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Peak Force and Rate of Force Development During Isometric and Dynamic Mid-Thigh Clean Pulls Performed at Various Intensities

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Abstract. Kawamori, N., S.J. Rossi, B.D. Justice, E.E. Haff, E.E. Pistilli, H.S. O'Bryant, M.H. Stone, and G.G. Haff. Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. *J. Strength Cond. Res. 20(3):483–491. 2006.*—Eight male collegiate weightlifters (age: 21.2 ± 0.9 years; height: 177.6 ± 2.3 cm; and body mass: 85.1 ± 3.3 kg) participated in this study to compare isometric to dynamic force-time dependent variables. Subjects performed the isometric and dynamic mid-thigh clean pulls at 30–120% of their one repetition maximum (1RM) power clean (118.4 ± 5.5 kg) on a 61 × 121.9–cm AMTI forceplate. Variables such as peak force (PF) and peak rate of force development (PRFD) were calculated and were compared between isometric and dynamic conditions. The relationships between force-time dependent variables and vertical jump performances also were examined. The data indicate that the isometric PF had no significant correlations with the dynamic PF against light loads. On the one hand, there was a general trend toward stronger relationships between the isometric and dynamic PF as the external load increased for dynamic muscle actions. On the other hand, the isometric and dynamic PRFD had no significant correlations regardless of the external load used for dynamic testing. In addition, the isometric PF and dynamic PRFD were shown to be strongly correlated with vertical jump performances, whereas the isometric PRFD and dynamic PF had no significant correlations with vertical jump performances. In conclusion, it appears that the isometric and dynamic measures of force-time curve characteristics represent relatively specific qualities, especially when dynamic testing involves small external loads. Additionally, the results suggest that athletes who possess greater isometric maximum strength and dynamic explosive strength tend to be able to jump higher.

Key Words. force-time curve, maximum strength, explosive strength

Introduction

The analysis of force-time curves has been widely used to evaluate neuromuscular function (4, 8). Both the peak rate at which force can be developed (PRFD, or peak rate of force development) and peak force (PF) have been investigated with respect to muscle fiber type (38), age (2, 3), gender (29), fatigue (13, 35), and performance (8, 24, 28, 34).

Of particular importance to sports scientists and coaches is the relationship of force-time curve variables to actual athletic performance measures. Traditionally, the PF and PRFD have been assessed using isometric testing methods, which have produced varying results (23, 25, 36, 39). Some investigators suggest that isometric force-time curve characteristics are significantly related to dynamic performance (8, 22, 36), yet others have reported no significant relationships (23, 37, 39). Two factors may explain such disparity in the research findings.

One factor is the joint angle selected in the isometric assessment. Murphy et al. (25) investigated the relationship between isometric measures of force-time characteristics at 2 different joint angles and dynamic performance. They found that the joint angle of isometric testing significantly affects the relationship to dynamic performance and suggested that the joint angle in the isometric assessment should be selected so that it represents the joint angle at which PF is developed in the performance of interest. Similarly, Haff et al. (8) standardized the joint angle and movement position during isometric and dynamic testing, and they found significant relationships between isometric and dynamic force-time curve characteristics. Collectively, these data indicate that the isometric testing protocol (e.g., joint angle, body position) should be as close as possible to the actual dynamic movement of interest when strong relationship is expected.

The other factor is the influence of the external load involved during dynamic muscle actions. Some investigators suggest that the correlation between isometric force-time characteristics and dynamic performance is strong when the external load involved during dynamic performance is relatively heavy (8, 22, 24). It is further suggested that this correlation decreases as the external load decreases (8, 22, 24, 28). Such phenomena were well observed in upper-body movements (22, 24, 28), but not in lower-body movements. Although Haff et al. (8) compared force-time characteristics in a lower-body movement (i.e., mid-thigh clean pull) between isometric and dynamic muscle actions and found significant relationships, they only used relatively heavy loads during dynamic muscle actions (80–100%) and further research is necessary to elucidate the relationship between isometric testing and dynamic performance that involves lighter loads.

The purpose of this investigation was to examine the relationship between isometric and dynamic force-time dependent variables using a standardized testing protocol. Specifically, dynamic testing involved a wide range of loads so the relationships of dynamic to isometric force-

Variables	● = Biometric Data ♦ = 1-RM Power Clean Test ♠ = Familiarization With Isometric and Dynamic Pull Tests ♥ = Abstain From Physical Activity						⊗ = Isometric Force-Time Curve Protocol ⊕ = Dynamic Force-Time Curve Protocol ∅ = Vertical Jump Force-Time Curve Protocol ° = Standardized Weightlifting Training					
-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7
● ♦ ♠	♠ °	♠ °	♥	♥	⊗/⊕	°	°	♥	∅	♥	♥	⊗/⊕

FIGURE 1. Testing timeline.

TABLE 1. Subject characteristics.

