Optimal depth jump height quantified as percentage of athlete stature

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ABSTRACT

Purpose: An individual's optimal depth jump platform height provides a resistive force which allows an athlete to rebound with substantial velocity resulting in maximum power exertion. The objective of this investigation was to show that the optimal platform height in a depth jump can be quantified as a percentage of individual body stature which can serve as measurable quantified value. Although athlete height is not highly correlated to power ability nor does a universal height exist, this value can provide a basis for a rehabilitation or strength and conditioning program. The desired intensity of a program can be prescribed as a percentage of the individual's optimal drop height. Methods*:* Sixteen male participants (age=21.7 ± 1.54 yrs., height=177.7 ± 11.4 cm, mass=77.7 ± 13.6 kg; mean ± SD) were tested in a depth jump through a range of platform heights based on percentage of the individual anthropometric data defined at 0-, 10-, 20-, 30-, 40-, and 50% of the participants' stature using a 3-D motion capture system (Qualysis) and force plates (Bertec) to calculate power. Results*:* The optimal drop height was found to be 21.3 (±10.3)% of the participants' heights for maximum peak power and 27.5 (±15.3)% for maximum average power. Conclusions*:* These results suggest that an individual optimal drop height does exist as a percentage of stature and could be applied to a rehabilitation or power-based training program using the drop height as a quantified basis allowing an athlete to gradually work toward their individual optimal drop height and exhibit maximum power. **Keywords:** Kinematics; Kinetics; Lower extremity assessment; Plyometrics; Power.

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INTRODUCTION

The ability to produce power in quick, forceful movements is key for an athlete to reach ultimate potential in nearly any sport (Baker, Nance, & Moore, 2001; Markovic & Jaric, 2007; McBride, Triplett-McBride, Davie, & Newton, 1999; Stone, 2003). Jumping, cutting, and sprinting (in both acceleration and top-end speed phases) are examples of powerful movements. Most powerful movements are done as an athlete exerts force into the ground for propulsion. In addition to exerting force, athletes need to absorb force when cutting, changing direction, or landing. Therefore, nearly every rapid movement an athlete makes in any sport or athletic competition involves both the production and absorption of power in some way. A jumping movement with a countermovement phase is a simple training exercise that incorporates both power absorption and production to help develop powerful athletes (Guillaume, Phillip, & Tom, 2013; Mackala, Stodolka, Siemienski, & Coh, 2013).

In the past, strength-based movements such as back squats have been used by sports medicine professionals and strength coaches to design rehabilitation and exercise programs that include both strength and power movements (Carlock et al., 2004; Harman, Rosenstein, Frykman, Rosenstein, & Kraemer, 1991; A. Lees & Fahmi, 1994). The programs use a strength-based one-repetition maximum (1RM) from which a percentage is taken to design a periodization scheme of prescribed sets and repetitions. However, using a strength-based 1RM is not ideal in a power movement because this clearly ignores the concept that a strong athlete is not always a powerful athlete (Baechle & Earle, 2008; Jovanonic & Flanagan, 2014; B. Mann, 2013; J. B. Mann, Ivey, & Sayers, 2015). Furthermore, repeated assessments of a strength-based heavy resistance movements such as a 1 RM back squat can be taxing and strenuous compromising the effectiveness of an efficient periodization program. Therefore, effective power-based programs structured on an individual power-based movement such as a depth jump (DJ) instead of a 1RM strength-based movement could alleviate these issues.

In a DJ, resistance is added to the countermovement phase by stepping off, falling, and landing from a raised platform. A DJ is defined as a movement striving for maximal rebound height in addition to minimal ground contact time and is not to be confused with a drop jump (or bounce jump) which focuses primarily on minimized ground contact time less than 0.25 seconds (Bobbert, Huijing, & van Ingen Schenau, 1987b, 1987a; Verkhoshansky, 2012). The DJ movement begins with an athlete standing upright on a platform of a specified height. In the past, this height was a set distance measurement (Earp et al., 2010; Lephart, Perrin, Fu, & Minger, 1991; Verkhoshansky, 2012). The athlete steps from the platform and falls to the ground where they immediately attempt to absorb the landing forces and then rebound to jump vertically as high as possible. During the step off, it is important that the athlete minimize any anterior movement as well as any upward or downward pre-movement that would alter the desired distance of the drop.

