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A biomechanical comparison of the vertical jump, power clean, and jump squat

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Abstract
The purpose of this study was to compare the kinetics, kinematics, and muscle activation patterns of the countermovement jump, the power clean, and the jump squat with the expectation of gaining a better understanding of the mechanism of transfer from the power clean to the vertical jump. Ground reaction forces, electromyography, and joint angle data were collected from 20 trained participants while they performed the three movements. Relative to the power clean, the kinematics of the jump squat were more similar to those of the countermovement jump. The order in which the ankle, knee, and hip began extending, as well as the subsequent pattern of extension, was different between the power clean and countermovement jump. The electromyography data demonstrated significant differences in the relative timing of peak activations in all muscles, the maximum activation of the rectus femoris and biceps femoris, and in the activation/deactivation patterns of the vastus medialis and rectus femoris. The greatest rate of force development during the upward phase of these exercises was generated during the power clean (17,254 $N \cdot s^{-1}$), which was significantly greater than both the countermovement jump (3836 $N \cdot s^{-1}$) and jump squat (3517 $N \cdot s^{-1}$) conditions ($P < .001$, $\eta_p^2 = .88$).

Keywords: *rate of force development, weightlifting, kinetic, kinematic, electromyography*

1. Introduction

The vertical jump is an explosive movement important in many sports (Harman, Rosenstein, Frykman, & Rosenstein, 1990). A review by Baker (1996) suggests that both *general* strength training (e.g. squats) and *specific* strength training (e.g. depth jumps) can play key roles in a programme designed to improve the vertical jump. However, *special* strength exercises, such as jump squats and Olympic-style lifts, are probably the most effective (Baker, 1996). In general, it is believed that a training exercise should follow the principle of specificity: the exercise should be similar to the targeted sport movement with regard to the kinetics, kinematics, and contraction type (Sale & MacDougall, 1981). Further, in order for a training exercise to facilitate an improvement in performance in a sport movement, such as vertical jumping, the exercise must stimulate a trainable feature of the neuromuscular system beyond the level that can be achieved when executing the sport movement.

Training programmes incorporating jump squats, which consist of performing a countermovement jump with a barbell on the shoulders, have been shown to increase vertical jump height by between 2.2% to 20% (Hori et al., 2008; Lyttle, Wilson, & Ostrowski, 1996; Newton, Kraemer, & Hakkinen, 1999; Wilson, Newton, Murphy, & Humphries, 1993). The instructions for performing a jump squat define it as being as similar to a countermovement jump as possible (Hoffman et al., 2005). It seems evident that using the jump squat to improve vertical jumping is in accordance with the principle of specificity and that the ability of the neuromuscular system to generate greater forces is also being trained due to the additional mass of the barbell placed on the shoulders.

Training programmes incorporating Olympic-style weightlifting exercises (variations of the Olympic clean and jerk, and the snatch lifts) have been shown to increase vertical jump height by between 2.8% to 9.5% (Channell & Barfield, 2008; Harris, Stone, O'Bryant, Proulx, & Johnson, 2000; Hawkins, Doyle, & McGuigan, 2009; Hoffman, Cooper, Wendell, Kang, 2004; Tricoli, Lamas, Carnevale, & Ugrinowitsch, 2005). The most common explanations for the transfer between weightlifting and the vertical jump are based on the idea that increased force demands are placed on the system while executing a very similar movement pattern

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(Canavan, Garrett, & Armstrong, 1996; Hawkins et al., 2009; Hedrick & Anderson, 1996; Hori, Newton, Nosaka, & Stone, 2005; Tricoli et al., 2005). Olympic-style lifts and jumping movements certainly have some general characteristics in common such as the thought of continually accelerating through the entire movement; however, the objectives of the movements are different. The intent while jumping is to maximise the vertical displacement of the *athlete*, while the focus of Olympic-style lifts is to vertically displace the *barbell*. While it is possible that Olympic-style lifts act in the same manner as jump squats to improve vertical jumping, it is not as readily evident, and as such, previous researchers have attempted to assess the similarities between weightlifting exercises and the vertical jump, with the implicit goal understanding the mechanism of transfer. In a published abstract, Garhammer and Gregor (1979, p. 106) stated that force time graphs were comparable for athletes performing vertical jumps and Olympic lifts and that "this was expected from visual similarities, and realizing that an Olympic lift primarily involves *jumping* vertically with the barbell." In an another abstract, which is commonly referenced, Burkhardt and Garhammer (1988) only report kinematic similarities during the final extension range for the slope of knee angular velocity time curves (angular acceleration). Garhammer and Gregor (1992) recorded force plate data during snatch lifts and vertical jumps, and although no inferential statistical calculations were performed to compare the two movements, they concluded that there were qualitative and quantitative similarities. Haff et al. (1997) examined only kinetic values and found moderate correlations (.7 to .8) between the pull phase of an Olympic lift and countermovement jump, in terms of peak force and peak power. Canavan et al. (1996) examined ground reaction forces, angular displacements, and moments of power for the hang snatch lift and squat vertical jump. They stated that significant kinetic relationships, but limited kinematic relationships existed.