Variable	Mean	*SD*
Age (y)	21.2	±2.4
Height (cm)	177.6	±6.5
Body mass (kg)	85.1	±9.3
Body fat (%)	12.2	±2.8
Max power clean (kg)	118.4	±15.4

time curve characteristics could be examined against light as well as heavy external loads. It was hypothesized that the correlation between isometric and dynamic force-time dependent variables decreases as the external load for dynamic muscle actions decreases. In addition, the relationship of dynamic force-time variables to dynamic athletic performance was of interest because such data is scarce, especially in lower-body multi-joint movements (24, 28).

METHODS

Experimental Approach to the Problem

A randomized counterbalanced testing protocol was utilized in order to evaluate the relationships between the force-time curve characteristics of dynamic mid-thigh clean pulls, isometric mid-thigh clean pulls, countermovement vertical jumps (CMJ), and static vertical jumps (SJ). A wide range of resistances (30–120% of one repetition maximum [1RM]) were tested in the dynamic mid-thigh clean pulls in order to get a better understanding of the role intensity plays in the relationships between dynamic and isometric muscle actions. The first testing session was utilized to collect each subject's biometric data and 1RM in the power clean with previously established methods (9, 31). Additionally, all subjects performed 3 familiarization trials with both the isometric and dynamic mid-thigh clean pulls. Sessions 2 and 4 consisted of either an isometric or dynamic mid-thigh clean pull test, with each test separated by 7 days. Session 3 was performed 4 days after session 2 and was designed to assess both CMJ and SJ force-time curve characteristics. A summary of the testing protocol is presented in Figure 1.

Subjects

Eight men who had a minimum of 2 years of collegiate weightlifting experience were recruited as subjects for the present investigation. All subjects had qualified for the collegiate weightlifting championships in their respective weight classes and were in a peaking phase of a periodized training program at the time of testing. A summary of the subjects' biometric data is presented in Table 1. Prior to participating in the present investigation, all subjects completed a health history questionnaire and signed an informed consent form in accordance with the guidelines set forth by Appalachian State University's Institutional Review Board.

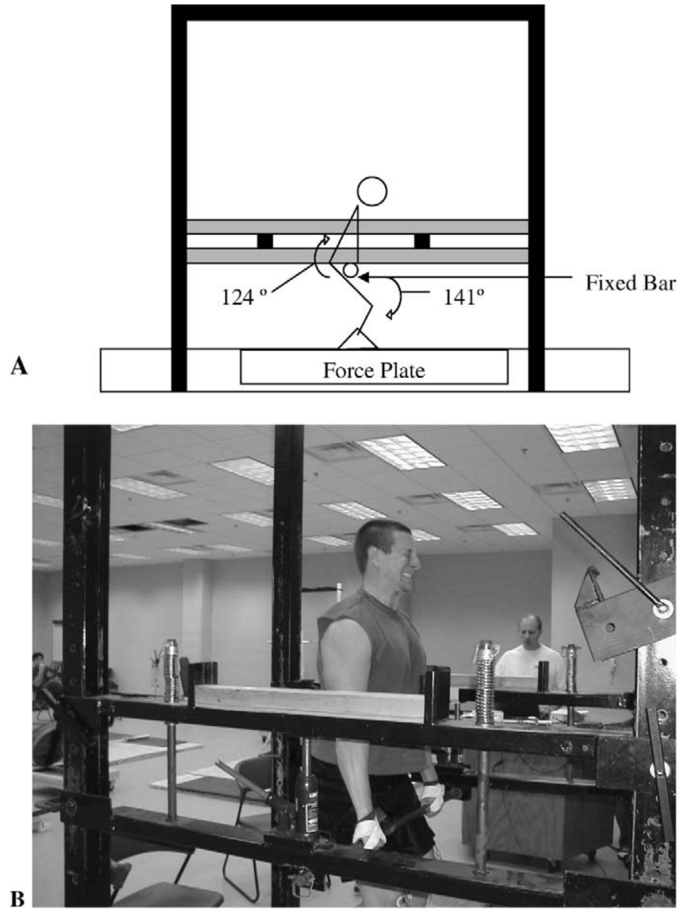

FIGURE 2. Isometric mid-thigh clean pull testing apparatus. (A) schematic of apparatus setup; (B) photo of testing apparatus setup.

Biometric Data

All subjects were assessed for height, body mass, and body composition prior to the initiation of the investigation. A stadiometer was used to measure the subjects' height to the nearest 0.1 cm, and an electronic scale was used to determine the subjects' body mass to the nearest 0.1 kg. Body composition was assessed with a 7-site skinfold measurement procedure. All skinfolds were measured on the right side of the body 3 times by the same tester using Harpenden Skinfold Calipers (Baty International, Burgess Hill, UK) with the mean value recorded. The intraclass correlation coefficient (ICC) for test-retest reliability for skinfold measures was 0.99. Body density then was calculated and body fat was estimated with previously published procedures (15, 30).