A DJ from a tall platform would have a greater impact force on the ground than a DJ from a short platform. Typically, an efficient athlete will take advantage of the increased potential energy through the stretch-shortening cycle for greater power output on the rebound jump from a tall platform (Asmussen & Bonde-Petersen, 1974; Lazaridis et al., 2013). However, increasing the platform height too much will lead to a landing force that is simply too great to benefit the athlete. Therefore, the increased landing force will begin to negate the benefit of the stretch-shortening cycle at some point and the rebound jump velocity will suffer. Any DJ from a higher platform than an optimal height can nullify the benefit of the stretch-shortening cycle because of the athlete's strength limitations and will only lead to a rebound vertical height the same or even less than a normal countermovement vertical jump (Bobbert et al., 1987b; Bobbert, Mackay, Schinkelshoek, Huijing, & van Ingen Schenau, 1986). Some previous investigations show conflicting results that athletes were able to jump just as high or higher when stepping off a platform of 20 cm or less compared to stepping off platforms of a greater height (Earp et al., 2010; Lephart et al., 1991; Luhtanen & Komi, 1978; Verkhoshansky, 2012). Conversely, other investigations maintain that the maximum power output in a DJ occurs when the drop height is closer to 40 cm but without significant difference when compared to 20 cm or 60 cm (Bobbert et al., 1987a; Harman et al., 1991; Voigt, Simonsen, Dyhre-Poulsen, & Klausen, 1995; Walsh, Arampatzis, Schade, & Brüggemann, 2004). Therefore, if an athlete is consistent with jump technique, it is a better approach to analyse DJ results on an individual basis and not as a universal height as not all athletes will have the same standard optimal height. Therefore, the optimal drop height for an individual should be represented as a percentage of the athlete's height and not a universally standard platform height. The objective of this investigation was to show the existence of an optimal drop height as individual body height percentage. It was hypothesized that the average optimal drop height would be between 0% and 50% of the participants' heights.

MATERIALS AND METHODS

Participants

Sixteen healthy males participated in the investigation (age: 21.7 ± 1.54 yrs., height: 177.7 ± 11.4 cm, mass: 77.7 ± 13.6 kg, Body Mass Index (BMI): 24.4 ± 2.4). The participants were notified of the potential risks involved and all participants gave their written informed consent which was approved by the institutional review board.

All participants were screened for fitness level through a questionnaire that inquired about athletic history, estimated 1RM squat, frequency of lifting and exercise, type of exercise, and history of injury. Each participant was required to be familiar with how to perform a maximum effort DJ including proper warm-up and execution. Exclusion criteria included recovery from any musculoskeletal injuries in the last six months, the inability to squat 1.5 times their body weight, and an exercise routine of less than three times per week. Furthermore, no participants were allowed to schedule their session within 48 hours of their most recent workout session to ensure adequate recovery.

Experimental Design

The data collection was done at an indoor, temperature-controlled facility on a hardwood floor. Each session lasted one hour and was scheduled at the participants' convenience. Each participant was allowed an indefinite amount of time to warmup with flexibility, agility, and cardiovascular exercise at their pace and comfort level to provide maximal effort for every jump. Once a participant was adequately ready to provide a maximal effort, 49 retro-reflective markers (B&L Engineering, Santa Ana, CA, USA) were placed on strategically determined locations of the body for biomechanical evaluation.

Methodology

The depth jumps were performed from platform heights of 0-, 10-, 20-, 30-, 40-, and 50% of each participant's standing height (± 2 cm due to the size increments of the plyo-boxes). To eliminate the benefit of upper-body movement, participants were required to either keep their hands on their hips or behind their back as arm swing can affect a vertical jump height by as much as 10% (Ashby & Delp, 2006; Ashby & Heegaard, 2002; Carlock et al., 2004; Feltner, Fraschetti, & Crisp, 1999; Adrian Lees, Vanrenterghem, & Clercq, 2004). The DJ at "zero" height, was essentially a simple countermovement vertical jump with restricted arm motion. The other DJs were done from a box of appropriate height ±2 cm from a set of Plyo-Safe Elite Plyo-Boxes (UCS Strength & Speed, Lincolnton, NC, USA).