The current understanding on the transfer between weightlifting training and improvements in vertical jump height appears to be the same as that for jump squat training: increased force demands are placed on the system while executing a very similar movement pattern. It is our contention that the existing body of research supporting this understanding would benefit from a more complete statistical comparison of the biomechanics of the movements. Further, if weightlifting is shown to be meaningfully different from the vertical jump and jump squat, from a quantitative biomechanical perspective, this would suggest that weightlifting may improve vertical jumping via a different mechanism than jump squatting. Understanding the specific mechanism that makes an exercise effective for improving vertical jump may provide reasons for using a certain technique or how best to incorporate the exercise into a periodised programme. Therefore, the purpose of this study was to compare the kinetics, kinematics, and muscle activation patterns of the countermovement jump, the power clean, and the jump squat with the expectation of gaining a better understanding of the mechanism of transfer from the power clean to the vertical jump. To the knowledge of the researchers, such a biomechanical comparison has yet to be conducted.

2. Methods

2.1 Participants

Ten university aged female volleyball players and ten university aged male football players volunteered to participate in the study (Table I). Participants were familiar with the exercise techniques (employed on a routine basis for at least 2 years (Haff et al., 1997)) and free from injury. University Ethics Review Board approval was obtained prior to data collection.

2.2 Procedures

Surface electrodes (silver chloride Delsys DE 2.3 Single Differential, Delsys Inc, Boston, MA, USA) were fixed to the belly of the medial gastrocnemius, vastus lateralis, rectus femoris, biceps femoris, and gluteus medius, parallel to the muscle fibres on the right leg (SENIAM, 2004). Electronic goniometers (S700 Joint Angle ShapeSensor, Delsys Inc, Boston, MA, USA) were attached across the ankle, knee, and hip joint centres of the right leg as defined by Robertson, Caldwell, Hamill, Kamen, and Whittlesey (2004). Participants warmed up with 5 min of stationary biking at a speed of 60 rpm and a resistance of 19.8 N, followed by 5 min of dynamic stretching, Warm-up continued with five countermovement jumps, five power cleans (three at 50% and two at 70% of the participant's one repetition maximum (1RM)), and five jump squats (three at 50% and two at 70% of the participant's power clean 1RM). Testing of the three exercises was performed in a randomised order on a force plate (AMTI

Table I. Participant characteristics.

Sex	Age (years)	Height (m)	Mass (kg)	Jump height (cm)
Male (N = 10)	22.7 ± 3.7	1.82 ± 0.05	88.2 ± 6.2	52.4 ± 6.8
Female (N = 10)	20.4 ± 0.7	1.74 ± 0.07	68.4 ± 7.5	36.0 ± 4.2

BP600900, AMTI, Watertown, MA, USA) with 1 min rest between trials. Two successful trials, for each exercise, were retained for data analysis. A video camera (Sony HDV HDR-HC7, Sony, New York, NY, USA) was placed perpendicular to the plane of motion and recorded each trial.

To complete the jump squat trials, participants were instructed to incorporate a countermovement by squatting to the depth they felt would allow them to jump as high as possible in one smooth "down/up" motion (upward motion shown in Figure 1A). For the countermovement jump condition, participants were instructed to keep their arms at their sides during the downward phase of the jump, but were free to swing their arms during the upward phase of the movement (Figure 1B). Power cleans were performed at 70% of the participant's 1RM as this represents a typically suggested training load (Channell & Barfield, 2008; Comfort, Fletcher, & McMahon, 2012). Participants were instructed to perform the power clean beginning from a standing posture so that a controlled countermovement would be evoked, as was with the other two exercises. The participants were instructed to lower the bar to mid-shin height (without contacting the floor) and clean it as explosively as possible in order to maximise the height of the bar prior to the catch phase (Figure 1C). The same weight was used for the power clean and jump squat trials. The barbell weight associated with 70% of each participant's 1RM power clean was well within the range of loads previously suggested in the literature for jump squat training (Dugan, Doyle, Humphries, Hasson, & Newton, 2004). Considering this, it seemed logical to use the same absolute weight for the power clean and jump squat conditions to facilitate a comparison. There are spectrums of technique variations for the clean, jump, and jump squat reported in the scientific and training literature. The variations described above fall within those spectrums and represent an attempt at making the jump squat and power clean as similar to the countermovement jump as possible.

