Learning the Hang Power Clean: Kinetic, Kinematic, and Technical Changes in Four Weightlifting Naive Athletes

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Abstract

Haug, WB, Drinkwater, EJ, and Chapman, DW. Learning the hang power clean: Kinetic, kinematic, and technical changes in four weightlifting naive athletes. *J Strength Cond Res* 29(7): 1766–1779, 2015—The investment in learning required to reach benefit with weightlifting training is currently not well understood in elite athletes. The purpose of this investigation was to quantify changes in vertical jump power production and kinematic variables in hang power clean (HPC) performance during the learning process from a naive state in a multiple single-subject research design. Four elite athletes undertook HPC learning for approximately 20–30 minutes twice per week over a 169-day period. Changes in parameters of vertical power production during squat jump (SJ) and countermovement jump (CMJ) were monitored from baseline (day 0) and at 3 additional occasions. Hang power clean movement kinematics and bar path traces were monitored from day 35 and at 3 additional occasions particular to the individual's periodized training plan. Descriptive statistics were reported within athletes as mean ± *SD*. We observed a 14.1–35.7% (SJ) and a −14.4 to 20.5% (CMJ) gain in peak power across the 4 jump testing occasions with improvements over the first 4 weeks (SJ: 9.2–32.6%; CMJ: −2.91 to 20.79%). Changes in HPC movement kinematics and barbell path traces occurred for each athlete indicating a more rearward-directed center of pressure over the concentric phase, greater double knee bend during the transition phase, decreased maximal plantar flexion, and minimal vertical displacement of body mass with HPC learning. Considering the minimal investment of 4 weeks to achieve increases in vertical power production, the benefits of training with HPC justified the associated time costs for these 4 elite athletes.

Key Words Olympic weightlifting, skill acquisition

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Introduction

The ability to produce concentric vertical power is a performance-determining variable in many sports and plays an important role in performance outcome. Although vertical power production is enhanced through repetition of relevant competition sporting movements (3–5), most elite training programs supplement with resistance-based modalities. Of the resistance training modalities shown to develop concentric vertical power production, the weightlifting movements are criterion within most elite environments. This is evidenced by 88% of National Football League (16), 100% of National Hockey League (17), and 95% of National Basketball Association (51) strength and conditioning coaches surveyed reporting the utilization of the weightlifting movements in the training of their athletes.

The weightlifting movements are used in elite training environments as they have been robustly reported to correspond with high power production capabilities and to directly increase vertical power production. Garhammer (22) reported peak power production in elite weightlifters between 1,853 and 4,807 W for snatch and 2,206 and 4,758 W for clean across weight classes, whereas Carlock et al. (8) reported correlations between 0.90 and 0.93 associating peak power during vertical jumping and the weightlifting competition movements in national and international caliber male weightlifters. Training investigations by Tricoli et al. (54) and Hawkins et al. (30) using subjects of unclear training histories and Hoffman et al. (31) using trained sub-elite athletes each reported a direct benefit of weightlifting training on vertical power production. Although these works provide insight into the relationship between weightlifting training and vertical power production, there is still a paucity of literature systematically detailing these effects on naive elite populations and the associated changes in movement technique.

Although it is acknowledged that weightlifting training develops vertical power production, teaching these lifts may not actually be a worthwhile endeavor in the strength and conditioning setting considering the significant time involvement (14,15,39) necessary to reach a minimal level

Table 1. Athlete characteristics at baseline before beginning the hang power clean learning process.

	Sex (M/F)	Age (y)	Weight (kg)	Height (cm)	Short track experience (y)	Gym experience (y)
Athlete A	M	19	63.2	175	4	2
Athlete B	F	17	49.8	165	11	3
Athlete C	M	17	75.3	180	6	2
Athlete D	M	22	75.6	175	13	7

of proficiency and initial benefit (24,47,49,55). This reported limitation may have the largest impact in elite training environments where the demands of maximizing sporting performance exceed the resources of the athlete. Because there may exist more areas of specific sporting mastery than can be effectively trained, elite-level coaches may be particularly weary of investing the time and athlete resources necessary to effectively implement weightlifting training.

Even though weightlifting training has been robustly demonstrated to increase vertical power production, it cannot be deemed a worthwhile strength and conditioning training modality for elite athlete populations until the initial time investment necessary to reach a power benefit is

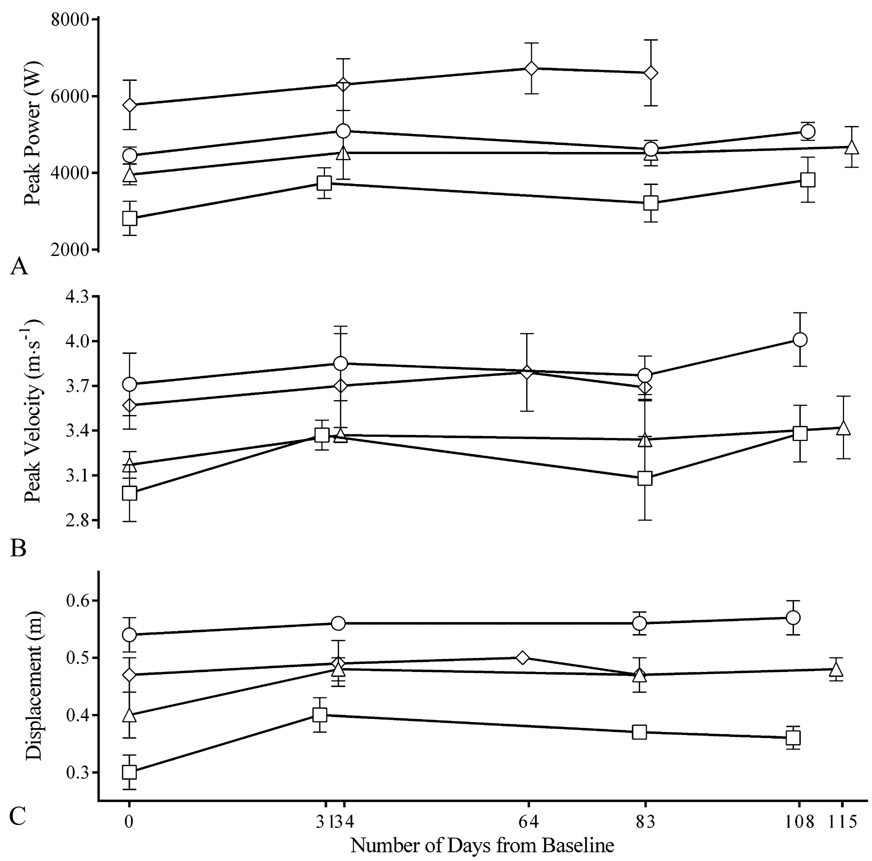


Figure 1. Changes in squat jump kinetic variables with hang power clean learning over the 4 testing occasions for athletes A (circle), B (square), C (triangle), and D (diamond). Each data point represents the mean ± *SD* of 4 trials for each athlete.