The participants were instructed to minimize any anticipatory effect of the drop to be consistent with the height of the platform. The participants dropped onto two force plates, with each foot landing on separate force plates simultaneously, and were instructed to immediately jump vertically with maximal effort focusing on both maximal jump height as well as a minimal time spent on the ground. Every participant performed three jumps at each box height for maximum effort in ascending order as encouraged by a professional athletic trainer. The best performance of the three jumps at each height was kept for analyzation. This is common practice for assessment in many athletic combines so as not to analyse subpar efforts (Kuzmits & Adams, 2008; Lephart et al., 1991; McGill, Andersen, & Horne, 2012). No coaching, biomechanical instruction, or verbal guidance was given unless there appeared to be a risk of injury. Between jumps, each participant was allowed enough time to have self-determined rest in order to perform the next jump with a maximum effort.

The kinematic data of the movements were gathered using an 18-camera motion capture system. Three-dimensional marker trajectories were collected at 200 Hz on the Oqus 400 cameras (Qualisys, Gothenburg, Sweden) to a residual of <2 mm for each camera and run through a 12 Hz low-pass Butterworth filter using Visual3D software to smooth any considerable signal noise.

The force data was collected on two 0.90 m x 0.90 m force plates (Bertec Corporation, Columbus, OH, USA). The two force plates were used for parallel foot placement with the data collected at 1000 Hz unfiltered, but down sampled to 200 Hz to match the kinematic data. The force data were synchronized to the kinematic data through Visual3D and also run through a 12 Hz low-pass Butterworth filter.

Statistical Analysis

All data are presented as mean (± SD). The centre of mass for all participants was estimated using anthropometric modelling obtained from the 49 reflective markers for all the jump movements through the Qualysis software. The displacement of the centre of mass was plotted against time throughout the jumping movement. Although the jumping action took place primarily in the vertical direction, the displacement was the measured change in three dimensions, as opposed to just the vertical displacement, in order to align with the resultant force production in three dimensions.

The derivative of the displacement with respect to time was calculated using a forward difference method to represent the velocity of the centre of mass of the participant. The sum of the forces on the two force plates was also plotted against time. The force plates measured the force vector in all dimensions corresponding to the 3-dimensional displacement and velocity variables analysed in all directions as mentioned previously. The centre of mass velocity was verified by the time integration of the instantaneous acceleration found from the force data (Davies & Rennie, 1968).

The instantaneous power output was then calculated by multiplying the velocity of the centre of mass and the force vectors at each data point throughout the movement creating a new time series of absolute power output. The absolute power was then normalized by body mass. The concentric phase of the jump was defined as the length of time from the moment of the beginning of knee extension by 1° until the time of toe-off from the force plate as defined by a measured force of less than 10 N (Cesar, Tomasevicz, & Burnfield, 2016). Peak power was determined as the maximum power at any single instant during the concentric phase while the AP was the statistical mean of the power output across the defined concentric phase.

An ANOVA test was performed with a level of significance set to $p \leq 0.05$ to see if a significant difference in power output existed between drop heights for each participant as well as the overall pool of participants.

Effect size (ES) estimates as partial eta squares (η^2) were found to confirm the meaningfulness of the results. A Pearson Correlation (r) was found between the participant height and the power outputs.

RESULTS

The PP output for each participant at each drop height is presented in Figure 1 along with the pooled average PP for each drop height. The greatest PP drop height was found to be at the 20% level with an average value of 66.9 (±4.1) W/kg. This was significantly different than all resistance levels except the 30% level ($p < 0.05$, $\eta^2 = 0.09$) as shown on Table 1.