2.3 *Data collection and analysis*

Both the goniometer and force plate data were sampled at 1000 Hz and filtered using a 4th order, zero-lag, low pass Butterworth filter with a cut-off frequency of 10 Hz. Initiation of the upward phase was defined as the point in time when the hip, knee, *or* ankle joint angle began to increase (extend) after the countermovement phase. Termination of the upward phase was defined as the point in time when all joints finished extending. Using a customised MatLab (MatLab R2007a, Math Works, Natick, MA, USA) script, force plate data were analysed to calculate jump height, maximum force, maximum rate of force development (instantaneous), maximum power as well as the percentage of upward movement when these maximums were achieved. Power was defined as the rate at which mechanical energy was transferred to the system centre of mass via the vertical component of the ground reaction force. At the start of each exercise, the participant stood motionless. This allowed the mass of the system to be determined from the vertical component of the ground reaction force and permitted the calculation of the net vertical force acting on the system. The instantaneous vertical velocity of the system was calculated by integrating the net vertical force with respect to time, and dividing by mass. Instantaneous power was then calculated by taking the product of the instantaneous vertical ground reaction force and instantaneous vertical velocity.

Surface electromyography (EMG), which was synchronised with the goniometer data, was sampled at 1000 Hz. Using a customised MatLab script, EMG data were full-wave rectified and linear enveloped using a low-pass, 4th order zero-lag Butterworth filter with a 7-Hz cut-off. Conditioned EMG data were analysed to determine maximum raw signal, percentage of upward movement when maximum signal occurred, and the number of times each muscle was activated during the upward phase. Muscle activation was defined as a signal greater than 20% of the maximum signal attained during the trial. These EMG collection and analysis procedures follow very closely to those of Baum and Li (2003) and are in accordance with recognised guidelines for this type of EMG analysis (Kamen & Gabriel, 2010).

Each joint angular displacement signal, during the upward phase, was fit to a quintic spline as a function of time, and then resampled to generate 101 data points, in order to express joint angular displacement as percentage of the upward phase. The same procedure was applied to the force plate and EMG data. Standardising in this manner facilitated statistical comparison and permitted data from all participants to be graphed simultaneously as the mean ± 95% confidence interval.

2.4 *Statistical analysis*

Two trials for each exercise, from each participant, were analysed in MatLab. The vertical jump and jump squat trials with the highest jump height, and the power clean with the highest bar height prior to the catch, were selected for statistical analysis. One-way repeated measures analyses of variance (ANOVAs) were conducted on the dependent variables outlined in the previous section. The within-participants independent variable (exercise) had

