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Abstract

Purpose: The aim of this study was to ascertain the biomechanical differences between better and poorer performers of the vertical jump in a homogeneous group of children. Method: Twenty-four girls were divided into low scoring (LOW) (6.3 ± 0.8 years) and high scoring (HIGH) (6.6 ± 0.8 years) groups based on their performance in the vertical jump. The force-, velocity-, displacement-, and RFD-time curves of vertical jumps were analyzed in order to determine the differences between groups. Results: The analysis of the data showed differences in the pattern of the ensemble mean curves of the HIGH and LOW groups, although the majority of the differences occurred during the eccentric contraction phase of the jump. The differences in the HIGH group with respect to the LOW group were: Lower force at the beginning of the movement, higher speed and rate of force development (RFD) during the eccentric phase, high force at the beginning of the concentric phase, higher velocity during the concentric phase, and a higher position at takeoff. Conclusion: The results showed that the HIGH group achieved a higher jump height than the LOW group by increasing the effectiveness of the counter-movement and achieving a more advantageous position at take-off.

Keywords: Biomechanics, skill development, stretch shortening cycle, vertical jump

Introduction

During growth, children's games and physical activities often involve various forms of jumping. This skill is usually acquired during the fundamental movement phase which normally occurs between 4 and 7 years old (Gallahue & Ozmun, 2006). Many studies have observed progressive increases in jumping performance from childhood to adolescence (Malina, Bouchard, & Bar-Or, 2004; Taylor, Cohen, Voss, & Sandercock, 2010; Temfemo, Hugues, Chardon, Mandengue, & Ahmaidi, 2009). These increases are often associated with changes in anthropometric characteristics and in the movement pattern of the jump (Clark, Phillips, & Petersen, 1989; Jensen, Phillips, & Clark, 1994; Temfemo et al., 2009). During the growth of children, leg strength and power are correlated with leg muscle cross-sectional area and volume (Barrett & Harrison, 2002), while the increase of jumping performance is correlated with lean body mass, the magnitude and velocity of movement as well as the reduction of movement variability (Clark et al., 1989; Gerodimos et al., 2008; Harrison & Gaffney, 2001; Jensen et al., 1994; O'Brien, Reeves, Baltzopoulos, Jones, & Maganaris, 2009; Temfemo et al., 2009; Wang, Lin, & Huang, 2004). In contrast, the coordination of movement and the use of stretch-shortening cycle (SSC) appear to remain stable from childhood to adulthood (Clark et al., 1989; Gerodimos et al., 2008; Harrison & Gaffney, 2001; Jensen et al., 1994).

Many of the experimental studies on the development of jumping performance focus on comparing differences between various age groups but little is known about possible differences in performance within the same age group during development. Since growth rates are known to vary considerably within any given age group, it is possible that differences in performance at any age may arise simply as a result of differences in size rather than function. Therefore, any evaluation of performance related factors in jumping in children, needs to control for the large variations in anthropometry that occur during childhood. Based on the literature, there are few studies that ascertain the jumping performance differences between children of the same age, but there are studies that have assessed different levels of jumping performance in adults (Cormie, McBride, & McCaulley, 2009; Sheppard et al., 2008; Vanezis & Lees, 2005). These studies concluded that the superior performance of the best jumpers was due to their ability to produce greater muscle force and power while the technical aspects of performance (i.e., coordination of body segments, magnitude of counter-movement) played a less important role. While the differences in jumping performance among adults are focused on application of force rather than in the technical execution, it is not clear if differences in performance between children can be explained in the same way. In a recent study, Flоría and Harrison (in press) observed that the vertical jump height in a group of girls aged 4 to 8 years was related to increases in both the application of force and the range of motion, but the latter had more influence on jumping performance than the former. This may indicate that from childhood to adulthood the influence of movement patterns on performance decreases while the strength related parameters become more predominant.

Many of the studies analyzing the development of vertical jump use a series of discrete measures such as maximum or mean values as indicators of performance. Although this type of analysis is useful, the process of deriving these discrete parameters tends to discard a large amount of data which may contain important information to evaluate the motion or forces. Therefore, an analysis of variations in the patterns of the force-, velocity-, and displacement-time curves could provide important insights on how changes in the kinematic or kinetic time series may result in improvement of jumping performance. Recent studies (Cormie, McBride, & McCaulley, 2008; Cormie et al., 2009) have examined the force-, velocity-, and power-time curves to evaluate the impact of load and training during the vertical jump. These studies observed differences in both instantaneous variables as well as in the shape of the curves. The authors concluded that the curve analysis offers a simple yet powerful monitoring technique that can be used to gain insight into the precise nature and timing of adaptations to load and training. Despite the utility of this methodology, it has rarely been used to assess the jumping performance in children.