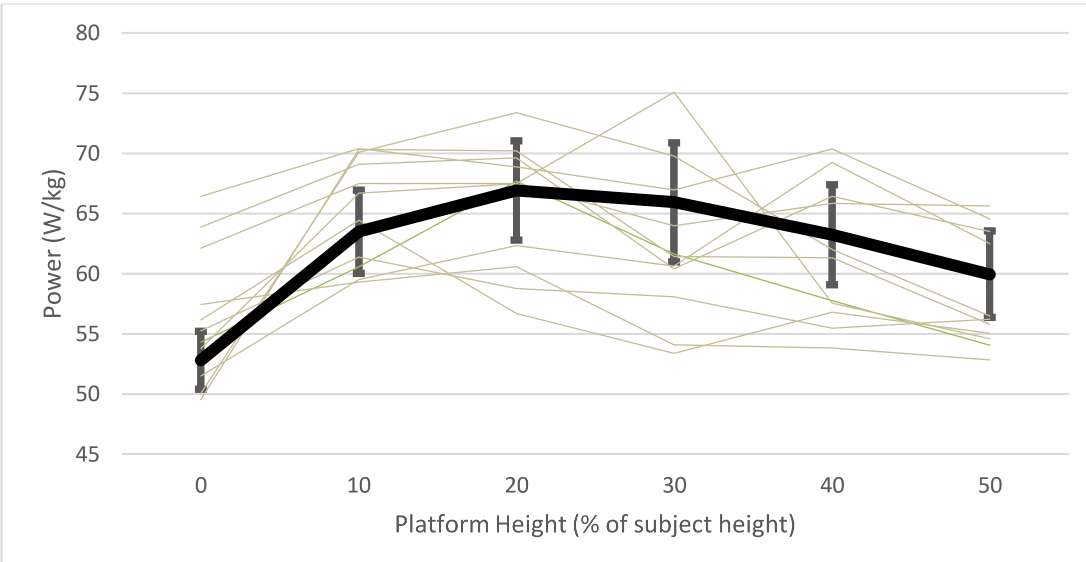

Figure 1. Peak power output at six depth jump platform heights as percentage of subject stature.

Table 1. Power output from six DJ heights.

Drop Height (% of Participant Height)	Peak Power (W/kg)	Average Power (W/kg)
0	52.8 (±2.4) † ‡ Δ ¥ $	27.7 (±1.3) † ‡ Δ ¥ $
10	63.2 (±3.5) # ‡ Δ $	35.9 (±2.1) # ‡ Δ
20	66.9 (±4.1) # † ¥ $	38.8 (±2.5) # † ¥ $
30	65.9 (±4.9) # † ¥ $	38.5 (±2.9) # † ¥ $
40	63.2 (±4.2) # ‡ Δ $	37.3 (±2.4) # ‡ Δ $
50	60.3 (±3.6) # † ‡ Δ ¥	36.0 (±2.3) # ‡ Δ ¥

 # Significant difference from 0% drop height ($p < 0.05$).
† Significant difference from 10% drop height ($p < 0.05$).
‡ Significant difference from 20% drop height ($p < 0.05$).
Δ Significant difference from 30% drop height ($p < 0.05$).
¥ Significant difference from 40% drop height ($p < 0.05$).
$ Significant difference from 50% drop height ($p < 0.05$).

Individually, 6 of the 16 participants maximized their power output at the 20% resistance level while none of the participants had a PP output at 0% or 50% (Figure 2). When the optimal drop height for each individual was averaged, the optimal peak power output for the sample group occurred most near the 20% drop height at 21.3 (±10.3)%.