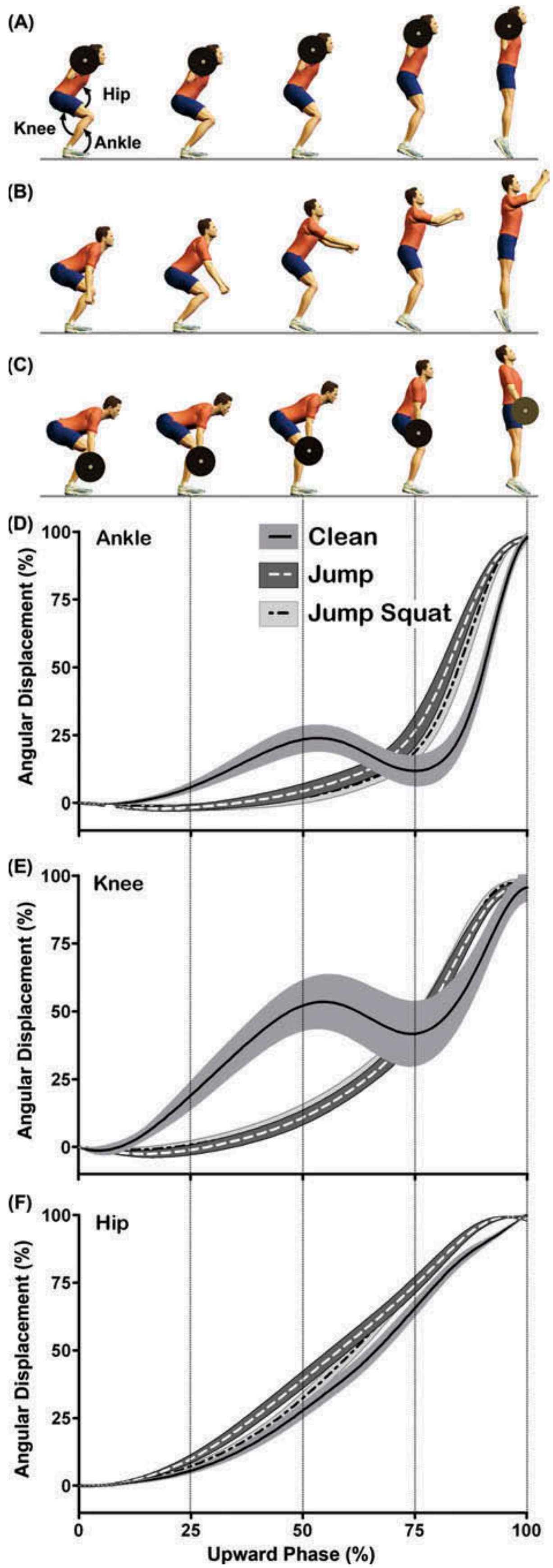

Figure 1. Upward phase of the (A) jump squat, (B) vertical jump, and (C) power clean. Plot of (D) ankle, (E) knee, and (F) hip angle as a percentage of the maximum joint angle reached during the upward phase of the clean, jump, and jump squat. Curves are ensemble average for all participants, while the shaded bands represent the 95% confidence interval.

three levels: power clean, jump, and jump squat. If the assumption of sphericity was not met, as determined using Mauchly's Test, then Greenhouse–Giesser corrections were applied. When significant value were determined, Bonferroni post-hoc tests, with adjustments to control for Type I error, were used to determine where significant differences exited between exercises. Effect sizes were estimated using partial eta squared (η_p^2). A chi-square test of independence was used to determine the significance of the number of times each muscle was activated across conditions. The standardised residuals were used as a post-hoc test to determine exactly where the significant differences were located (Beasley & Schumacker, 1995). This was found to maintain Type I error at a satisfactory level (MacDonald & Garner, 2000). Statistical analyses were performed using SPSS 17.0 (SPSS Inc, Chicago, IL, USA). Significance for all statistical tests was defined as $P \le .05$.

3. Results

It is clear that ankle and knee kinematics, during the power clean, differed markedly from that of both jumping movements (Figure 1D and 1E). Two distinguishing features are evident from the graphs. First, there was significantly more extension during the first 50% of the upward phase of the power clean at the ankle ($F(2, 38) = 55.7$, $P < .001$, $\eta_p^2 = .75$) and knee ($F(2, 38) = 85.8$, $P < .001$, $\eta_p^2 = .82$). Second, as is characteristic of the so-called double knee bend in the power clean, there was a period (~50–75% of the upward phase) of joint flexion, at the ankle and knee, which was not evident in the two jumping movements. Although not as marked, there were also meaningful differences in the hip joint kinematics (Figure 1F). During the vertical jump, hip extension occurred earlier and to a significantly greater degree during the first 50% of the movement compared to the power clean ($F(2, 38) = 29.1$, $P < .001$, $\eta_p^2 = .61$). The jump squat was noticeably different from the vertical jump between 30% and 60%, but the curves almost completely overlap during the final 30% (Figure 1F). During the final 10% of the upward phase, hip extension plateaued for both jumping movements, while it increased for the power clean (Figure 1F).

On average, power cleans elicited a significantly greater maximum force (2411 N) than jump squats (2234 N) and vertical jumps (1770 N), while jump squats elicited a significantly greater maximum force than vertical jumps ($F(2, 38) = 119.4$, $P < .001$, $\eta_p^2 = .86$) (Figure 2A). On average, the greatest maximum power was observed in the vertical jump condition (4384 W) and was significantly greater than the maximum power generated in the power clean