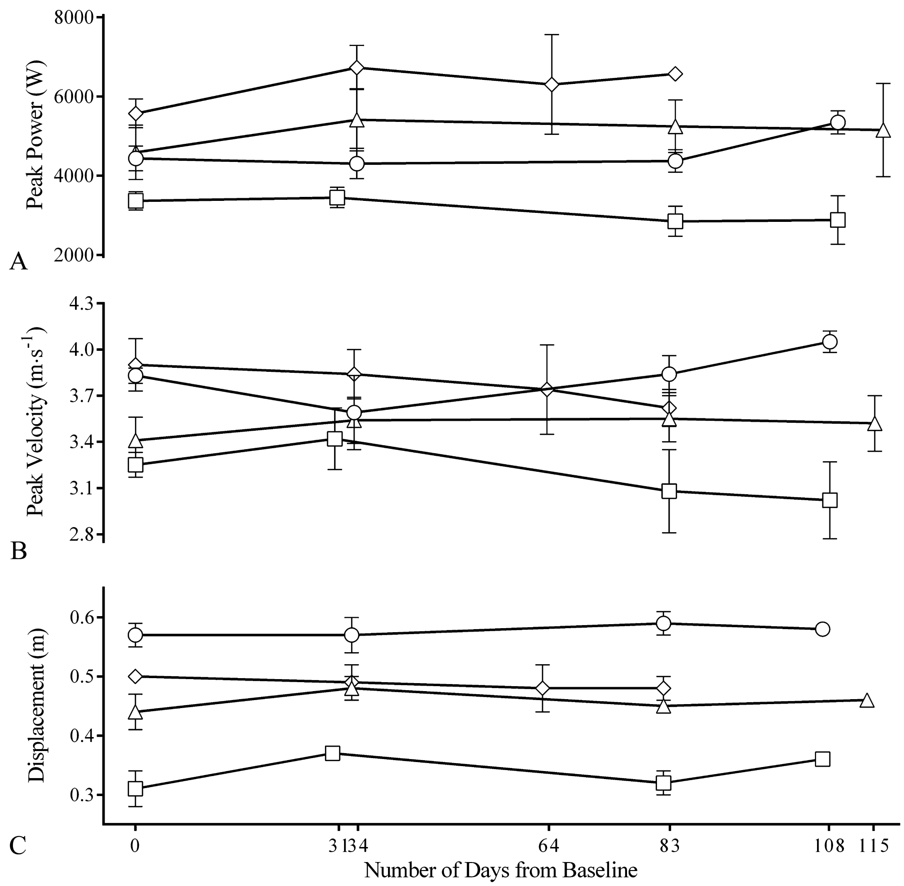


Figure 2. Changes in countermovement jump kinetic variables with hang power clean learning over the 4 testing occasions for athletes A (circle), B (square), C (triangle), and D (diamond). Each data point represents the mean ± *SD* of 4 trials for each athlete.

understood. Thus, the purpose of this investigation was to establish and systematically document the learning investment necessary to benefit vertical power production during the squat jump (SJ) and countermovement jump (CMJ) with weightlifting learning in elite athletes from a naive state. Additionally, this investigation tracked the associated kinematic changes in weightlifting technique over the course of the learning process to document technical flaws in naive elite athletes and changes with learning experience. To best understand the time investment interaction in the elite athlete training environment, particularly during an Olympic preparation, a single-subject research design was employed.

Methods

Experimental Approach to the Problem

This investigation used a single-subject time series design of 4 international caliber athletes naive to weightlifting (34). Over the course of the investigation period (maximum of 169 days), athletes regularly attended 2 hang power clean (HPC) learning sessions every 7 days in addition to their regular sport-specific training. Monitoring of jump performance occurred approximately every 28 days during the first 110 days of the learning process using measurement of kinetic data from SJ and CMJ. Kinematic monitoring of the learning progression occurred approximately every 28 days commencing after the 34th day of learning and continued through the learning process. Hang power clean learning was performed as the first exercise after the warm-up during twice weekly gym sessions and preceded by classic free-weight exercises for the lower body, including back squat, front squat, lunge, step-up, and Romanian deadlift (RDL). A single low- to medium-level plyometric (e.g., jump rope, low lateral hops) exercise was introduced to the program on an individual basis after the 64th day from baseline; however, volumes were kept low and the exercise used was familiar from training history. All other weighted and unweighted jump exercises historically used in the training of these athletes were omitted from the program during the investigation period. All HPC learning sessions were taught directly via one-to-one instruction by the first author

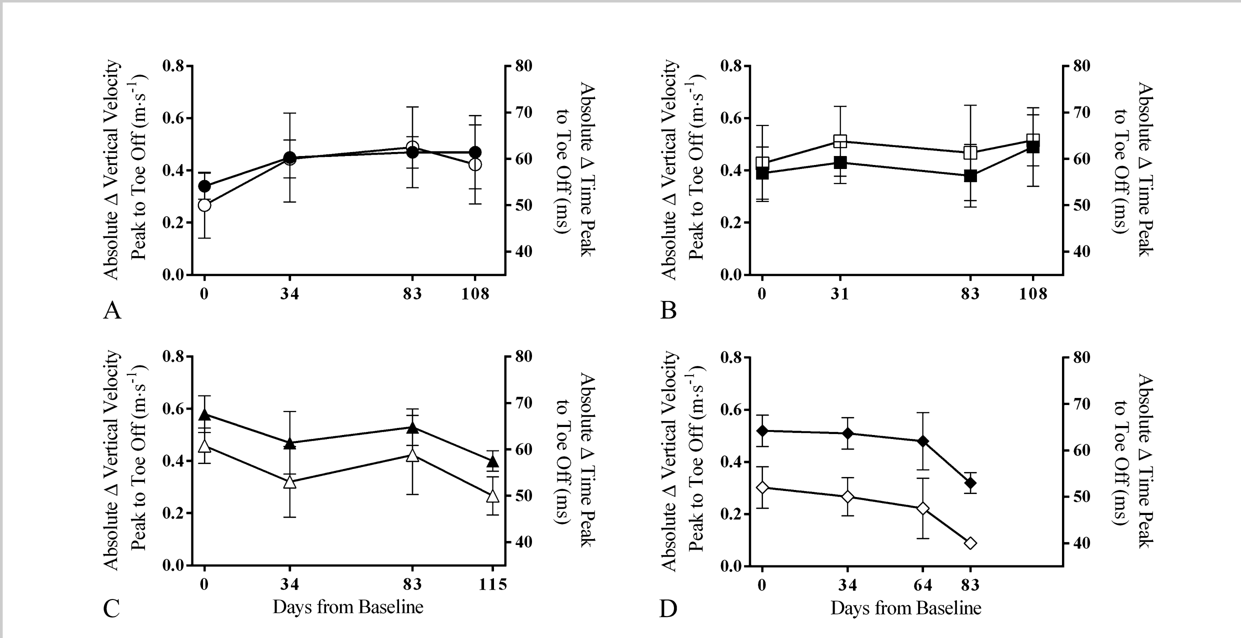


Figure 3. Changes in end range of motion countermovement jump kinetics: difference between peak and toe off velocities (filled shape); timing of peak velocity relative to toe off (open shape) with hang power clean learning over the 4 testing occasions for athletes A (circle), B (square), C (triangle), and D (diamond). Each data point represents the mean ± *SD* of 4 trials for each athlete.