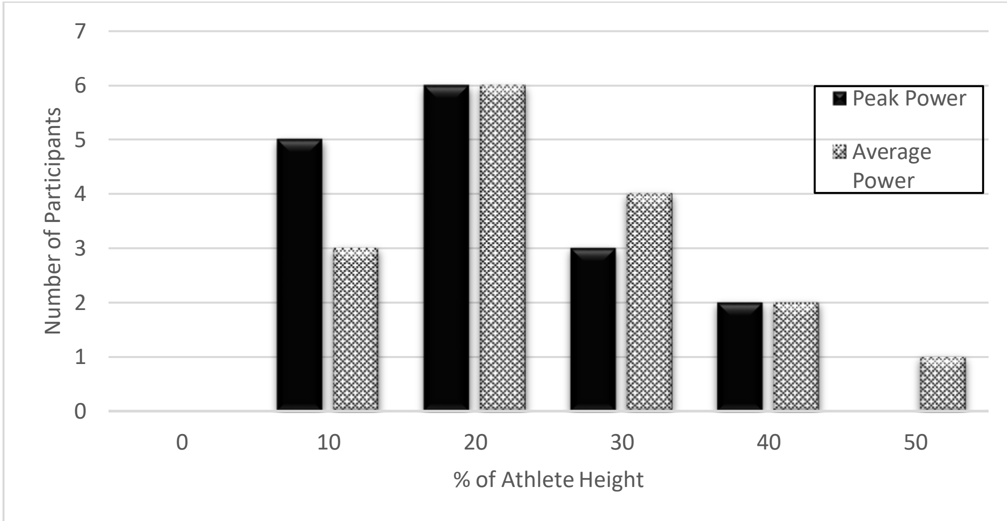

Figure 2. Optimal drop height for peak and average power.

The AP output for each participant at every resistance is shown in Figure 3. The mean of the AP output at each drop height across all participants was also found to be at the 20% level at 38.8 (±2.5) W/kg as shown on Table 1. Similar to the PP results, this level was significantly different than the 0-, 10-, 40-, and 50% levels, but not the 30% level ($p < 0.05$, $\eta^2 = 0.13$).

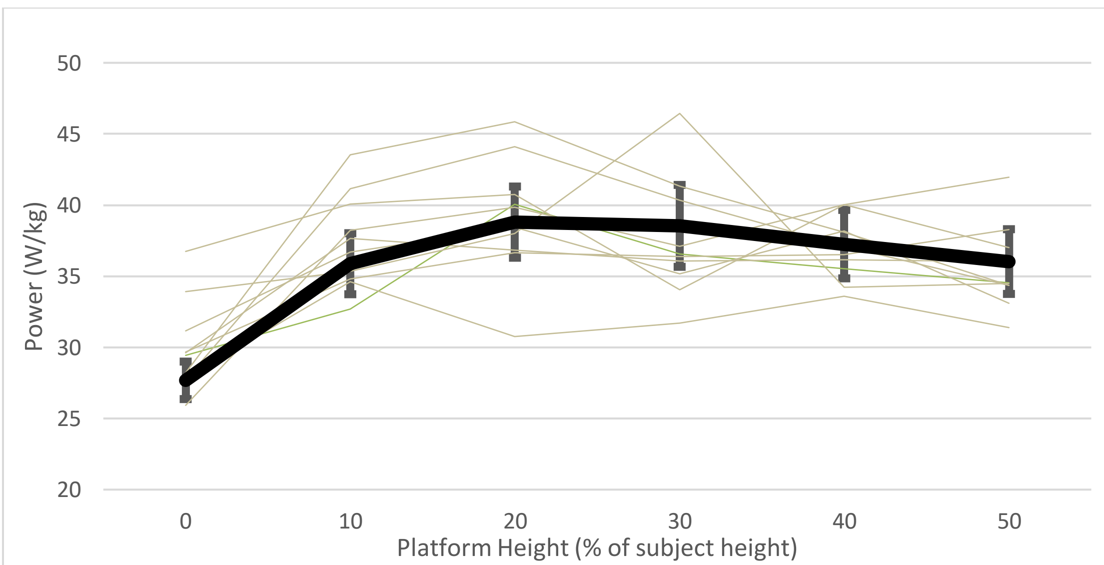

Figure 3. Average power output at six depth jump platform heights as percentage of subject stature.

When the AP optimal height for each individual was averaged, the pooled optimal drop height of the group was found to be 27.5 (±15.3)%. The mode height was also at the 20% level with 6 participants (Figure 2).

Participant height was found to have a positive small correlation with maximum PP and AP regardless of drop height (r = 0.42 and 0.49 respectively). With 14 *df*, the critical value was 0.497. Therefore, the correlations of athlete stature and drop height prove to not be significant reinforcing that a tall athlete does not necessarily correlate to a powerful athlete. Ground contact time was also captured for each jump. The average ground contact time was 0.39 (±0.13) s confirming that the movement was indeed defined as a depth jump and not a drop jump where the ground contact time is less than 0.25 s (Verkhoshansky, 2012).