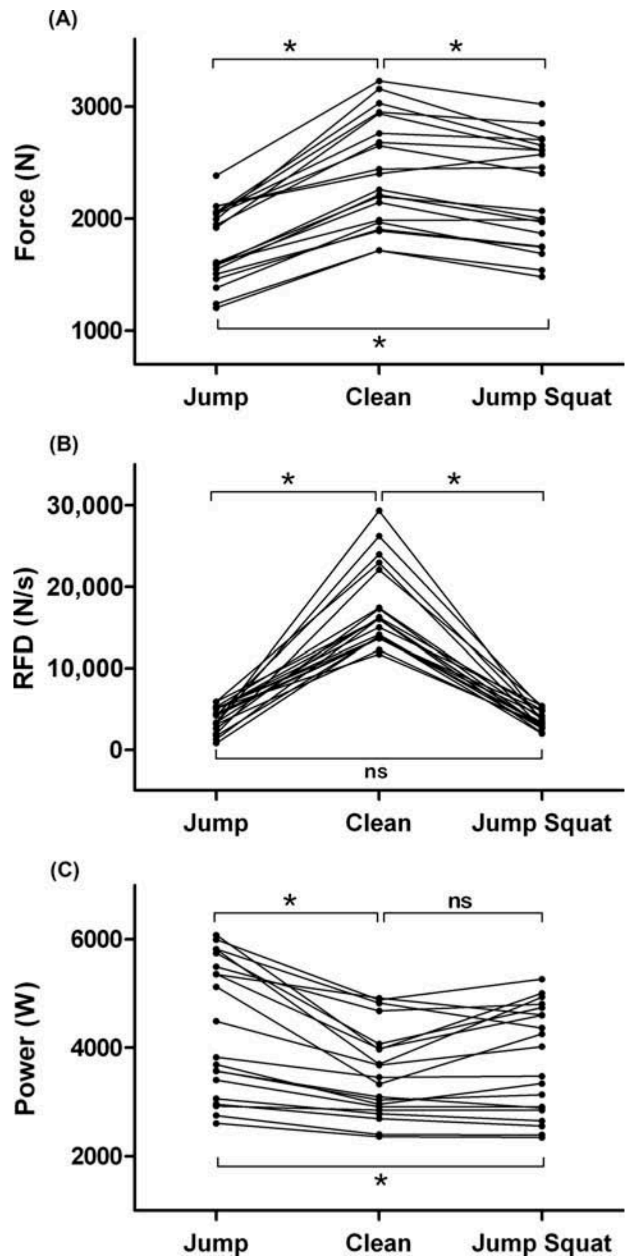

Figure 2. (A) Peak vertical ground reaction force, (B) peak rate of force development (RFD), and (C) peak power generated during the upward phase of the jump, power clean and jump squat. Connected dots indicated individual participants. (* indicates $P \le .05$; ns = not significant)

(3532 W) and jump squat conditions (3772 W), which were not significantly different from each other ($F(2, 38) = 32.0$, $P < .001$, $\eta_p^2 = .63$) (Figure 2C). On average, the greatest rate of force development was generated during the power cleans ($17254\ N \cdot s^{-1}$), which was significantly greater than both the vertical jump ($3836\ N \cdot s^{-1}$) and jump squat ($3517\ N \cdot s^{-1}$) conditions, which were not significantly different from each other ($F(2, 38) = 137.0$, $P < .001$, $\eta_p^2 = .88$) (Figure 2B). The reliability of the rate of force development measure was estimated by

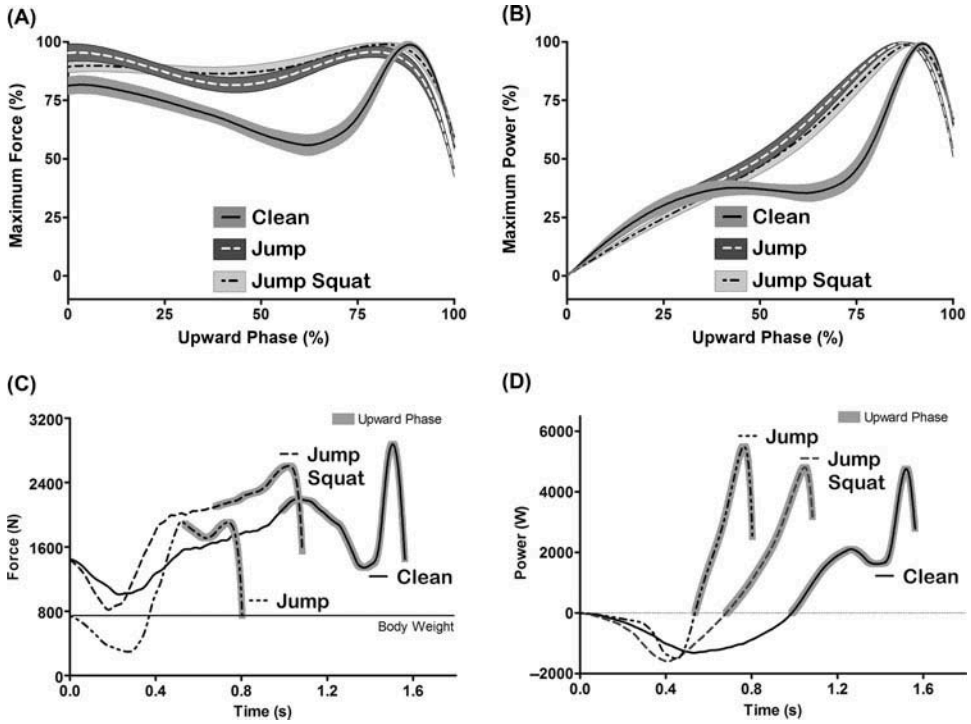

Figure 3. (A) Vertical ground reaction forces and (B) power as a percentage of the maximum values attained during the upward phase of the clean, jump, and jump squat. Curves are ensemble averages for all participants, while the shaded bands represent the 95% confidence interval. (C) Typical vertical ground reaction force and (D) power profiles, for Participant 2, for the clean, jump, and jump squat. Curves start at the initiation of the downward phase, while the shaded portions indicate the upward phase. Curves end when the weight of the participant, or participant and barbell, exceeded the magnitude of the vertical ground reaction force.

calculating Cronbach's alpha for the two trials. The values were .77, .72, and .99 for the jump, jump squat, and power clean, respectively.