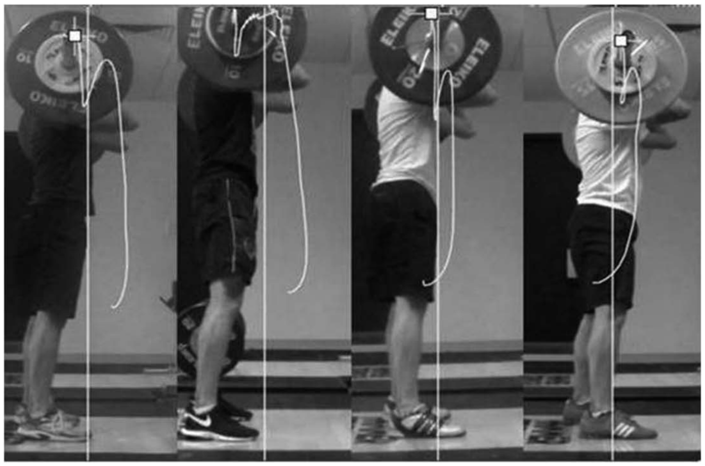
(holding qualifications with NSCA CSCS, USAW level 1, and 4+ years of experience instructing and programming the weightlifting movements to National Collegiate Athletic Association Division I and Olympic-level athletes). Teaching progression used a "part-whole" and "top-down" approach as suggested in common coaching literature (14,15,33,39). Briefly, each athlete began with a basic group of exercises (e.g., shrug, jump shrug) and progressed to greater complexity movements only when deemed proficient; however, earlier progressions were revisited throughout the learning period based on individual need. Initial teaching sessions for the first 14–28 days were time based with 20–30 minutes per gym session allocated to HPC learning. Then, based on individual athlete technical progression, duration-based sessions yielded to formalized training consisting of planned volumes, relative intensities, and rest periods. The number of total repetitions and rest periods per session were determined by the investigator and based primarily on the load and movement pattern used with earlier progressions involving bar work permitting the highest volume of repetitions and later progressions under greater loading permitting the fewest repetitions (all in a periodized manner). As athlete movement proficiency progressed with training experience, the load used was determined in consultation between athlete and investigator. The primary loading emphasis was a relative intensity sufficient to create a training stimulus, but not so intense as to cause premature fatigue or technical breakdown with subsequent repetitions.

Subjects

Athletes ($n = 4$) were members of the Australian National Short Track Speed Skating Team and were registered members of the Australian Olympic Shadow team with each voluntarily participating in the investigation. Each athlete had previous experience with free-weight resistance training consisting predominantly of multi-joint lower-body strength exercises, including squat variations, deadlifts, and lunge variations. However, all athletes were naive to the weightlifting movements (i.e., snatch, clean, jerk) and their variations (e.g., clean pull). Athletes' physical characteristics, sex, age, weight, height, short track experience, and resistance training experience, are shown in Table 1. Athletes were between the ages of 17 and 22 years at the beginning of the investigation. No parameters of on-ice performance were kept during the investigation period as regular time trials were not part of training in this phase of their periodized plan and supplemental testing was not possible during an Olympic season. Informed consent was obtained from each participant or from participant and parent or guardian if under the age of 18 years. The Australian Institute of Sport and the Charles Sturt University Human Research Ethics Committees both approved this investigation.

Monitoring Parameters

Hang power clean monitoring commenced on the 35th day as the athletes were naive and thus incapable of producing an HPC movement pattern at baseline (day 0). During HPC monitoring, athletes performed 3 sets of 2–3 repetitions



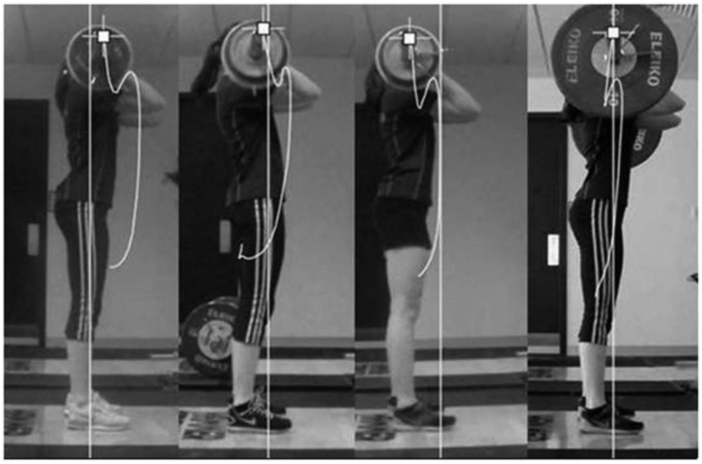
Variable	Days from Baseline			
	34	62	99	163
START				
Hip (°)	104.75 (4.06)	99.00 (5.48	100.75 (4.98)	105.33 (3.32)
Knee (°)	143.63 (6.48)	134.75 (7.09)	144.00 (2.62)	145.56 (3.68)
Ankle (°)	91.50 (3.78)	91.86 (1.73)	95.50 (1.20)	107.33 (2.06)
TRANSITION				
Hip (°)	120.50 (2.07)	114.75 (5.65)	122.88 (2.30)	119.44 (3.94)
Knee (°)	116.88 (3.14)	112.75 (5.78)	124.00 (4.21)	122.56 (3.54)
Ankle (°)	87.38 (2.50)	88.50 (2.51)	92.38 (2.77)	96.67 (3.00)
Shin v Perpendicular (°)	30.75 (0.71)	29.00 (2.20)	23.50 (2.00)	20.22 (1.39)
PEAK EXT				
Hip (°)	179.50 (1.20)	181.25 (1.49)	177.63 (2.13)	176.33 (2.40)
Knee (°)	176.75 (1.83)	177.13 (2.42)	174.13 (4.49)	174.44 (2.74)
Ankle (°)	141.25 (2.55)	139.50 (2.27)	126.63 (3.50)	124.78 (2.33)
CATCH				
Back v Horizon (°)	87.13 (3.91)	88.00 (2.25)	87.25 (3.41)	82.89 (2.85)

Figure 4. Changes in kinematic variables and sagittal plane bar path trace over the 4 testing occasions for athlete A. Vertical reference line is drawn from right metatarsal-phalangeal joint at start position; deviation from this line in the finish position indicates the athlete has moved forward or backward during the catch phase. Data collection ceased when the bar reached peak vertical displacement after the catch. Values represent mean (*SD*) of 6–9 trials for the individual athlete.

filmed from the sagittal plane (GoPro Hero4; GoPro, San Mateo, CA, USA) at 120 Hz with a minimum of 3 minutes rest between sets. Subject to athlete training status, testing sets employed 75–90% loads of an estimated 1 repetition maximum (1RM). The following HPC kinematic variables were identified from each testing occasion: hip, knee, and ankle joint angles at start concentric phase HPC (START); hip, knee, ankle joint angles, and shin angle vs. vertical at peak knee flexion of double knee bend HPC (TRANSITION); hip, knee, and ankle joint angles at completion of second pull (PEAK EXT); torso angle vs. horizon at the final rack position (CATCH); peak vertical displacement of right ankle as an indicator of vertical body mass displacement (ANKLE PVD); maximal horizontal displacement of barbell anterior to metatarsal-phalangeal joint (BB MAX HD); and qualitative analysis of the concentric bar path trace.