Isometric and Dynamic Mid-Thigh Clean Pull Procedures

All lifts were performed on a custom isometric rack (Sorinex Inc., Irmo, SC), which was designed to allow the bar to be fixed at any height above the floor (Figures 2 and 3) (8). A 61 × 121.9–cm AMTI forceplate (Advanced Mechanical Technologies, Newton, MA) was placed under the isometric rack and was set to sample at a rate of 500

A

B

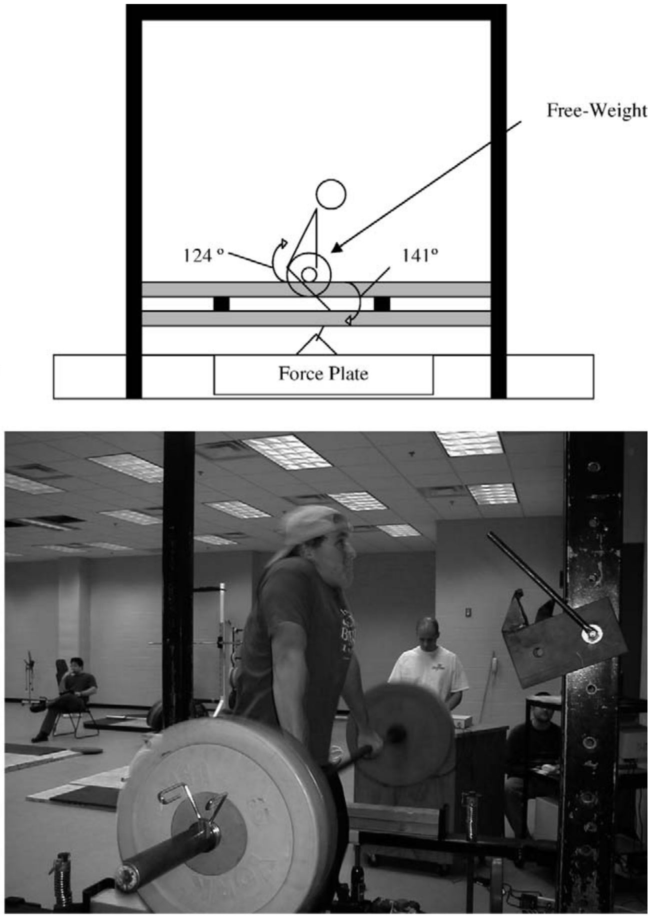

FIGURE 3. Dynamic mid-thigh clean pull testing apparatus. (A) schematic of apparatus setup; (B) photo of testing apparatus setup.

Hz. All force-time curve analyses were performed with previously established methodologies (8).

Briefly, the ground reaction force data collected over the sample period were utilized to calculate several variables from the vertical force components (F_z). The differences between 2 adjacent force samples were divided by the intersample time interval (0.002 second) in order to calculate the force–rate change. The principle that net force × time = the product of mass and change in velocity served as the basis for the calculation of the vertical velocity of the center of mass. Therefore, the net vertical force on the body was multiplied by the intersample time period and then was divided by the mass in order to calculate the change in vertical velocity of the center of mass during a sampling interval. The net force then was taken as the vertical force platform reading minus the weight.

The mass and weight used were considered those of the jumper during all of the vertical jump tests. For the weightlifting trials, the lifter plus the barbell were utilized as the mass and weight. A procedure that added the velocity change over the sample interval to the preinterval absolute velocity, which was zero at the initiation of the movement, was utilized in order to calculate the absolute velocity at the end of each sampling interval. Absolute velocity was then multiplied by the time interval in order to calculate the vertical position change over each interval. Position changes then were added in succession, beginning with the position at the start, to yield an absolute vertical position at the end of each interval. Vertical force then was multiplied by concurrent vertical velocity in order to calculate instantaneous power. Once all of these variables were calculated over the entire movement, each variable's peak and time to peak were determined.

Prior to the initiation of the isometric mid-thigh clean pull tests, subjects performed a dynamic warm up based upon previously published literature (8, 19). After completing the dynamic warm up, 2 trials were performed for the isometric mid-thigh clean pull assessments. The isometric mid-thigh clean pulls were performed with standardized procedures based upon the work of Haff et al. (8) and Stone et al. (33). The mid-thigh clean pull was chosen because it corresponds to the portion of the clean where the highest velocities and forces are generated (7). After the subjects were placed in position, knee and hip angles (141 ± 10°; 124 ± 11°, respectively) were measured with goniometry in order to ensure that the position was accurately reproduced during each isometric and dynamic trial (Figures 2 and 3). During the isometric pull trials, subjects were strapped to the bar using standard lifting straps and athletic tape and were instructed to pull as fast and as hard as possible (8, 33). Bemben et al. (1) suggest that when testing for maximal force and peak rate of force development, these instructions produce optimal results. Three minutes' rest was given between each isometric trial in order to ensure complete recovery.

The dynamic mid-thigh clean pull assessment was performed using a certified Olympic bar and plates (York Barbell Co., York, PA). The loaded barbell was placed on the adjustable rack, allowing the subjects to initiate the dynamic mid-thigh clean pull from the appropriate position, based upon the knee and hip angles established during the isometric trial during each dynamic trial. This practice was based upon the work of Murphy et al. (25), who suggest that the joint angle used for testing specifically affects the relationship between isometric and dynamic muscle actions. Subjects performed 2 trials with a 3-minute rest between each attempt at 30, 60, 90, and 120% of their established 1RM in the power clean (118.4 ± 5.5 kg). During all dynamic trials, subjects were allowed to use standard lifting straps (Dynamic Fitness Co., Livonia, MI) and were again instructed to pull as fast and as hard as possible (8, 33). Subjects had 3 minutes of rest between each trial.