On average, maximum force was achieved significantly earlier in the vertical jump condition (28%) as a percentage of upward movement than the jump squat (74%) and power clean (88%) conditions, neither of which achieved maximum force at significantly different percentages of the upward phase ($F(2, 38) = 30.9$, $P < .001$, $\eta_p^2 = .62$) (Figure 3A). Maximum power was achieved first during the vertical jump (87%) followed by jump squat (89%), then followed by power clean (92%), all three of which were significantly different than each other ($F(2, 38) = 63.0$, $P < .001$, $\eta_p^2 = .77$) (Figure 3B). Maximum rate of force development was achieved significantly later during the power clean (79%) than the vertical jump (57%) and jump squat (56%) trials, which were not significantly different from each other ($F(2, 38) = 9.5$, $P < .001$, $\eta_p^2 = .33$).

While representing dependent variables as a function of percentage of movement facilitates a statistical comparison, some of the features of the data, such as the absolute timing of events are difficult to discern. For example, inspection of typical vertical ground reaction force curves demonstrates the absolute timing of peak forces and provides a qualitative indication of the timing of peak rates of force development (Figure 3C). Figure 3D demonstrates typical instantaneous power curves of the three exercises performed by a single participant. This participant had a mass of 76 kg and used a barbell mass of 80 kg for the power clean and jump squat. For the curves shown, jump height was 57 cm for the jump and 23 cm for the jump squat. While the focus of this paper was on the upward phases of the exercises, it is worth noting that significantly higher rates of force development were present during the countermovement phase of the jump ($t(19) = 9.26$, $P < .001$) and jump squat ($t(19) = 6.96$, $P < .001$) in comparison with the upward phases of these exercises. This can be qualitatively observed by close inspection the slopes in Figure 3C. However, even when these higher values are compared to the power cleans, the outcome is the same as previously reported in Figure 2B. On average, the greatest rate of force development was generated during the power cleans ($17254\ N \cdot s^{-1}$), which was significantly greater than both the vertgical jump ($9465\ N \cdot s^{-1}$) and jump squat ($7920\ N \cdot s^{-1}$) conditions, which were not significantly different from each other ($F(2, 38) = 50.4$, $P < .001$, $\eta_p^2 = .73$).

The activation pattern of vastus medialis, during the power cleans, was markedly different from the pattern seen in the two jumping movements (Figure 4A). At the start of the upward motion in

