conditioning training. Despite the popularity of collegiate American football and GRF assessments of vertical jump performance, this study is the first we are aware of to assess changes in DJ and RJ performance via GRFs before and after an offseason strength and conditioning program among collegiate Division I American football players. For both jump types, this study primarily demonstrated increases in propulsive phase and performance metrics over the course of the training program. Together, these results point to potential improvements in utilization of the stretch-shortening cycle, particularly the slow stretch shortening cycle, which likely has direct implications for on-field performance in American football. Thus, strength and conditioning coaches may benefit from including DJ and RJ assessments to monitor the effectiveness of the strength and conditioning program. Nevertheless, with the lack of studies quantifying and comparing changes in vertical jump performance for American football players using GRFs, further research is needed to better understand musculoskeletal adaptations that may be expected over the course of the training year.

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CONFLICTS OF INTEREST

The author has no conflicts of interest that are directly relevant to the contents of this manuscript.

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ETHICAL APPROVAL

Ethics for this study were approved in line with the Mississippi State University's Institutional Review Board.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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