Although much research has examined the vertical jump in children, most studies have compared children of different ages (Floría & Harrison, in press; Gerodimos et al., 2008; Harrison & Gaffney, 2001; O'Brien et al., 2009; Wang et al., 2004). Little is known about the biomechanical differences between children in the same phase of growth. In order to improve understanding of child development, it is important to evaluate why some children of similar age and size are able to jump higher than others. Consequently, the purpose of this study was to ascertain the biomechanical differences between better and poorer performers of the vertical jump in a homogeneous group of children. Therefore, this study compared the force-, velocity-, displacement-, and rate of force development (RFD) -time curves between girls of similar age and anthropometric characteristics. Quantitative data about the changes in the analyzed curves and the resulting changes in the jump performance are necessary to plan training progressions to enhance vertical jump and the identification of children with atypical development.

Methods

Participants

Selection of the participants took place in different phases. The procedure started with 36 acrobatic gymnastics girls with an age range of 4 to 8 years. No participants had any past history of nervous system or muscular dysfunction. The study had obtained ethical approval from the University Research Ethics Committee. All parents/guardians of participants signed informed consent forms before participating in the study.

Vertical Jumping Test

Participants were instructed to perform counter-movement jumps (CMJ) on a portable force platform (Quattro Jump®, Kistler Instrumente AG, Winterthur, Switzerland). Before each test, the all participants performed 10 minutes of warm-up activity which included a brief period of low-intensity aerobic exercise, some short duration static stretching exercises (each stretch were held for 15 s with 5 s rest between repetitions) and one set of 5 sub-maximal jumps. Since all participants were physically active and regularly performed activities including jumping, a short familiarization session was sufficient to ensure the participants could complete the jumping tasks to a satisfactory level. Vertical ground reaction force (Fz) data were sampled at 500 Hz and the duration of data collection period was 5 seconds. A force plate computer software (QuattroJump, Type 2822A1-1, Version 1.0.9.2) was used to record the force values.

The instructions for each participant were standardized. They included a detailed verbal explanation and a physical demonstration by the experimenter. The importance of jumping as high as possible was emphasized. In performing the CMJ, the participants stood upright and stationary for at least 2 seconds during which body weight was recorded, then jumped as high as possible. For all jumps, participants retained the “hands on hips” position until the landing phase. Three successful jumps were recorded for each participant, with at least 2 minutes of rest between jumps. The average of the three successful jumps was used for analysis.

Analysis

The vertical component of center of mass (CoM) velocity was estimated using the impulse method (Linthorne, 2001). Net impulse was obtained by integrating the net Fz, from 2 s prior to the first movement of the participant (Street, McMillan, Board, Rasmussen, & Heneghan, 2001), using the trapezoid method (Kibele, 1998). Subsequently, the vertical velocity of the CoM was calculated by dividing the net impulse by the participant's body mass. Vertical CoM displacement throughout the ground contact period was derived by numerically integrating the vertical CoM velocity. Finally, the RFD throughout the motion was calculated from first derivative of Fz using the following equation:

$$RFD_i = \frac{Fy_{i+1} - Fy_{i-1}}{t_{i+1} - t_{i-1}}$$

Where:

RFD (i) is the rate of force development at time, t(i)

Fz (i+1) is the vertical ground reaction force at time, t(i+1)

Temporal phase analysis of the jumps was conducted as follows: The force-, velocity-, displacement-, and RFD-time curves from all participants were selected from the start of the movement to instant of take-off. The start of the movement was identified on the recommendations of Street et al. (2001) by inspecting the force-time records to identify the first instant where Fz deviated above or below body weight (BW) by more than one threshold. The threshold was defined as 1.75 times the peak residual found in the 2 seconds of the BW averaging period. A backward search was then performed until Fz passed through BW. The instant of take-off was defined as the first intersection of Fz with an offset threshold where, the threshold was determined by adding the average flight time (i.e., 0.4 seconds) and the peak residual to the offset (Street et al., 2001).