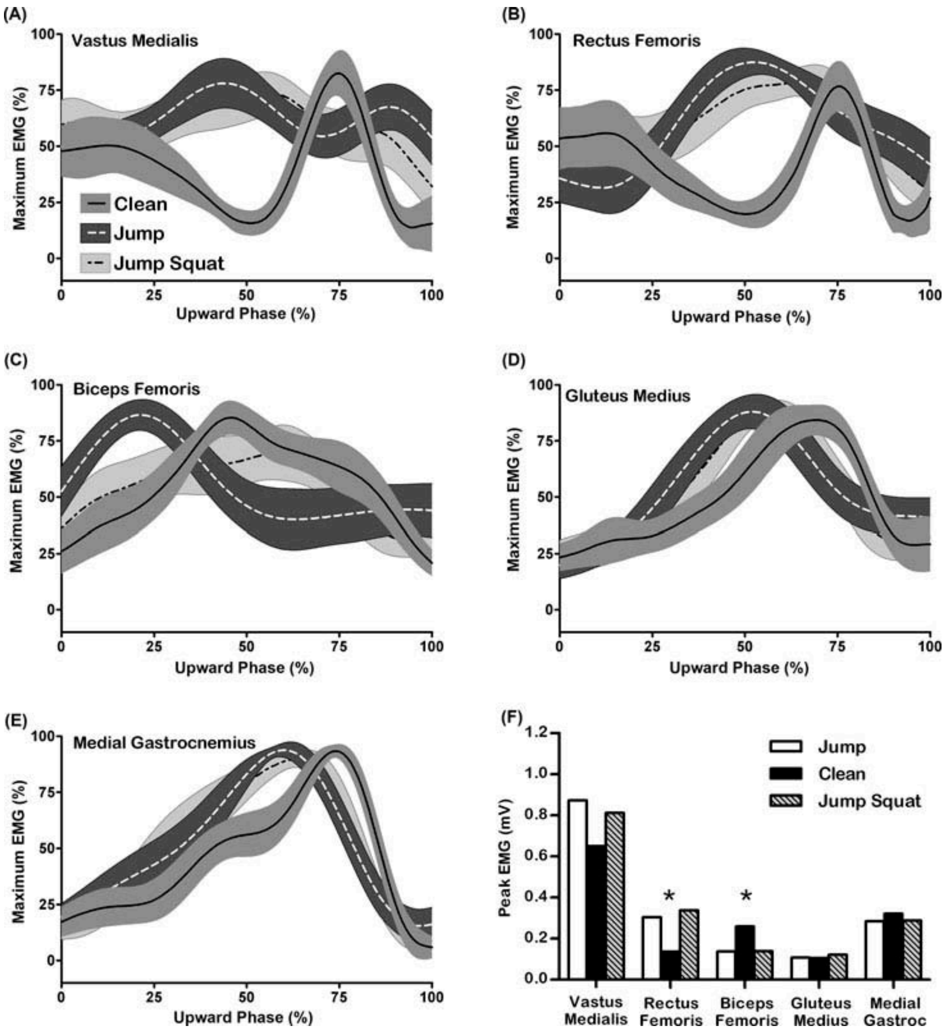

Figure 4. Linear enveloped EMG curves for (A) vastus medialis, (B) rectus femoris, (C) biceps femoris, (D) gluteus medius, and (E) medial gastrocnemius as a percentage of the maximum signal attained during the upward phase of the clean, jump, and jump squat. Curves are ensemble averages for all participants, while the shaded bands represent the 95% confidence interval. (F) Peak EMG values during the jump, clean, and jump squat for each of the five muscles tested. (* indicates $P \leq .05$)

all exercises, the vastus medialis was activated at about half of the maximum level achieved in the respective trials. However, at about 20% into the upward phase, vastus medialis activation noticeably increased for the two jumping movements, while it clearly decreased during the power clean. After about 50% into the upward phase, the vastus medialis demonstrated a dramatic increase in activity during the power clean, which was not present in either jumping movements. Although vastus medialis activity declined over the final 25% of each movement, the rate of deactivation was noticeably less for the jumping exercises. The rectus femoris showed very similar activation patterns as the vastus medialis (Figure 4B). On average, activity of the biceps femoris peaked significantly earlier in the jump trials (32%) compared to either the jump squat (54%) or power clean (50%) trials, which were not significantly different from each other ($F(2, 38) = 6.5$, $P < .004$, $\eta_p^2 = .26$) (Figure 4C). On average, activity of the gluteus medius peaked significantly later in the power clean trials (67%) compared to either the jump (50%) or jump squat (54%) trials, which were not significantly different from each other ($F(2, 38) = 22.7$, $P < .001$, $\eta_p^2 = .55$) (Figure 4D). Similarly, activity of the medial gastrocnemius peaked significantly later in the power clean trials (72%) compared to either the jump (58%) or jump squat (59%) trials, which were not significantly different from each other ($F(2, 38) = 20.1$, $P < .001$, $\eta_p^2 = .51$) (Figure 4E). As all participants performed each exercise without electrode adjustment, it is reasonable to compare the peak EMG scores, without normalisation, for each muscle between exercises. The rectus femoris was activated to a significantly greater extent in the jumping exercises compared to the power cleans, while there was no significant difference between the two jumping conditions ($F(2, 38) =$

10.6, $P < .002$, $\eta_p^2 = .36$) (Figure 4F). Although not statistically significant, the vastus medialis showed the same pattern. The biceps femoris was activated to a significantly greater extent in the power cleans compared to either jumping exercise, while there was no significant difference between the two jumping conditions ($F(2, 38) = 14.2$, $P < .001$, $\eta_p^2 = .43$) (Figure 4F).

Results of the chi-square test of independence indicated that the pattern of activation/deactivation for the vastus medialis, during the upward phase, was significantly different between exercises ($\chi^2(2) = 26.0$, $P < .001$, $\phi = .66$). Post-hoc tests, using standardised residuals, indicated that the vastus medialis had two distinct periods of activation during the power clean, while it maintained a single period of activation for both jumping movements. Results of the chi-square test for the rectus femoris were very similar to those of the vastus medialis ($\chi^2(2) = 17.5$, $P < .001$. $\phi = .54$).

4. Discussion

This study compared the kinetics, kinematics, and muscle activation patterns of the countermovement jump, the power clean, and the jump squat with the expectation of gaining a better understanding of the mechanism of transfer from the power clean to the vertical jump. Previous postulations have mostly been founded in the belief that, comparable to the jump squat, kinetic and kinematic similarities along with increased force demands are responsible for the transfer.

The results of this study indicated that the upward phase of the power clean and vertical jump were not similar from a quantitative (statistical) perspective. Both the order in which the ankle, knee, and hip joints began extending as well as the subsequent pattern of extension, throughout the vast majority of the upward phase, were different between the power clean and vertical jump (Figures 1D–F). These different kinematic patterns were supported by the muscle activation data, which demonstrated significant differences in the relative timing of peak activations in all muscles measured (Figures 4A–E), significant differences in the maximum level of activation in the rectus femoris and biceps femoris (Figure 4F), and significant differences in the activation/deactivation patterns of the vastus medialis and rectus femoris (Figures 4A–B). Further, there were significant differences between the vertical jump and power clean in terms of peak force, rate of force development, and peak power (Figure 2A–C).