DISCUSSION

Every participant in the investigation demonstrated a maximum PP output from an intermediate drop height greater than 0% but less than 50% of their body height (Figure 2). This shows that, as hypothesized, there is, in fact, an optimal drop height that enables an athlete to be forceful at a high velocity producing maximum power. The optimal height is when the athlete drops from a platform height to incorporate the stretch-shortening cycle efficiently to enhance their ability to produce power. Added impact force from the two highest platforms (40% and 50%) no longer aided the stretch-shortening cycle and created too much resistance in the form of impact force for the participants to overcome efficiently which led to hindered PP and AP performance.

The power output at the 20% drop height was significantly different from the two lowest drop heights (0% and 10%) as well as the two highest drop heights (40% and 50%) ($p < 0.05$) (Table 1). The optimal resistance level in PP output for all the participants was averaged giving an optimal level of 21.3 (±10.3)% which aligns with previous investigations that used a set universal height rather than a percentage of individual body height (Bobbert et al., 1987a; Harman et al., 1991). Those investigations concluded that the optimal height for trained athletes is near 40 cm. In this investigation, the optimal resistance of 21.3% of the average height of 177.7 cm was 37.7 cm. However, the optimal standard height of 40 cm in the other investigations failed to show significant difference from other heights. This is most likely due to the variability in individual athlete size and ability. An individual quantifiable representation of the optimal height would be more appropriate when considering individual athletes. The optimal height represented by a percentage of body stature and not a universal platform height can enable individual periodization training sets and repetition schemes to be prescribed as a percentage of that athlete's optimal drop height.

Similarly, in the AP output analysis, the maximum power output occurred between the 10% and 40% resistance levels for all but one of the participants (Table 1). Significant difference between the optimal level of 20% and the extreme levels of 0-, 10-, 40-, and 50% demonstrates that an optimal drop height existed in which an athlete could exert maximum AP in addition to PP. The data showed that the average maximum AP output occurred from a drop of 27.5 (±15.3)% of the individual participants' heights (Figure 3). Despite the large variance, when considering the mean value in combination with the mode, it is concluded that an optimal drop height does exist between 0% and 50% of an athlete's height.

Only small positive correlations between participant height and power output were found (0.42 for PP and 0.49 for AP) demonstrating that the height of an athlete has limited to no effect on his or her ability to exert power especially when the absolute power is normalized by size (body mass in this investigation). Therefore, the optimal absolute height of a DJ platform will vary among athletes due to a variety of variables such as strength, body mass, training experience, and more. However, this investigation does show that an optimal level does indeed exist for each athlete and this level can be quantified individually for reference and exercise training program prescription.

The results from this study support the results from previous studies in which a universal optimal platform height was found (Bobbert et al., 1987a; Earp et al., 2010; Luhtanen & Komi, 1978; Verkhoshansky, 2012). However, it is now clear that the optimal drop height would be better described as an individual percentage of athlete height rather than a standard universal height. To further define a more precise optimal height percentage, future research could be done with a narrowed range of drop heights and smaller increments to seek an average optimal drop height with a smaller variance.

CONCLUSION

The DJ movement initiates the stretch-shortening cycle more effectively than a simple countermovement jump from zero height due to increased impact resistance of the drop. However, impact forces from substantial drop heights are too large for an athlete to overcome, impeding the power production. Therefore, maximum peak power production in a DJ is possible from an intermediate optimal drop height that is greater than zero but less than 50% of an athlete's height. For PP output, the optimal height was found to be about 21.3 (±10.2) % of an athlete's anthropometric body height. The AP output was maximized from a drop height of about 27.5 (±15.3) % for the pooled group. Therefore, the drop height was shown to be a quantifiable value to represent the resistance necessary to overcome in a DJ.

Using the drop heights based on individual athlete stature as a quantifiable measure of resistance, power can be calculated (PP and AP) allowing a sports medicine or strength and conditioning professional to incorporate a DJ movement in a power-based program similar to other traditional externally weighted movements in a strength-based program. For example, a set-repetition scheme may be comprised of 3 sets of 5 DJs at a specific percentage of an athlete's height dependent on their individual optimal drop height. Applying this method of DJ prescription could be especially beneficial as an athlete is rehabbing from an injury and gradually increasing intensity toward maximum power exertion.