Vertical Jump Assessments

All vertical jump trials were performed on a 61 × 121.9–cm AMTI (Advanced Mechanical Technologies, Watertown, MA) forceplate. The warm-up protocol was based on work published by Kirksey et al. (19). All subjects performed 6 vertical jump trials (3 CMJ and 3 SJ). All vertical jumps were executed with hands on hip (8, 12) and were separated by 3 minutes' rest. The SJ were all initiated from a position that represented the mid-thigh pull position used in the isometric tests.

Force-Time Curve Analyses

Force-time curve analyses were performed on all dynamic and isometric muscle actions. The force-time curve assessments for all dynamic mid-thigh clean pulls and vertical jump tests included: PRFD, PF, and peak power (PP). Vertical displacement also was assessed during each

TABLE 2. Performance characteristics ($N = 8$).*

Variable	Isometric pull	DP 120	DP 90	DP 60	DP 30	CMJ	SJ
Peak force (N)							
Mean	3,177.5†‡§‖	2,604.5†‡§	2,327.3†‡‖	2,140.3†§‖	1,817.0‡§‖	1,449.6‡§¶	1,663.0‡§¶
SD	±285.3	±137.5	±113.7	±130.5	±157.0	±112.5	±103.3
PRFD ($N \cdot s^{-1}$)							
Mean	22,008.9	20,018.5	23,472.3	24,086.0	27,607.4	12,093.0	11,529.4
SD	±4,269.7	±2,814.6	±4,141.1	±3,768.2	±4,608.3	±1,273.3	±1,022.1
Peak power (W)							
Mean		2,062.8	2,085.3	2,228.9	2,203.8	6,931.4‡§¶	6,053.0‡§¶
SD		±211.8	±191.2	±192.3	±216.6	±430.9	±436.8
Vertical disp. (m)							
Mean						0.65	0.60
SD						±0.04	±0.03
Time to PRFD (ms)							
Mean	121.1	144.8	156.8	131.8	99.8	263.3	194.7
SD	±19.0	±29.2	±19.6	±17.7	±14.0	±63.5	±27.0
Time to PF (ms)							
Mean	256.1	276.5†	254.9†	205.3†	152.1	397.1‡§¶	324.3†
SD	±37.7	±33.0	±25.0	±22.4	±20.6	±42.5	±53.0

* DP 120 = dynamic pull at 120%, DP 90 = dynamic pull at 90%; DP 60 = dynamic pull at 60%; DP 30 = dynamic pull at 30%; CMJ = countermovement vertical jump; SJ = static vertical jump; PRFD = peak rate of force development; disp. = displacement; PF = peak force.
† = significantly different from DP 30 ($p < 0.01$).
‡ = significantly different from DP 60 ($p < 0.01$).
§ = significantly different from DP 90 ($p < 0.05$).
‖ = significantly different from DP 120 ($p < 0.01$).
¶= significantly different from the isometric trial ($p < 0.001$).

vertical jump trial. The PRFD and PF were analyzed during the isometric trials. The time to PRFD, PF, and PP also were assessed. Test–retest reliability for the isometric force-time curve tests for PF and PRFD were ICC = 0.97 and ICC = 0.96, respectively. During the dynamic mid-thigh clean pull trials the test–retest reliability was as follows: 30% trial—PF: ICC = 0.90, PRFD: ICC = 0.99, PP: ICC = 0.93; 60% trial—PF: ICC = 0.94, PRFD: ICC = 0.91, PP: ICC = 0.86; 90% trial—PF: ICC = 0.92, PRFD: ICC = 0.98, PP: ICC = 0.88; 120% trial—PF: ICC = 0.94, PRFD: ICC = 0.90, PP: ICC = 0.89. Test–retest reliability during the CMJ and SJ trials was as follows: CMJ—PF: ICC = 0.96, PRFD: ICC = 0.89, PP: ICC = 0.93, displacement: ICC = 0.99; SJ—PF: ICC = 0.90, PRFD: ICC = 0.86, PP: ICC = 0.92, displacement: ICC = 0.99.

Statistical Analyses

Paired *t*-tests were used to determine the difference between multiple isometric and dynamic trials, with an alpha level of $p \leq 0.05$. A 1-way repeated measures analysis of variance (ANOVA) was used to analyze selected force-time curve values. When significant F values were found ($p \leq 0.05$), paired comparisons were used in conjunction with the Holm's Bonferroni method for controlling type I error (14) to determine the significant differences. Effect size and statistical power were calculated. Statistical power was determined to range from 0.50–1.0, depending upon the variable analyzed for a subject pool this size. Generally, statisticians regard correlational analyses with small subject samples to be somewhat unstable. We chose to utilize Pearson product moment correlation coefficients to add a descriptive view to the relationships between the isometric and dynamic muscle action force-time curve variables, based upon the methods of previously published literature (8).