Although differences were noted, it seems reasonable to conclude that the vertical jump was more similar to the jump squat, than it was to the power clean, in terms of the kinematics, kinetics, and muscle activation patterns. If it is true that the most important factor when selecting a training exercise is similarity of movement, then the most similar training method that follows the principle of progressive overload should be the ideal exercise. Based on the data presented in the current study, this would indicate that the jump squat should be a better training exercise to improve vertical jump than the power clean. This is in agreement with the literature, which tends to show slightly greater improvement in jump squat training studies. However, serious limitations such as differences between participant populations, training volumes, length of interventions, and measurement methods exist when trying to compare findings from previous studies. As such, more direct comparison training studies are required before such a conclusion can be made.

Considering the substantial kinematic differences between the power clean and vertical jump, and the similarities between the countermovement jump and the jump squat, it suggests that the manner in which weightlifting exercises act to improve vertical jump may be different than that of the jump squat. In order for a training exercise to facilitate an improvement in performance in a specific sport movement, such as vertical jumping, the exercise must stimulate a trainable feature of the neuromuscular system beyond the level that can be achieved when executing the sport movement. Results from this study suggest two possibilities for trainable features of the neuromuscular system that are heavily stimulated during the power clean and are also central to vertical jump performance: peak force and rate of force development.

Higher peak ground reaction forces strongly suggest greater peak tension in the muscles producing hip, knee, or ankle extension, which could arguably be responsible for a portion of the training effects. Higher peak forces were generated during the power clean and jump squat, in comparison with the vertical jump condition, primarily due to the force–velocity property of muscle. The added mass of the barbell probably resulted in slower concentric contraction speeds during the upward phase of these exercises. However, despite the fact that the same barbell mass was used for the jump squat and the power clean, the power clean generated significantly greater maximum force (Figure 2A). The presence of the double knee bend is the probable cause of the higher peak force and will be discussed in the next paragraph.

Alternatively, rate of force development may play a more prominent role in the training crossover between weightlifting and jumping. Research has shown that rate of force development is a good indicator of vertical jump (Jarić, Ristanović, &

Corcos, 1989; Kraska et al. 2009; Papadopoulos et al., 2009) and weightlifting performances (Haff et al., 2005). There is a limited amount of time to generate force for both movements and the amount of force generated in that small time interval is directly proportional to performance. For example, the vertical component of the ground reaction force is reduced to initiate the countermovement of a vertical jump (Figure 3C). Theoretically, this force should then be maximised prior to the athlete's centre of mass moving vertically. Therefore, the faster force is produced (the greater the rate of force development), the greater the average force generated during the upward phase and the higher the jump or the more weight lifted during a power clean. The significantly greater rate of force development during the power clean, as shown in this study, can be explained by the double knee bend (Figure 2B). It is well known that a concentric contraction that is preceded by an eccentric contraction will generate greater force, due to the mechanical properties of muscle (Enoka, 1979). All three exercise types were performed with an initial countermovement (eccentric contraction), but only the power clean exhibited the double knee bend pattern during the upward phase. The double knee bend is characterised by a period of knee flexion, which probably results in a brief eccentric contraction of the knee extensors (e.g. vastus lateralis) prior to the final period of knee extension during the second pull. The double knee bend occurs at a point during upward movement when the joint angles are such that the extensor muscles are in positions of optimal sarcomere overlap, which allows them to generate greater force (Enoka, 1979). An eccentric contraction at the optimal position is what allows for the extremely high rate of force development, and subsequent peak force, observed during the final concentric phase of the power clean.

5. Conclusions

In conclusion, this study suggests that the power clean is not kinematically similar to the vertical jump, whereas the jump squat is similar. Therefore, similarity of movement may not be the most important factor for training crossover between Olympic-style lifting and vertical jump performance. While muscle coordination is important in jumping performance, if it is achieved in a separate facet of training, an athlete's strength and conditioning programme need not focus on kinematics. Instead, exercises should be prescribed based on an understanding of the specific motor ability that is being trained. For example, this study suggests that while both the jump squat and power clean stimulate maximum strength more than vertical jumping (as indicated by higher peak forces), the power clean seems to be better suited for stimulating explosive strength (as indicated by greater rates of force development). Further research may be conducted to confirm the role of rate of force development in training crossover. For example, a training study could measure jump performance and several kinetic variables before and after a weightlifting training programme and search for a relationship between improvement in rate of force development and vertical jump. Additionally, researchers may want to study several weightlifting variations such as the snatch, hang lifts, or lifts with and without a countermovement to determine which variation optimises rate of force development.

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