CONFLICT OF INTEREST

The authors report no potential conflict of interest, financial or otherwise. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation and do not constitute endorsement by the ACSM.

REFERENCES

Ashby, B. M., & Delp, S. L. (2006). Optimal control simulations reveal mechanisms by which arm movement improves standing long jump performance. Journal of Biomechanics, 39(9), 1726–1734. https://doi.org/10.1016/j.jbiomech.2005.04.017

Ashby, B. M., & Heegaard, J. H. (2002). Role of arm motion in the standing long jump. Journal of Biomechanics, 35(12), 1631–1637. https://doi.org/10.1016/s0021-9290(02)00239-7

Asmussen, E., & Bonde-Petersen, F. (1974). Storage of Elastic Energy in Skeletal Muscles in Man. Acta Physiologica Scandinavica, 91(3), 385–392. https://doi.org/10.1111/j.1748-1716.1974.tb05693.x

Baechle, T. R., & Earle, R. W. (Eds.). (2008). Essentials of Strength Training and Conditioning (3rd ed.).

Baker, D., Nance, S., & Moore, M. (2001). The Load That Maximizes the Average Mechanical Power Output During Jump Squats in Power-Trained Athletes. Journal of Strength and Conditioning Research, 15(151), 92–9792. https://doi.org/10.1519/00124278-200102000-00016

Bobbert, M. F., Huijing, P. A., & van Ingen Schenau, G. J. (1987a). Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. Medicine and Science in Sports and Exercise, 19(4), 332–338. https://doi.org/10.1249/00005768-198708000-00003

Bobbert, M. F., Huijing, P. A., & van Ingen Schenau, G. J. (1987b). Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. Medicine and Science in Sports and Exercise. https://doi.org/10.1249/00005768-198708000-00004

Bobbert, M. F., Mackay, M., Schinkelshoek, D., Huijing, P. A., & van Ingen Schenau, G. J. (1986). Biomechanical analysis of drop and countermovement jumps. European Journal of Applied Physiology and Occupational Physiology, 54(6), 566–573. https://doi.org/10.1007/bf00943342

Carlock, J. M., Smith, S. L., Hartman, M. J., Morris, R. T., Ciroslan, D. A., Pierce, K. C., … Stone, M. H. (2004). The Relationship Between Vertical Jump Power Estimates and Weightlifting Ability: A Field-Test Approach. The Journal of Strength and Conditioning Research, 18(3), 534. https://doi.org/10.1519/00124278-200408000-00025

Cesar, G. M., Tomasevicz, C. L., & Burnfield, J. M. (2016). Frontal plane comparison between drop jump and vertical jump: implications for the assessment of ACL risk of injury. Sports Biomechanics / International Society of Biomechanics in Sports, 3141(June), 1–10. https://doi.org/10.1080/14763141.2016.1174286

Davies, C. T. M., & Rennie, R. (1968). Human power output. Nature, 217(5130), 770–771. https://doi.org/10.1038/217770a0

Earp, J. E., Joseph, M., Kraemer, W. J., Newton, R. U., Comstock, B. A., Fragala, M. S., … Maresh, C. M. (2010). Lower-body muscle structure and its role in jump performance during squat, countermovement, and depth drop jumps. Journal of Strength and Conditioning Research, 24(3), 722–729. https://doi.org/10.1519/jsc.0b013e3181d32c04

Feltner, M. E., Fraschetti, D. J., & Crisp, R. J. (1999). Upper extremity augmentation of lower extremity kinetics during countermovement vertical jumps. Journal of Sports Sciences, 17(March 2015), 449–466. https://doi.org/10.1080/026404199365768

Guillaume, L., Phillip, W., & Tom, T. (2013). Countermovement Jump Height. Journal of Strength and Conditioning Research, 28(4), 1.