RESULTS

A summary of the force-time curve dependent variables analyzed for both isometric and dynamic muscle actions is listed in Table 2. The correlations achieved between the force-time curve variables for the isometric mid-thigh clean pulls, dynamic mid-thigh clean pulls, and vertical jump trials are presented in Tables 3, 4, 5, and 6.

There were no significant differences between the multiple isometric trials ($p = 0.89$, $\eta^2 = 0.003$, $1\text{-}\beta = 0.50$) or the multiple dynamic trials performed at 30% ($p = 0.28$, $\eta^2 = 0.16$, $1\text{-}\beta = 0.55$), 60% ($p = 0.21$, $\eta^2 = 0.21$, $1\text{-}\beta = 0.59$), 90% ($p = 0.89$, $\eta^2 = 0.003$, $1\text{-}\beta = 0.50$), and 120% of 1RM power clean ($p = 0.12$, $\eta^2 = 0.31$, $1\text{-}\beta = 0.67$).

Peak force was significantly different between the isometric and dynamic mid-thigh clean pull trials ($p < 0.05$, $\eta^2 = 0.86$, $1\text{-}\beta = 0.97$). Follow-up tests indicated that the PF during the isometric trial was significantly greater than the PF during the 30% ($p = 0.001$, $\eta^2 = 0.78$, $1\text{-}\beta = 1.0$), 60% ($p = 0.004$, $\eta^2 = 0.70$, $1\text{-}\beta = 1.0$), and 90% ($p = 0.007$, $\eta^2 = 0.64$, $1\text{-}\beta = 1.0$) dynamic trials. No significant difference was noted between the isometric and 120% dynamic trials. The PF during the 120% dynamic trial was significantly greater than the PF during the 30% ($p = 0.002$, $\eta^2 = 0.76$, $1\text{-}\beta = 1.0$), 60% ($p = 0.002$, $\eta^2 = 0.76$, $1\text{-}\beta = 0.96$), and the 90% ($p = 0.007$, $\eta^2 = 0.66$, $1\text{-}\beta = 0.90$) dynamic trials. The PF during the 90% dynamic trial was significantly greater than the 30% ($p = 0.005$, $\eta^2 = 0.73$, $1\text{-}\beta = 0.98$) and 60% ($p = 0.016$, $\eta^2 = 0.55$, $1\text{-}\beta = 0.77$) dynamic trials. The PF during the 60% dynamic trial was significantly ($p = 0.005$, $\eta^2 = 0.67$, $1\text{-}\beta = 0.93$)

TABLE 3. Correlations (r) between isometric (ISO) and dynamic mid-thigh clean pulls.*

	Dynamic mid-thigh clean pull											
	At 120%			At 90%			At 60%			At 30%		
ISO-Pull	PRFD	PF	PP	PRFD	PF	PP	PRFD	PF	PP	PRFD	PF	PP
PF												
r	0.74†	0.60	0.22	0.69†	0.82†	0.31	0.54	0.55	0.15	0.67	0.51	0.40
R^2	0.55	0.36	0.05	0.48	0.67	0.10	0.29	0.30	0.02	0.49	0.26	0.16
PRFD												
r	0.20	0.28	0.09	−0.14	0.17	−0.24	0.12	0.60	0.58	0.26	0.40	0.55
R^2	0.04	0.08	0.008	0.02	0.03	0.06	0.01	0.36	0.34	0.07	0.16	0.30

* PRFD = peak rate of force development ($N \cdot s^{-1}$); PF = peak force (N); PP = peak power (W).
† = significant ($p < 0.05$).

TABLE 4. Correlations (r) between isometric and vertical jump variables.*

	Isometric PRFD		Isometric PF	
	r	R^2	r	R^2
CMJ				
PF	0.08	0.006	0.87†	0.77
PRFD	0.18	0.03	0.85†	0.72
PP	0.02	0.0001	0.95†	0.90
Disp.	0.14	0.02	0.82†	0.67
SJ				
PF	0.28	0.08	0.67	0.45
PRFD	0.72	0.52	0.43	0.18
PP	−0.45	0.20	0.70	0.49
Disp.	0.12	0.01	0.87†	0.76

* PRFD = peak rate of force development; PF = peak force; CMJ = countermovement vertical jump; PP = peak power; Disp. = displacement; SJ = static vertical jump.
† = significant ($p < 0.05$).

greater than the PF during the 30% dynamic trial. The PF during the isometric trial was significantly greater than the PF during the CMJ ($p < 0.001$, $\eta^2 = 0.87$, $1\text{-}\beta = 1.0$) and SJ ($p < 0.001$, $\eta^2 = 0.83$, $1\text{-}\beta = 1.0$). The CMJ PF was significantly smaller than the PF during the 60% ($p = 0.001$, $\eta^2 = 0.81$, $1\text{-}\beta = 1.0$), 90% ($p < 0.001$, $\eta^2 = 0.93$, $1\text{-}\beta = 1.0$), and 120% ($p < 0.001$, $\eta^2 = 0.96$, $1\text{-}\beta = 1.0$) dynamic trials. The SJ PF was significantly smaller than the PF during the 60% ($p = 0.001$, $\eta^2 = 0.82$, $1\text{-}\beta = 1.0$), 90% ($p < 0.01$, $\eta^2 = 0.93$, $1\text{-}\beta = 1.0$), and 120% ($p < 0.001$, $\eta^2 = 0.92$, $1\text{-}\beta = 1.0$) dynamic trials. No differences were noted between the SJ and CMJ PF ($p = 0.24$, $\eta^2 = 0.17$, $1\text{-}\beta = 0.57$). Overall, PF tended to increase as the resistance increased from the 30% dynamic trial to the isometric trial.