All joint angle trackings were performed and analyzed with Kinovea version 7.1 (Kinovea.org, open source); bar path tracking was performed with Dartfish TeamPro (Dartfish; Fribourg, Switzerland) and analyzed with Image J software (National Institutes of Health, Bethesda, MD, USA). For a given frame, a measurement scale was set with a known distance of the weightlifting plate visible in frame. To compare changes in concentric sagittal plane bar path over time, a digital trace of the second repetition's bar path from a set using a load between 75 and 85% estimated 1RM HPC set at each time point was determined. To determine BB MAX HD, a vertical reference line was placed at the metatarsal-phalangeal joint from the start position and peak horizontal distance between reference line and barbell trace recorded.

To provide insight into kinetic changes accompanying HPC learning process, vertical SJ and CMJ measurements were recorded via a linear position transducer (GymAware; Kinetic Performance, Mitchell, Australia). To examine how the HPC learning process affected CMJ end range of motion (ROM) strategy, force production at toe off, changes in the timing of peak velocity, and the decrease in velocity from peak to toe off were determined at each testing occasion via force plate (FT 400; Fitness Technologies, Skye, Australia). Vertical jump testing commenced at baseline (day 0), and on each testing occasion, athletes first performed 1 set of 4 SJ and then a single set of 4 CMJ repetitions with no added resistance (all at body weight). All jumps were performed with a bar of minimal mass (0.2 kg) placed on the shoulders in a high barbell squat position. A minimal pause separated each jump repetition as each athlete returned themselves to the initial starting position and reset to perform the next repetition with each set of SJ and CMJ separated by a minimum of 8 minutes. The variables monitored for both SJ and CMJ were as follows: peak vertical power, peak vertical velocity, peak vertical displacement, difference between peak velocity and velocity at toe off, and elapsed time between peak velocity and toe off. Although the athletes performed no additional resistance-based power training over the course of the investigation, they did perform on-ice sprint protocols in conjunction with dryland skating–specific



Variable	Days from Baseline			
	34	62	99	124
START				
Hip (°)	115.22 (7.52)	112.86 (2.04)	103.44 (2.65)	103.29 (1.38)
Knee (°)	138.13 (6.15)	144.57 (3.41)	130.56 (3.94)	141.86 (1.95)
Ankle (°)	89.63 (4.90)	95.14 (2.34)	93.78 (2.86)	95.71 (2.29)
TRANSITION				
Hip (°)	117.25 (2.43)	117.43 (4.28)	117.89 (3.62)	114.86 (4.56)
Knee (°)	122.25 (3.06)	127.71 (3.90)	125.22 (2.05)	131.14 (2.34)
Ankle (°)	85.00 (2.62)	88.71 (3.45)	89.44 (2.83)	90.29 (2.56)
Shin v Perpendicular (°)	21.88 (2.53)	18.86 (2.27)	19.78 (1.56)	15.57 (1.27)
PEAK EXT				
Hip (°)	173.88 (5.25)	175.00 (3.96)	178.33 (1.00)	180.00 (1.91)
Knee (°)	167.00 (2.27)	169.71 (2.36)	174.56 (1.94)	172.29 (2.75)
Ankle (°)	127.38 (1.30)	132.29 (2.14)	132.22 (1.56)	135.57 (0.98)
CATCH				
Back v Horizon (°)	81.25 (2.66)	84.00 (5.69)	80.44 (1.67)	80.43 (1.72)

Figure 5. Changes in kinematic variables and sagittal plane bar path trace over the 4 testing occasions for athlete B. Vertical reference line is drawn from right metatarsal-phalangeal joint at start position; deviation from this line in the finish position indicates the athlete has moved forward or backward during the catch phase. Data collection ceased when the bar reached peak vertical displacement after the catch. Values represent mean (*SD*) of 6–9 trials for the individual athlete.

endurance vertical jump protocols approximately 1–2 times every 7 days as part of their regular training. All on-ice sprint and dry-land jump protocols had been performed in a similar manner by each athlete for a minimum of 3 years.

Statistical Analyses

Hang power clean data are reported as mean ± *SD* of all within-testing session repetitions. Vertical jump data are reported as mean ± *SD* of all within-testing session repetitions for either SJ or CMJ. Typical error of measurement for CMJ has been reported as 0.02 m (57), whereas the typical error of measurement across all joint angles was 1.77° and 0.016 m for distances.

Results

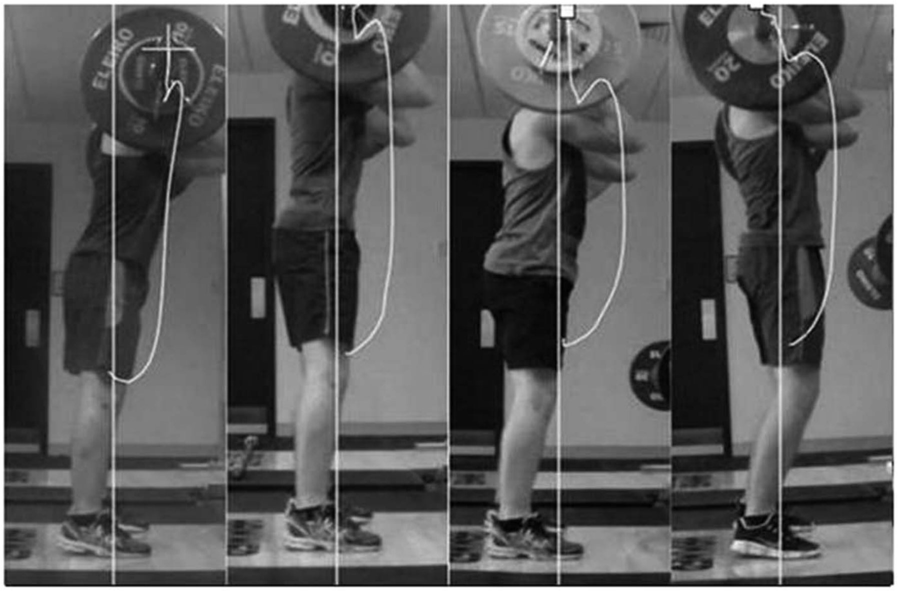
The mean number of sessions attended by each athlete was 26.00 ± 5.89 resulting in 494 ± 157.89 HPC repetitions completed. Each athlete missed a 20-day period of specific HPC training because of an international on-ice training camp where HPC training was deemed inconsistent with the periodized plan. However, HPC 3RM improved 60–70% for each athlete over the course of the investigation.

Learning Progression Vertical Jump Kinetic Changes

The Squat Jump Performance. At baseline (day 0), the athletes produced 4,452.78 ± 216.83, 2,814.13 ± 445.75, 3,957.49 ± 271.83, and 5,772.46 ± 644.38 W peak power (athletes A–D, respectively). By the first jump testing occasion (day 34), peak power increased 14.1–35.7% in all athletes, with similar positive changes observed for peak velocity (3.4–13.4%) and peak vertical displacement (3.7–20.0%) (Figure 1). This trend continued through the third testing occasion (athlete D: day 64; athletes A–C: day 83) as all athletes demonstrated increases in peak power, velocity, and vertical displacement (Figure 1). Across all 4 jump testing occasions (athlete D: 84 days; athletes A and B: 109 days; athlete C: 116 days), all athletes demonstrated improved peak power (14.1–35.7%) and peak velocity (3.4–13.4%); however, only 3 of 4 athletes exhibited an increase in peak vertical displacement (5.6–20.0%) with the fourth athlete observed no change (Figure 1).