Group Analysis

In order to control for the effects of age, height, and weight on jump performance, the following criteria were applied. From the original group a sample was selected of participants aged between 5 and 7 years old. The participants were chosen in this age range, since this approximates the fundamental movement phase where the development of a mature vertical jumping sequence is normally achieved (Gallahue & Ozmun, 2006). This sample was divided into low scoring (LOW) and high scoring (HIGH) groups based on the participants' mean jump height of three trials performed during the CMJ test. To ensure the two groups were relatively similar in age, height, and weight but clearly different in jump performance, the two highest jumpers of the LOW group and the two lowest jumpers of the HIGH group were discarded. Finally, a Student t-test was used to assess whether the differences were statistically significant between LOW group and HIGH group with regard to age (t = 0.888, p = .384, ES = -0.3), height (t = 1.709, p = .102, ES = -0.7), weight (t = 1.141, p = .266, ES = -0.5) and jumping performance (t = 7.853, p < .001, ES = -3.3). The LOW group consisted of 12 girls aged 6.3 ± 0.8 years old (mean ± SD), with a mass of 20.4 ± 2.8 kg and a height of 1.14 ± 0.07 m. The HIGH group consisted of 12 girls aged 6.6 ± 0.8 years old, with a mass of 21.8 ± 3.0 kg and a height of 1.19 ± 0.06 m (Table 1).

To compare the curves between the LOW and HIGH groups, the dataset of each parameter was normalized to 500 points using a cubic interpolation. This was processed using a free scientific data analysis software SciDavis (http://scidavis.sourceforge.net/). This allowed for all force-, velocity-, displacement-, and RFD-time curves to be expressed over normalized periods of percentage time. Each normalized trace was averaged over all participants and all trials to provide a mean curve for each variable.

Table 1. Descriptive characteristics of the participants in each group.

	LOW		HIGH	
	Mean ± SD	Range	Mean ± SD	Range
Age (years)	6.3 ± 0.80	5.0 – 7.60	6.6 ± 0.80	5.3 – 7.90
Weight (kg)	20.4 ± 2.80	15.4 – 26.4	21.8 ± 3.00	15.6 – 26.2
Height (m)	1.14 ± 0.07	1.03 – 1.26	1.19 ± 0.06	1.07 – 1.27
Height jump (m)	0.19 ± 0.02	0.14 – 0.21	0.26* ± 0.02	0.22 – 0.29

* $p < .05$

Statistical Analysis

Normality of the data sets was verified using the Shapiro-Wilk test. If the data were normally distributed within groups, an independent samples Student t-test was applied at each time point throughout the movement to determine differences in the force-, velocity-, displacement-, and RFD-time curves between LOW and HIGH groups. If the data were not normally distributed, then a Mann-Whitney U-test was used. Statistical analysis was completed by the estimation of the effect size (ES) using Cohen's d_z (1977) to evaluate the magnitude of differences. The criteria for interpreting the ES were: trivial = 0.00 – 0.19, small = 0.20 – 0.59, moderate = 0.60 – 1.20, and large >1.20 (Hopkins, 2004). Statistical significance level was set at $p < .05$. All statistical analysis were conducted using SPSS version 18.0.

Results

The results of this study showed differences in the pattern of the ensemble mean curves of the HIGH and LOW groups (Figure 1). There were significant differences in the force-time curve in two different intervals (Figure 1a). The first interval of significant difference occurred from 37.4% to 48.2% of normalized time, in which the forces were less than 1 BW and LOW group achieved higher force values than the HIGH group ($t \leq -2.101$, $p \leq .047$, ES ≤ -0.9). The second interval of significant difference in which the HIGH group applied higher amounts of force than LOW group, was at 63.8% to 74.2% of normalized time ($t \geq 2.097$, $P \leq .048$, ES ≥ 0.9). This interval coincided with the period of transition from eccentric to concentric muscle action. Similarly, differences were found in the velocity-time curve between the two groups at two different intervals (Figure 1c). The first took place during the downward movement, from 45.6% to 63.4% of normalized time ($t \leq -2.111$, $p \leq .046$, ES ≤ -0.9), while the second took place during the upward movement, from 78.2% to take-off of normalized time ($t \geq 2.099$, $p \leq .048$, ES ≥ 0.9). In both intervals, the velocity of the HIGH group was significantly higher than the LOW group. The only interval of significant difference in displacement-time curve (Figure 1d) was produced in the final instants of the movement, from 96.4% to take-off of normalized time ($t \geq 2.142$, $p \leq .044$, ES ≥ 0.9). During this interval the position of the CoM was higher in the HIGH group than in the LOW group. In two separate intervals, significant differences were found between groups in the RFD-time curve (Figure 1b). The first occurred during the downward phase of CMJ, from 51.8% to 63.4% of normalized time ($t \geq 2.123$, $p \leq .045$, ES ≥ 0.9). In this interval, RFD values were greater in the HIGH group than in the LOW group. The second interval was during the upward movement phase of CMJ, from 76% to 76.6% of normalized time ($t \leq -2.086$, $p \leq .049$, ES ≤ -0.9), and RFD values were higher in the LOW group with respect to the HIGH group.