The ANOVA revealed that the PRFD was significantly different ($p = 0.03$, $\eta^2 = 0.90$, $1\text{-}\beta = 0.78$) between the isometric and dynamic mid-thigh clean pull trials. When correcting for type I errors, follow-up tests indicated that there were no significant differences between the different muscle actions for the PRFD. No significant differ-

TABLE 5. Correlations (r) between dynamic mid-thigh clean pulls and countermovement vertical jump variables.*

	Countermovement vertical jump							
	PF		PRFD		PP		Disp	
	r	R^2	r	R^2	r	R^2	r	R^2
120%								
PF	0.74	0.55	0.65	0.42	0.80†	0.64	0.32	0.10
PRFD	0.52	0.27	0.33	0.11	0.56	0.31	0.72	0.52
PP	0.41	0.17	0.39	0.15	0.44	0.19	−0.28	0.08
90%								
PF	0.90†	0.81	0.71	0.50	0.98†	0.96	0.64	0.41
PRFD	0.35	0.12	0.77	0.59	0.43	0.18	0.65	0.42
PP	0.73	0.53	0.43	0.18	0.50	0.25	0.10	0.01
60%								
PF	0.85†	0.72	0.50	0.25	0.83†	0.69	0.33	0.11
PRFD	0.22	0.05	0.31	0.10	0.56	0.31	0.74	0.55
PP	0.76†	0.58	0.71	0.50	0.80†	0.64	0.23	0.05
30%								
PF	0.67	0.45	0.33	0.11	0.70	0.49	0.41	0.17
PRFD	0.51	0.26	0.57	0.32	0.66	0.44	0.67	0.45
PP	0.83†	0.69	0.75	0.56	0.92‡	0.85	0.43	0.18

* PF = peak force; PRFD = peak rate of force development; PP = peak power; Disp = displacement.
† = significant ($p < 0.05$).
‡ = significant ($p < 0.01$).

TABLE 6. Correlations (r) between dynamic mid-thigh clean pulls and static vertical jump variables.*

	Static vertical jump							
	PF		PRFD		PP		Disp	
	r	R^2	r	R^2	r	R^2	r	R^2
120%								
PF	0.90	0.81	0.58	0.34	0.65	0.42	0.27	0.07
PRFD	0.38	0.14	0.46	0.21	0.73	0.53	0.69	0.48
PP	0.68	0.46	0.45	0.20	0.24	0.06	−0.26	0.07
90%								
PF	0.94‡	0.88	0.85†	0.72	0.80†	0.64	0.72	0.52
PRFD	0.38	0.14	0.46	0.21	0.62	0.38	0.71	0.50
PP	0.40	0.16	0.14	0.02	0.33	0.11	0.13	0.02
60%								
PF	0.80†	0.64	0.93†	0.86	0.64	0.41	0.40	0.16
PRFD	0.46	0.21	0.44	0.19	0.69	0.48	0.72	0.52
PP	0.83†	0.69	0.65	0.42	0.42	0.18	0.22	0.05
30%								
PF	0.70	0.49	0.85†	0.72	0.77	0.59	0.46	0.21
PRFD	0.21	0.04	0.28	0.08	0.46	0.21	0.70	0.49
PP	0.64	0.41	0.60	0.36	0.52	0.27	0.50	0.25

* PF = peak force; PRFD = peak rate of force development; PP = peak power; Disp = displacement.
† = significant ($p < 0.05$).
‡ = significant ($p < 0.01$).

ences were found between the PRFD during any of the dynamic mid-thigh clean pulls, isometric mid-thigh clean pulls, and the PRFD during the SJ or CMJ. However, the PRFD exhibited a general decline as the resistance increased from the 30% dynamic trial to the isometric trial.

No significant differences were determined in the time to PRFD between the isometric and dynamic mid-thigh clean pulls ($p = 0.18$, $\eta^2 = 0.73$, 1-β = 0.95). No significant differences were noted in the time to PRFD when comparing the dynamic mid-thigh clean pulls with the SJ or CMJ ($p = 0.21$, $\eta^2 = 0.82$, 1-β = 0.98). When correcting for type I errors, no significant differences were found between the time to PRFD during the isometric pull and the CMJ ($p = 0.07$, $\eta^2 = 0.45$,1-β = 0.67) or SJ ($p = 0.03$, $\eta^2 = 0.52$,1-β = 0.70).