The Countermovement Jump Performance. Athletes at baseline produced 4,437.57 ± 313.21, 3,363.93 ± 231.11, 4,589.93 ± 686.25, and 5,773.81 ± 363.83 W peak power (athletes A–D, respectively). By the first jump testing occasion, peak power increased for 3 of 4 athletes; peak velocity and peak displacement increased for 2 of 4 athletes (Figure 2). By the third testing occasion, 2 of 4 athletes demonstrated increases in peak power and peak velocity; peak displacement increased for 3 of 4 athletes (Figure 2). Across all 4 jump testing occasions, 3 of 4 athletes demonstrated increases in peak power and peak displacement; 2 of 4 athletes demonstrated increases in peak velocity (Figure 2).

Difference in Vertical Velocities Between Peak and Toe Off. Two of 4 athletes recorded a reduction in the difference between



Variable	Testing Occasion			
	34	77	126	170
START				
Hip (°)	90.75 (3.41)	103.25 (2.38)	101.67 (2.29)	109.56 (3.47)
Knee (°)	141.88 (3.60)	152.75 (3.49)	146.56 (3.28)	154.78 (3.15)
Ankle (°)	99.25 (2.25)	102.00 (3.80)	99.33 (3.28)	98.50 (1.58)
TRANSITION				
Hip (°)	116.13 (3.40)	119.13 (2.85)	115.44 (4.19)	121.56 (3.28)
Knee (°)	111.63 (4.44)	117.13 (1.55)	113.89 (3.55)	131.00 (4.27)
Ankle (°)	84.63 (2.72)	87.13 (3.56)	84.22 (1.92)	93.00 (2.44)
Shin v Perpendicular (°)	31.50 (2.39)	28.13 (1.64)	25.00 (1.00)	17.67 (1.58)
PEAK EXT				
Hip (°)	181.50 (2.00)	180.25 (2.31)	170.67 (4.06)	173.78 (3.11)
Knee (°)	173.13 (4.32)	174.00 (2.73)	168.78 (3.27)	168.33 (4.09)
Ankle (°)	141.88 (2.10)	141.86 (1.46)	137.44 (2.13)	133.67 (2.00)
CATCH				
Back v Horizon (°)	89.89 (5.58)	98.00 (7.14)	94.14 (6.72)	87.00 (1.41)

Figure 6. Changes in kinematic variables and sagittal plane bar path trace over the 4 testing occasions for athlete C. Vertical reference line is drawn from right metatarsal-phalangeal joint at start position; deviation from this line in the finish position indicates the athlete has moved forward or backward during the catch phase. Data collection ceased when the bar reached peak vertical displacement after the catch. Values represent mean (*SD*) of 6–9 trials for the individual athlete.

peak and toe off vertical velocities (athlete A: 38.24%; athlete B: 25.64%; athlete C: −31.03%; athlete D: −38.46%) across all 4 jump testing occasions (Figure 3). Of the 2 athletes exhibiting this trend, athlete C decreased on 3 of the 4 testing occasions (day 0: 0.58 ± 0.07 $m \cdot s^{-1}$; day 34: 0.47 ± 0.12 $m \cdot s^{-1}$; day 83: 0.53 ± 0.07 $m \cdot s^{-1}$; day 115: 0.40 ± 0.04 $m \cdot s^{-1}$) and athlete D decreased on each occasion (day 0: 0.52 ± 0.06 $m \cdot s^{-1}$; day 34: 0.51 ± 0.06 $m \cdot s^{-1}$; day 64: 0.48 ± 0.11 $m \cdot s^{-1}$; day 83: 0.32 ± 0.04 $m \cdot s^{-1}$).

Timing of Peak Velocity. Changes in the elapsed time between peak velocity and toe off (Figure 3) indicate that athletes C and D had substantial time reductions across all 4 jump testing occasions (athlete A: 17.60%; athlete B: 8.47%; athlete C: −17.76%; athlete D: −23.08%). Interestingly, athlete C demonstrated a decrease on 3 testing occasions (Day 0: 61 ± 4 ms, Day 34: 53 ± 8 ms; Day 83: 59 ± 9 ms; Day 115: 50 ± 4 ms), whereas athlete D demonstrated a reduction on each occasion (Day 0: 52 ± 5 ms, Day 34: 50 ± 4 ms; Day 64: 48 ± 7 s; Day 83: 40 ± 0 ms).

Learning Progression Kinematic Changes

The changes in kinematic variables during HPC learning for each athlete are summarized in Figures 4–8.

Variable	Days from Baseline			
	34	64	99	126
START				
Hip (°)	106.33 (6.76)	103.00 (2.45)	109.14 (2.85)	109.83 (6.52)
Knee (°)	142.33 (4.87)	151.00 (5.86)	150.29 (5.25)	146.33 (4.41)
Ankle (°)	102.56 (2.30)	107.57 (2.76)	109.00 (5.23)	109.17 (2.04)
TRANSITION				
Hip (°)	124.67 (4.80)	128.29 (4.07)	124.71 (3.20)	122.17 (3.43)
Knee (°)	123.78 (4.58)	124.43 (4.50)	136.57 (4.16)	127.00 (2.68)
Ankle (°)	105.89 (2.37)	112.43 (3.10)	106.29 (4.07)	104.17 (2.32)
Shin v Perpendicular (°)	25.22 (1.48)	23.57 (1.62)	17.29 (1.89)	19.83 (0.98)
PEAK EXT				
Hip (°)	184.89 (4.96)	184.57 (3.99)	183.00 (3.92)	177.83 (2.56)
Knee (°)	174.67 (5.45)	174.71 (2.36)	175.71 (3.59)	172.50 (1.38)
Ankle (°)	151.67 (4.47)	156.86 (3.02)	137.71 (2.69)	136.50 (2.88)
CATCH				
Back v Horizon (°)	85.50 (2.00)	87.50 (3.38)	88.44 (2.24)	83.78 (2.59)

Figure 7. Changes in kinematic variables and sagittal plane bar path trace over the 4 testing occasions for athlete D. Vertical reference line is drawn from right metatarsal-phalangeal joint at start position; deviation from this line in the finish position indicates the athlete has moved forward or backward during the catch phase. Data collection ceased when the bar reached peak vertical displacement after the catch. Values represent mean (*SD*) of 6–9 trials for the individual athlete.

START. Across HPC kinematic testing (athlete A: 129 days; athlete B: 90 days; athlete C: 136 days; athlete D: 92 days), 3 of 4 athletes increased their ankle joint angle at the START position (athlete A: 17.30%; athlete B: 6.78%; athlete C: −0.76%; athlete D: 6.45%). This trend was evident by the second testing occasion with all 4 athletes demonstrating increase (day: 62–77; athlete A: 0.39%; athlete B: 6.15%; athlete C: 2.77%; athlete D: 4.88%).