Harman, E. A., Rosenstein, M. T., Frykman, P. N., Rosenstein, R. M., & Kraemer, W. J. (1991). Estimation of Human Power Output from Vertical Jump. The Journal of Strength & Conditioning Research, 5(3), 116–120. https://doi.org/10.1519/00124278-199108000-00002

Jovanonic, M., & Flanagan, E. P. (2014). Researched applications of velocity based strength training. Journal of Austrailan Strength and Conditioning, 22(2), 58–69.

Kuzmits, F. E., & Adams, A. J. (2008). The NFL combine: does it predict performance in the National Football League? Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 22(6), 1721–1727. https://doi.org/10.1519/jsc.0b013e318185f09d

Lazaridis, S. N., Bassa, E. I., Patikas, D., Hatzikotoulas, K., Lazaridis, F. K., & Kotzamanidis, C. M. (2013). Running Head. Computer Science and Communications Dictionary, 25(1), 1509–1509. https://doi.org/10.1123/pes.25.1.101

Lees, A., & Fahmi, E. (1994). Optimal drop heights for plyometric training. Ergonomics, 37(1), 141–148. https://doi.org/10.1080/00140139408963632

Lees, Adrian, Vanrenterghem, J., & Clercq, D. D. (2004). Understanding how an arm swing enhances performance in the vertical jump. Journal of Biomechanics, 37(12), 1929–1940. https://doi.org/10.1016/j.jbiomech.2004.02.021

Lephart, S. M., Perrin, D. H., Fu, F. H., & Minger, K. (1991). Functional performance tests for the anterior cruciate ligament insufficient athlete. Journal of Athletic Training, 26, 44–50.

Luhtanen, P., & Komi, P. V. (1978). Segmental contribution to forces in vertical jump. European Journal of Applied Physiology and Occupational Physiology, 38(3), 181–188. https://doi.org/10.1007/bf00430076

Mackala, K., Stodolka, J., Siemienski, A., & Coh, M. (2013). Biomechanical analysis of squat jump and countermovement jump from varying starting positions. Journal of Strength and Conditioning Research, 27(10), 2650–2661. https://doi.org/10.1519/jsc.0b013e31828909ec

Mann, B. (2013). Developing Explosive Athletes: Use of Velocity Based training in Training Athletes. E-Book, 22–26.

Mann, J. B., Ivey, P. A., & Sayers, S. P. (2015). Velocity-Based Training in Football. Strength and Conditioning Journal, 37(6), 52–57. https://doi.org/10.1519/ssc.0000000000000177

Markovic, G., & Jaric, S. (2007). Is vertical jump height a body size-independent measure of muscle power? Journal of Sports Sciences, 25(12), 1355–1363. https://doi.org/10.1080/02640410601021713

McBride, J. M., Triplett-McBride, T., Davie, A., & Newton, R. U. (1999). A Comparison of Strength and Power Characteristics Between Power Lifters, Olympic Lifters, and Sprinters. Journal of Strength and Conditioning Research, 13(1), 58–66. https://doi.org/10.1519/00124278-199902000-00011

McGill, S. M., Andersen, J. T., & Horne, A. D. (2012). Predicting performance and injury resilience from movement quality and fitness scores in a basketball team over 2 years. Journal of Strength and Conditioning Research, 26(7), 1731–1739. https://doi.org/10.1519/jsc.0b013e3182576a76

Stone, M. H. (2003). Power and Maximum Strength Relationships During Performance of Dynamic and Static Power and Maximum Strength Relationships. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 17(March), 140–147. https://doi.org/10.1519/00124278-200302000-00022

Verkhoshansky, N. (2012). Shock method and plyometrics. Central Virginia Sport Performance, 75.

Voigt, M., Simonsen, E. B., Dyhre-Poulsen, P., & Klausen, K. (1995). Mechanical and muscular factors influencing the performance in maximal vertical jumping after different prestretch loads. Journal of Biomechanics, 28(3), 293–307. https://doi.org/10.1016/0021-9290(94)00062-9

Walsh, M., Arampatzis, A., Schade, F., & Brüggemann, G.-P. (2004). The effect of drop jump starting height and contact time on power, work performed, and moment of force. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 18(3), 561–566. https://doi.org/10.1519/00124278-200408000-00030