The time to PF was significantly different between the isometric and dynamic mid-thigh clean pulls ($p = 0.03$, $\eta^2 = 0.89$, 1-β = 0.98). The time to PF during the 30% dynamic trial was significantly shorter than the time to PF during the 60% ($p = 0.003$, $\eta^2 = 0.70$, 1-β = 0.96), 90% ($p = 0.002$, $\eta^2 = 0.74$,1-β = 0.98), and 120% ($p = 0.002$, $\eta^2 = 0.75$,1-β = 0.99) dynamic mid-thigh clean pulls. The time to PF was significantly longer in the CMJ when compared with the 30% ($p < 0.001$, $\eta^2 = 0.86$, 1-β = 1.0), 60% ($p < 0.001$, $\eta^2 = 0.85$, 1-β = 1.0), 90% ($p = 0.003$, $\eta^2 = 0.70$, 1-β = 0.96), and 120% ($p = 0.019$, $\eta^2 = 0.54$, 1-β = 0.74) dynamic trials. The time to PF during the SJ was significantly longer than the 30% ($p = 0.007$, $\eta^2 = 0.64$, 1-β = 0.92) dynamic trial. The time to PF during the isometric trial was significantly shorter than the time to PF during the CMJ ($p = 0.008$, $\eta^2 = 0.63$, 1-β = 0.88).

The ANOVA indicated that there was a significant difference between the peak power output during the dynamic mid-thigh clean pulls, SJ, and CMJ ($p = 0.001$, $\eta^2 = 0.99$, 1-β = 1.0). Follow-up tests indicated that there were no differences between PP during the multiple dynamic mid-thigh clean pull trials. The PP during the CMJ was significantly greater than the PP during the 30% ($p < 0.001$, $\eta^2 = 0.99$, 1-β = 1.0), 60% ($p < 0.001$, $\eta^2 = 0.97$, 1-β = 1.0), 90% ($p < 0.001$, $\eta^2 = 0.97$, 1-β = 1.0) and 120% ($p < 0.001$, $\eta^2 = 0.96$, 1-β = 1.0) dynamic mid-thigh clean pull trials. The PP during the SJ was significantly greater than the PP during the 30% ($p < 0.001$, $\eta^2 = 0.93$, 1-β = 1.0), 60% ($p < 0.001$, $\eta^2 = 0.93$, 1-β = 1.0), 90% ($p < 0.001$, $\eta^2 = 0.93$, 1-β = 1.0) and 120% ($p < 0.001$, $\eta^2 = 0.93$, 1-β = 1.0) dynamic mid-thigh clean pull trials. The PP during the CMJ was significantly higher than the PP during the SJ ($p = 0.019$, $\eta^2 = 0.52$, 1-β = 0.73).

DISCUSSION

The results of the present investigation suggest that the ability to exert isometric PF shares some functional foundation with the ability to exert dynamic PF against heavy loads, but not against light loads. In the current study, the isometric PF had strong to very strong correlations (r = 0.51–0.82) with the dynamic PF during the mid-thigh clean pulls at 30–120% 1RM power clean. Such values are comparable to those reported by Murphy et al. (24) (r = 0.37–0.81) and Haff et al. (8) (r = 0.66–0.80). The findings of the present and previous studies could be explained partially by the similar joint angle and body positions used during dynamic and isometric testing (25). However, the correlations between the isometric and dynamic PF appear to be lower and statistically nonsignificant at light load conditions as compared to heavy load conditions. Therefore, it could be argued that isometric testing of the PF can be used to evaluate the ability to exert dynamic PF against heavy loads, but may have limited value when predicting the ability to exert dynamic PF against light loads.

On the other hand, the isometric PRFD showed very weak nonsignificant correlations (r = −0.14–0.26) with the dynamic PRFD even against heavy external loads in spite of the effort to standardize the testing protocols between isometric and dynamic actions. Such correlations are much smaller than previously reported values for the upper-body movement (r = 0.41–0.73) (28) and for the lower-body movement (r = 0.84–0.88) (8). The very weak correlations found in the present study could be attributed partially to different neural patterns between dynamic and isometric testing (26). Although electromyography data were not reported in the current investigation, the past literature indicates that different motor unit activation patterns exist between dynamic and isometric muscle actions; this could explain, in part, the poor correlations found in the present investigation between the dynamic and isometric PRFD (23, 26). Therefore, the present study indicates that the isometric and dynamic PRFD are independent qualities and should be evaluated individually.