TRANSITION. All athletes decreased the shin angle vs. perpendicular (athlete A: −34.24%; athlete B: −28.84%; athlete C: −43.90%; athlete D: −21.37%) and increased peak knee flexion (athlete A: 4.86%; athlete B: 7.27%; athlete C: 17.35%; athlete D: 2.60%) across HPC kinematic testing in the TRANSITION position. This trend was evident for both variables by the second testing occasion for all 4 athletes (athletes A and B: day 62; athlete D: day 64; athlete C: day 77). The magnitude of reduction in shin angle vs. perpendicular at this time ranged between −5.69 and −13.80% across the 4 athletes. However, only 3 of 4 athletes at the second testing occasion were observed to have increased peak knee flexion (athlete

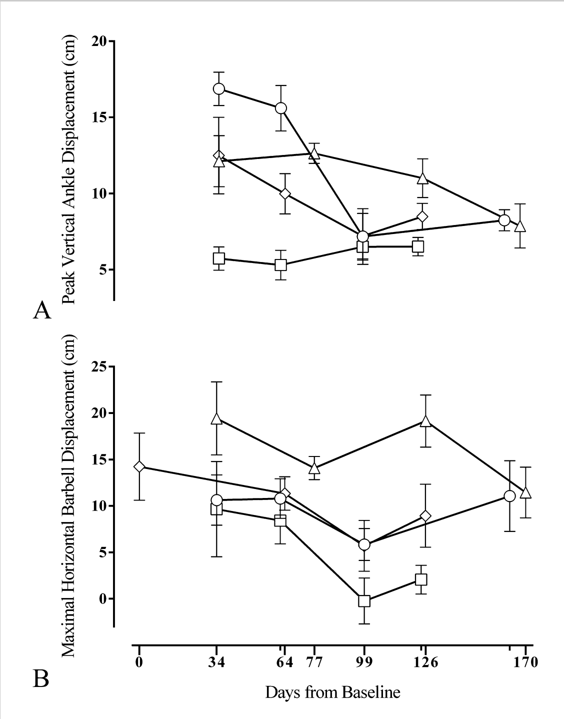


Figure 8. Changes in (A) ANKLE PVD and (B) BB HD MAX for each athlete over the 4 testing occasions for athletes A (circle), B (square), C (triangle), and D (diamond). Each data point represents the mean ± *SD* of 6–9 trials for each athlete. *X* axis short tick marks indicate days from baseline of 62, 124, and 163.

A: −3.53%; athlete B: 4.47%; athlete C: 4.93%; athlete D: 0.53%).

PEAK EXT. Three of 4 athletes decreased plantar flexion (athlete A: −11.66%; athlete B: 6.43%; athlete C: −5.79%; athlete D: −10.00%) during HPC learning with this trend observed in 2 of 4 athletes by the second occasion (athlete A: −1.24%; athlete B: 3.85%; athlete C: −0.01%; athlete D: 3.42%). At peak extension, the decrease in plantar flexion was observed to occur in isolation of changes in other kinematic variables as no visible pattern of change was evident at the hip or knee for the involved athletes.

CATCH. All athletes reduced their torso angle at CATCH across HPC kinematic testing; however, the decrease in all athletes was not observable by the second testing occasion (athlete A: 1.00%; athlete B: 3.38%; athlete C: 2.34%; athlete D: 9.02%).

ANKLE PVD. At the initial HPC kinematic testing occasion (day 34), the athletes exhibited a range of peak ankle vertical displacement with greatest displacement recorded by athlete A (day 34: 16.87 ± 1.09 cm) and the smallest initial displacement by athlete B (day 34: 5.73 ± 0.76 cm). In contrast, by the completion of the formal learning process (athlete B: day 124; athlete D: day 126; athlete A: day 163; athlete C: day 170), all athletes exhibited similar peak ankle vertical displacements ranging between 6.51 ± 0.60 cm (athlete B) and 8.49 ± 0.86 cm (athlete D).

BB MAX HD. Three of 4 athletes decreased (athlete A: 4.05%; athlete B: −78.65%; athlete C: −41.04%; athlete D: −37.13%) across all 4 HPC kinematic testing occasions with this trend emergent by the second testing occasion (athlete A: 1.51%; athlete B: −12.75%; athlete C: −27.50%; athlete D: −20.32%).

Discussion

A key finding of this investigation is weightlifting training–benefited vertical power production in all 4 elite athletes within the first 35 days of learning from a naive state with continued effects for 84–116 days. This is evident from increased SJ peak power both at the second jump testing occasion (9.2–32.6% increase) and across all 4 jump testing occasions (14.1–35.7% increase) for all 4 athletes (Figure 1). Accompanying changes in CMJ power production, 2 athletes demonstrated changes in end ROM force application through clear trends toward better timing of peak velocity and a decreased velocity differential between peak and toe off (Figure 3) across all jump testing occasions. Accompanying increases in power production were changes in technique exhibited across all stages of the HPC for each athlete. Although previous works have demonstrated the benefits of training with weightlifting techniques on vertical jump performance (30,31,54), this is the first to specifically use an elite group of athletes and the first to report changes in vertical power production simultaneously with technical skill acquisition. Furthermore, this is the first investigation to track changes in movement kinematics under practical loading conditions and the first longitudinal investigation. In addition to improvements in vertical power production, we observed consistent kinematic (technique) changes in athletes' performance of the HPC. A learning theme common to the 4 athletes was changes in kinematics suggesting barbell center of mass shifted to a position more over the base of support and a more efficient utilization of hip extension to drive vertical power production. This is apparent from increases in ankle angle at START, smaller shin angles vs. perpendicular at TRANSITION (Figures 4–7), and the minimization of BB MAX HD (Figure 8B) across all 4 HPC kinematic testing occasions. When considered together, these adjustments provide evidence of a posterior-directed shift in center of pressure (COP) throughout the concentric phase of HPC and the possibility of a corresponding increase in utilization of the hip extensors to drive vertical barbell velocity (19). We also demonstrate a shift with increased expertise toward decreased plantar flexion at PEAK EXT (Figures 4–7). A further important finding is the shift toward minimal but existent ANKLE PVD with HPC learning (Figure 8A). Importantly, all these technical changes were observed during HPC performance under loads of 75–90% 1RM (estimated), providing substantiative evidence under conditions experienced in practical training environments (46,53). We believe that the underpinnings of these shifts are multifactorial with the need to maximize impulse, limit the amount of ground reaction force directed at moving body mass, and perform a ballistic-intentioned movement all playing a role.

A major finding of this investigation is HPC learning from a naive state yielded benefits to vertical power production within the initial 4 weeks of learning for 4 elite short track speed skating athletes. This is the first investigation to our knowledge that systematically documents the time frame to initial power benefit with weightlifting learning in elite athletes. These changes are verified through gains by all athletes in all parameters of SJ (peak power, peak velocity, peak displacement) and gains in CMJ peak power experienced by 3 of 4 athletes by day 34. Although the HPC may be a more technical movement pattern than other power development modalities like plyometric and weighted jumps (11,13,47,55), it was capable of producing benefit within similar time frames for our athletes (11,12). Considering the long-term demonstrated benefit of weightlifting training on vertical power production in combination with the flat learning curve reported in this investigation, we consider weightlifting training to be a worthwhile power development tool for these elite athletes.