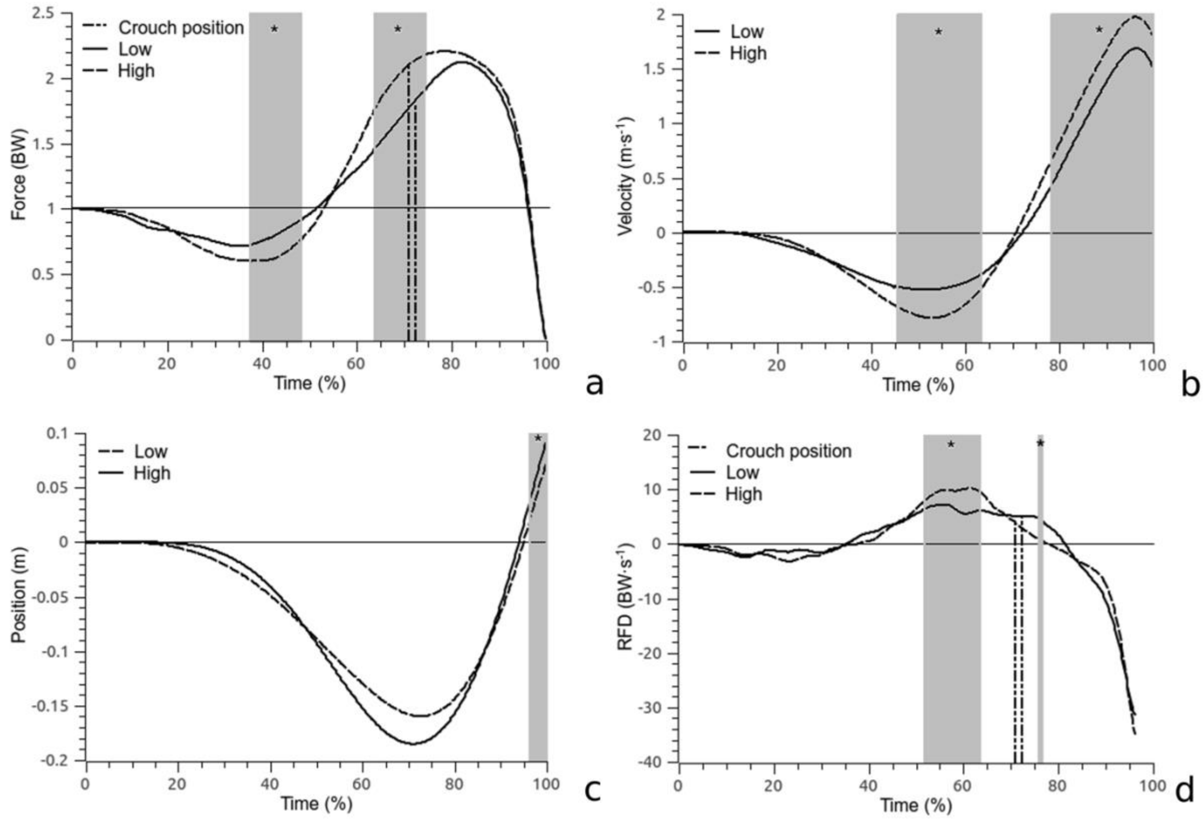

Figure 1. Comparison of the ensemble average force-time (a), RFD-time (b), velocity-time (c), and displacement-time (d) curves during a counter-movement jump (CMJ) between HIGH and LOW groups. * Denotes statistically significant difference between groups ($p < .05$).

Discussion

The results of this study indicated several biomechanical differences in the CMJ between two groups of children of similar age and size but different in their level of performance. From the analysis of the curves, it was observed that the level of performance in the vertical jump caused differences in the shapes of the ensemble mean curves throughout the movement. Therefore, this type of analysis was helpful in providing information on the biomechanical factors related to vertical jump performance in children that were independent of differences in anthropometry or age.