Concerning the relationship of force-time dependent variables to dynamic athletic performance, the isometric PF showed very strong significant correlations with both CMJ (r = 0.82) and SJ (r = 0.87) displacements, whereas the dynamic PF was not significantly correlated with the vertical jump performances (r = 0.27–0.72). The former finding agrees with some previous studies that found significant relationships between the isometric PF and dynamic performance (6, 21, 34), though other studies reported contrary results (i.e., poor correlations between the isometric PF and dynamic performance) (8, 39). In addition, previous research that compared the isometric and dynamic testing indicated that dynamic PF is superior to isometric PF in predicting dynamic athletic performance, possibly due to their neural and mechanical similarities (24). However, this was not supported by the results of the present study, which demonstrated the superiority of the isometric PF in predicting vertical jump performances. The disparity in the research findings of the present and previous studies could be attributed partly to the testing protocol used in the present study for dynamic muscle action. At the beginning of the concentric phase of the dynamic mid-thigh clean pulls, subjects assumed a fairly upright position with large knee and hip joint angles (141 ± 10°; 124 ± 11°, respectively). From such a position, subjects began developing force against the ground, which resulted in the extension of the lower extremities. Consequently, the PF presumably was achieved at an even more upright position with larger knee and hip joint angles during the dynamic mid-thigh clean pulls. It is possible that such a force-angle profile is different from that during the vertical jump. Such mechanical differences could be partly responsible for the poor relationship of the dynamic PF to vertical jump performances. Therefore, changing the starting position of the dynamic testing so that the joint angle at which the PF is developed corresponds with that during the performance of interest (e.g., vertical jump) might enhance the relationship of the dynamic PF to athletic performance. Although the effects of joint angles during the isometric assessment of force-time curve was investigated and found to be significant (20, 25), there are minimal data available on the effects of joint angles on the external validity of the dynamic force-time curve assessment. Therefore, future research should investigate the effects of starting body position (i.e., joint angle) of dynamic testing on the magnitude and the external validity of dynamic force-time dependent variables.

On the one hand, dynamic PRFD had strong to very strong correlations with vertical jump performances (r = 0.65–0.74) even though the correlations were not statistically significant. On the other hand, the correlations with CMJ and SJ displacements were much weaker for the isometric PRFD (r = 0.12–0.14). The poor correlations between the isometric PRFD and dynamic performance are similar to the research by Wilson et al. (39), who found no significant relationships between the isometric PRFD and sprint performance. Therefore, it could be argued that the ability to develop force rapidly in dynamic movements, but not in isometric muscle actions, has some importance in dynamic athletic performance. Pryor et al. (28) also observed a superiority of dynamic PRFD tests as compared to isometric PRFD tests in predicting dynamic performance, emphasizing the need for specificity of dynamic muscular function assessment. Therefore, it is recommended to evaluate PRFD in dynamic muscle actions, because dynamic PRFD appears to have greater relevance to dynamic athletic performance than does isometric PRFD.

Concerning the influence of external loads on the magnitude of dynamic PF and PRFD, there were general trends of increasing PF and decreasing PRFD as the external load was increased from 30–120% during the dynamic mid-thigh clean pull in the present study. The former finding is supported by the majority of the past research (8, 22, 24, 27), whereas the latter is not always the case (22, 28). Although Haff et al. (8) reported a similar trend of decreasing PRFD as the external load increased from 80–100%, other investigators did not find such a trend (22, 28).Therefore, the exact influence of external loads on the magnitude of PRFD during dynamic actions still remains to be concluded and warrants further investigation.

Traditionally, most of the past force-time curve evaluations have been done with the use of isometric testing protocols, and there is limited research that investigated the methods to determine force-time curve variables in dynamic actions (10, 11, 21). Therefore, more research is necessary in order to establish valid and reliable testing methods of dynamic force-time curve. Future research should investigate the influence of external loads, starting body position (e.g., joint angle), and types of muscle action (e.g., concentric, eccentric, stretch-shortening cycle) on the magnitude of dynamic force-time variables and their relationships to athletic performance.

Additionally, the influence of external loads on the magnitude of power outputs is of interest and has been investigated extensively using different resistance-training movements (16, 27, 32). Of particular importance for the athletes and coaches is the optimal load that maximizes power output during commonly used dynamic resistance-training exercises (18). Although it has been reported that power output is maximized at approximately 30% of maximum isometric force during single joint movements (16), it seems that a relatively wide range of loads (e.g., 10–70% 1RM) can maximize power output during different types of multi-joint movements (5, 32). In the present study, the PP was maximized at 60%, which is comparative to the finding of Kawamori et al. (17) that the optimal load for the highest PP was 70% 1RM during the hang power clean. However, the interpretation of the present finding should be made with caution, because power outputs were measured during the mid-thigh clean pull, whereas the 1RM was tested in the power clean.

In summary, the present data indicate that the isometric and dynamic measures of force-time curve characteristics represent specific or independent qualities, especially when dynamic testing involves small external loads. However, there was a general trend of increasing relationship of the ability to exert PF in isometric and dynamic muscle actions as the external load increased during dynamic muscle actions. Furthermore, the present investigation has shown that the isometric PF and dynamic PRFD were correlated strongly with vertical jump performances.

Practical Applications

The assessment of strength qualities (e.g., PF, PRFD) is essential for various purposes such as (a) identifying strength qualities that are important to the target sport, (b) monitoring training adaptations, (c) diagnosing strength, and (d) identifying talent. Therefore, evaluating isometric and dynamic force-time curve with testing protocols as used in the present investigation has the potential to provide information that would increase training efficiency and help talent identification.

Furthermore, the results of the present study indicate that athletes should train to increase isometric maximum strength and dynamic explosive strength if they intend to improve their vertical jump performances. This can be achieved through the combined use of heavy resistance training and explosive type resistance training in a periodized manner. However, because correlations do not necessarily imply "cause and effect" relationships, a longitudinal training study should be conducted in order to validate such a suggestion.

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