In addition to the novel short-term benefits documented, the results of our investigation support continued benefits on vertical power production with 3 of 4 athletes demonstrating gains in peak power and peak velocity for SJ between the final 2 jump testing occasions. Although it is possible that the 125- to 171-day period was approaching a performance plateau, the comparatively technical nature of the weightlifting movements suggests much longer time frames to staleness of stimulus. Although all 4 athletes in this investigation were elite and quickly grasped the HPC movement pattern, no athlete approached the attainment of technical mastery at study completion. The notion of multiyear time frames to exhibit mastery of the weightlifting movements is supported in the literature (2,37,55), though we would contend that mastery is not necessary to use HPC to improve vertical power production as observed by the SJ and CMJ performances of these athletes (Figures 1 and 2). Considering HPC technical development can be partially defined as improved power production efficiency, improvement in technical parameters is likely to be associated with further power gains.

Although athletes C and D failed to demonstrate substantial changes in CMJ peak vertical displacement with HPC learning, both nonetheless demonstrated shifts in force application strategy. This is the first investigation to report direct changes in end ROM jump kinetics with weightlifting training. Changes were evident from increases in vertical velocity at toe off relative to peak vertical velocity and the timing of peak vertical velocity closer to toe off with HPC learning (Figure 3). This trend is important as the performance outcome (i.e., peak displacement) is determined entirely by vertical velocity in combination with height of center of mass at toe off (9,38). Thus, the minimization of velocity loss between peak and toe off, potentially resulting from the timing of peak closer to toe off, should maximize peak vertical displacement. We hypothesize that trained weightlifters will tend to produce vertical velocity values at toe off closer to peak velocity than elite jumping athletes naive to the lifts and weightlifters accomplish this through deceleration of the hip and knee joints later in the ROM; however, this is yet to be systematically confirmed. This hypothesis is supported by modeling work reported by Pandy et al. (43), who determined that the theoretical maximization of displacement requires the complete absence of joint deceleration during ground contact as a means to maximize impulse. Strategies completely void of deceleration may not be practical because of the need to protect joint integrity (1); however, weightlifting training may function to improve vertical power production by delaying the timing of deceleration.

As suggested in coaching literature (14,23,27,36,44,45,47) and confirmed through kinematic analysis performed with elite weightlifters (28,29,32), proficiency in the above-knee HPC start position is characterized by a mid- to rear-directed COP, with the shoulders “covering the bar” as viewed from the sagittal plane. Hip (42,48,55) and ankle (42,47,48) angles tend to approach a right angle, and knee angles tend to be obtuse and between 145° and 155° (35,47,55). All athletes in this investigation showed an intuition for the start position at baseline, which we attribute to preexisting familiarity with the RDL. Despite understanding the initial start position, athletes nonetheless demonstrated kinematic changes over the course of the investigation with differences about the ankle being the most consistent and notable (Figures 4–7). Increases in START ankle angle with learning were observed in athletes A, B, and D, indicating a shift toward a mid to rear-based COP, which is expected when compared with elite weightlifter kinematic analyses (20,23,27,47,55). An appropriate rearward shift keeps the bar in a more biomechanically efficient position as the knees navigate the bar and may allow for a more efficient utilization of hip extension over the course of the transition and second pull. Hip and knee start kinematics also showed change in athletes B, C, and D, but a greater variation in the pattern of change between athletes was observed (Figures 4–7). We propose that this between-athlete variation occurs as each athlete moves from a basic conceptual understanding of the general HPC movement pattern to a more specialized motor pattern specific to their individual genetics. Once a general movement framework is understood, the kinesthetic feedback provided by the hundreds of HPC repetitions performed affords each athlete an opportunity to understand optimal hip and knee positions for their individual joint leverages and technical style. An individual outcome as optimal is supported by the between-athlete differences reported in hip and knee joint angles within elite weightlifting populations (47,48,55), suggesting that a specific value or combination of values is not a criterion.

Similar to START, best evidence suggests TRANSITION (position of maximal knee flexion) is characterized by a mid- to ball of foot–directed COP (27,47,55) and a shoulder position that continues to cover the bar, although to a lesser extent (23,47,48). In comparison with START, proficient TRANSITION is marked by relatively greater hip angles and lesser knee and ankle angles (47,48,55), which is intuitive considering the repositioning of the knees to a more flexed position (18,27) and force developed through hip extension (55) as the barbell passes the lower thigh. It was observed that over time, all athletes exhibited an increase in knee flexion during TRANSITION (Figures 4–7). Enoka (18), and later supported by Garhammer and Taylor (27), reported that the knee extensors play a pivotal role in driving power production during the second pull of the clean. Thus, knee extension–based power production over a greater ROM is an intuitive progression for novice athletes. Although the results of this investigation lend support, this hypothesis must be considered in context, as the knee does not work in isolation during the transition phase or the second pull. Novice athletes may underuse knee ROM during the second pull (Figures 4–7) because of an inability to effectively drive vertical barbell velocity through hip extension while simultaneously repositioning the knees to an optimal position. It is this balance between effective hip extension and simultaneous knee flexion that deems the transition phase of the HPC the toughest to master during weightlifting pulls (50,52).

The descriptive results of this study indicate improvements in transition phase mechanics as evidenced by changes in ankle and shin angles at TRANSITION with all athletes demonstrating a more vertical shin angle at TRANSITION and athletes A, B, and C concurrently showing greater ankle angles. These changes provide for a more vertical shank position and corresponding mid- to ball of foot–directed COP (19). This positioning allows not only a more efficient utilization of hip extension during the transition phase (7,55) but also the continuous use of hip extension to drive power in combination with the knee and ankle extensors during the subsequent second pull (47). The purpose of the HPC transition is to produce vertical barbell velocity through hip extension while simultaneously setting the hips and knees in a position to maximize further power contribution during the subsequent second pull. The more mid-directed COP with HPC learning and the increased knee flexion at TRANSITION support the concept of transition mechanics moving in a direction of greater efficiency for these 4 athletes.

Criterion angles for each joint at PEAK EXT have not been established and are hotly debated in both weightlifting and strength and conditioning circles with some coaches advocating full "triple extension" (6,21,33,44,45) and others preferring more acute angles across some or all lower-body joints (28,29,32,47,48). Although the benefits of maximizing impulse would support triple extension as the criterion, various analyses with elite weightlifters tend to discount the maximization of plantar flexion (27,28,47) in proficient HPC mechanics. The observations of this investigation clearly dispute the efficacy of triple extension at the ankle joint with all athletes progressing toward a tendency of submaximal plantar flexion at PEAK EXT despite being instructed to use maximal ankle extension during HPC execution (Figures 4–7). Although athletes A, C, and D trended toward decreased plantar flexion with HPC learning and the fourth athlete toward increased plantar flexion, all finished the investigation within a similar range of submaximal values ($124.78 \pm 2.33°$ to $136.50 \pm 2.88°$).

Our reported observation of submaximal plantar flexion with HPC learning in conjunction with elite weightlifter analyses (29,47,49) suggests submaximal plantar flexion as necessary to maximize the kinematic links during HPC. Although advocating ankle joint utilization over a fuller ROM is intuitive considering the reliance of force production on impulse, this model does not consider lower-body biomechanics as a system. Thus, it is possible that usage of the ankle joint over its end ROM may come at the expense of effective hip extension. An optimal HPC strategy requires power production through hip extension (47,49,55), which may only be possible when the COP is more mid-foot directed through the transition and into the second pull. Under this strategy, the COP still shifts toward the tarsals during the second pull; however, it may not permit a complete distal shift thus limiting plantar flexion.

There is a paucity of literature detailing joint-specific angles at CATCH; however, technically proficient weightlifters have been reported to demonstrate more acute angles than do less proficient weightlifters (47,55). Proficient CATCH may be an indicator of correct sequencing and utilization of the lower-body musculature over the preceding second pull with aggressive but inefficient utilization of the hip resulting in larger CATCH angles. The naive athletes in this investigation demonstrated proficient CATCH angles (Figures 4–7). The ability to perform a proficient CATCH in a relatively short learning period may indicate a more intuitive understanding of proficient hip mechanics and lower-body sequencing over the course of the second pull. It is possible that this intuition is the same trait that allows elite skaters to efficiently learn technical short track skills from a naive state. Alternatively, it could be a learned skill exhibiting direct transfer from the jump training used by these athletes as the clean is known to be a vertical jump applied to a barbell (25).

ANKLE PVD as a measure of center of mass displacement is a source of contention in weightlifting and strength and conditioning circles with some coaches advocating minimal values and others preferring continuous contact or zero displacement (47,55). The argument for continuous contact is to ensure true maximal time to apply vertical force and the minimization of vertical body mass displacement; however, this coaching theory may not consider the link between maximal power production and ballistic movement patterns. The ANKLE PVD is used as an indicator of athlete vertical center of mass displacement during HPC with technically proficient weightlifters tending to demonstrate smaller vertical ankle displacement values than less proficient weightlifters (47,49). Minimizing vertical center of mass displacement may be an important factor in HPC efficiency as it creates longer times of contact between the lifter and the platform potentially aiding impulse (49) and because a greater percentage of vertical power production is directed at moving the mass of the bar as opposed to mass of the bar and the lifter (26). Our observational data support minimal, but not absent, ANKLE PVD values as the criterion measure of HPC efficiency as this movement pattern provides the benefits of extended contact time and approaching minimal body mass vertical displacement allowing the kinematic links to maximize power production through the given ROM. Although 3 athletes in this investigation demonstrated a consistent trend with learning toward smaller ANKLE PVD values, the fourth athlete remained relatively the same with all athletes finishing in a similar range of small, but not absent, peak vertical displacements (6.51 ± 0.60 to 8.24 ± 0.69 cm; Figure 8A). When gravitation toward a minimal ANKLE PVD value with HPC learning is considered in conjunction with gains in vertical jump parameters and HPC training maximums, it appears possible that a minimal, but present, level of ANKLE PVD is necessary to maximize HPC efficiency via a ballistic motor pattern. Based on the analyses of bench press and squat motions (10,13,40,56), greater vertical power production is possible when ballistic versions of the movement are used (e.g., bench throw vs. bench press). Thus, ballistic movements via changes in neural strategies allow for agonist contribution over a greater ROM and decreased antagonist inhibition as compared with the nonballistic counterpart (13,40). Considering, it is likely that maximal vertical power production during HPC must be associated with a pseudoballistic motor pattern. We propose that during performance of HPC, the lifter aims to redirect the potential large displacements of body mass as ballistic power production into the bar; however, for the kinematic links of the body to function ballistically, a minimal level of displacement may still be necessary.

The findings of this investigation indicate a consistent trend for our elite athletes from novice toward proficient weightlifter mechanics as summarized by changes in bar path trace and BB MAX HD with HPC learning. Although the athletes in this investigation demonstrated differences in HPC intuition at baseline, all exhibited common initial beginner tendencies and trends in technical improvement with learning. By learning completion, each athlete demonstrated a more posterior sagittal plane barbell starting position, steeper bar path traces during the transition phase, and reduced BB MAX HD compared with baseline (Figures 4–7, 8B). These changes may be important as they direct the barbell center of mass more over the base of support thus limiting torque requirements (41) and because they create biomechanical positions allowing for more efficient utilization of the relevant musculature. In many regards, the sagittal barbell trace may be viewed as an indicator of kinematic movement proficiency. As all our athletes demonstrate, with learning, not only did the barbell remain closer to the base of support over the course of HPC, but also the initial concentric movement of the barbell tended to be more vertically directed (i.e., steeper movement gradient initiating concentric phase). This may suggest increased utilization of hip extension to drive vertical power production over the transition phase as opposed to only knee extension in accordance with the previously discussed variables in this investigation.

In summary, training with the HPC-benefited power production in these 4 elite short track speed skaters within the first 4 weeks, which despite the greater technical complexity attributed to HPC, is a comparable time frame with other power training modalities. Training with the HPC also continued to benefit vertical power production, with these athletes continuing to experience gains between the final 2 jump testing occasions. Considering that none of the athletes exhibited HPC mastery by investigation completion, continued benefits of HPC training on power production are possible. With HPC training, 2 out of 4 athletes demonstrated changes in force application strategy over the end ROM with both athletes achieving peak vertical velocity closer to toe off and exhibiting less decrease in velocity between peak and toe off with learning. These changes may demonstrate a mechanism by which HPC improves vertical power production. Despite different levels of intuition pertaining to HPC mechanics, all athletes demonstrated common technical inefficiencies at baseline and trends in HPC kinematics with learning. These inefficiencies were primarily related to execution of the transition phase and probably caused by a lack of innate programming and movement skill for proper double knee bend mechanics, although other potential factors cannot be discounted. With learning, all athletes trended toward more rearward-directed COPs during the transition phase and peak double knee bend position indicating a more efficient utilization of hip extension to affect vertical barbell power production. The athletes of this investigation did not trend toward triple extension through the ankle with learning as all moved toward submaximal plantar flexion values. This may be attributed to a potential need to maximize vertical power production through hip extension, with the hip and ankle extensors potentially incapable of simultaneous efficient power production. Furthermore, the athletes trended toward minimal, but existent, levels of peak vertical ankle displacement with training. This may be caused by the need for vertical displacement to approach zero to minimize the percentage of power production directed at moving body mass and to maximize the potential for impulse. However, a minimal displacement must exist to benefit from greater impulse and power production associated with ballistic movements. In summary, HPC learning from a naive state was worthwhile for our elite athletes as they experienced benefits in vertical power production within the first 4 weeks of learning despite previous experience with other power training modalities. Furthermore, although our athletes demonstrated different levels of HPC intuition at baseline, common technical inefficiencies were noted as were movement trends over the course of learning.

Practical Applications

These findings provide substantial supporting evidence for the use of weightlifting training within the elite strength and conditioning environment. Although previous works have demonstrated the benefits of weightlifting training on vertical power production, the amount of time investment necessary to reach a benefit was previously unknown. Considering these 4 athletes achieved substantial benefit within the first 4 weeks of learning, qualified coaches may consider removing the learning time investment as a deterrent from teaching the lifts. Additionally, coaches may consider recognizing the following beginner technical flaws and teaching the associated technical points to their elite athletes naive to the lifts: (a) a center to more rearward-directed COP throughout the concentric phase allowing more effective utilization of hip extension; (b) the intention to plantar flex maximally with corresponding production of submaximal values also potentially indicating more effective utilization of hip extension; and (c) minimal, but existent, vertical displacement of the athlete center of mass indicating maximization of ground contact time, effective transfer of vertical power production into the barbell, and a corresponding ballistic intention.

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