Although the general patterns of ensemble mean force-time curves was similar, there were significant differences between groups. The majority of these significant differences occurred during the eccentric contraction phase of CMJ. During this phase, the HIGH group exerted a lower vertical ground reaction force compared to LOW group. These results are in general agreement with Cormie et al. (2009) who reported a reduction in the force in the eccentric phase after 12 weeks of power training on adults. The reduction in ground force in this phase is likely to increase the net downwards force on the CoM thereby increasing the negative impulse and consequently resulting in an increased downward velocity of the CoM. This is confirmed by figures 1a and 1c, which show that the HIGH group achieved a lower force than LOW group and moments later reached a higher downward velocity. Previous studies have indicated the importance of increasing the downward velocity in the vertical jump to improve the performance (Aragón-Vargas & Gross, 1997; Cormie et al., 2009; Cormie, McGuigan, & Newton, 2010; González-Badillo & Marquez, 2010). Cormie et al. (2009, 2010) found that the velocity in the eccentric phase increased after training and that this was correlated with improvements in performance in the concentric phase. Similarly, previous studies have indicated that the maximum downward velocity can also be a good predictor of performance in CMJ since the downward velocity and jump height were correlated (Aragón-

Vargas & Gross, 1997; González-Badillo & Marquez, 2010).

Although the force and velocity throughout the eccentric phase differed significantly between groups, the ranges of motion during this phase remained similar in both groups. Figure 1d shows that the HIGH group increased their range of motion during eccentric phase and reached a lower position of the CoM compared to LOW group, however, this difference in mean range of motion was not statistically significant. This finding contrasts with previous studies, which highlighted the influence of range of motion on vertical jump performance in children (Floría & Harrison, in press; Wang et al., 2004). The reason for these contrasting results may be related to the high variability in the vertical jump of children compared to adults (Floría & Harrison, in press; Gerodimos et al., 2008; Harrison & Gaffney, 2001).

The present study showed that the HIGH group produced greater downwards velocity compared to the LOW group but no differences in the displacement of the CoM during the counter-movement. Therefore, it might be expected that the HIGH group developed a greater rate of force in the last phase of counter-movement to decelerate the CoM. Both RFD and force values were significantly higher during the last part of the downward movement in the HIGH group compared with the LOW group which facilitated a deceleration of the CoM. Furthermore, as result of this improvement in the eccentric phase, the HIGH group started the concentric phase with a greater vertical ground reaction force. This greater force resulted in the higher vertical velocity of the HIGH group than the LOW group for most of the concentric phase. This is supported by the findings of several studies on adults which concluded that the ability to generate higher force at the beginning of the concentric phase facilitated greater concentric force, velocity, and, ultimately, improved jump height (Bobbert, Gerritsen, Litjens, & Van Soest, 1996; Cormie et al., 2009, 2010; Ingen Schenau, Bobbert, & Haan, 1997). After the beginning of the concentric phase, the LOW group achieved higher RFD values than the HIGH group; however, force values in the concentric phase remained lower than the HIGH group. Therefore, the low group should generate lower impulse than HIGH group which probably resulted in a lower velocity throughout of the concentric phase. Based on these results, it appears that the ability to develop force quickly during concentric phase is not sufficient to distinguish between different levels of performance in the vertical jump in children. This finding was consistent with previous studies (Cormie et al., 2009; Ebben, Flanagan, & Jensen, 2007) which found no significant differences in concentric RFD between groups with different levels of performance. In summary, a lower force at the beginning of the movement together with high velocity and RFD suggests that the HIGH group could tolerate a higher load during the counter-movement and thus improve vertical jump performance. An eccentric phase alteration contributes to improved performance of the concentric phase (Cormie et al., 2010).

The jumping height is mechanically determined by the vertical velocity and height of the CoM at the instant of take-off. All of the above findings related to ability of the HIGH group to generate higher vertical velocity than the LOW group throughout the concentric phase, but they also achieved a more advantageous position to complete the vertical jump in the final stages of the activity. The results showed that the HIGH group elevated the position of the CoM more than the LOW group from the instant of maximum velocity to take-off. Research has shown that in order to achieve an effective jump the leg muscles must attain their maximum activations in a sequence from proximal to distal (Bobbert & Van Ingen Schenau, 1988). In this sequence, the activation of plantar flexor muscles occurs in the last moments of the push-off, therefore a relative muscle weakness in the plantar flexors of LOW group compared with the HIGH group could explain the differences between the groups. This result is consistent with previous studies (Jensen et al., 1994; Wang et al., 2004), which suggested that a lower CoM height at take-off in children compared to adults could be related to incomplete leg extension before take-off due to insufficient strength or postural control deficiencies.

No previous research has quantified the differences in the force-, velocity-, displacement-, and RFD-time curves between children of the same age and height but different level of performance. The analysis of these curves has provided important findings about the biomechanical characteristics which are linked to improved performance of the vertical jump in children. The results showed that the HIGH group achieved a higher jump height than the LOW group both by increasing the effectiveness of the counter-movement as well as achieving a more advantageous position at take-off. In particular, the HIGH group performed a faster eccentric phase with a rapid transition between stretching and shortening which allowed further increases in the effectiveness of the concentric phase.

What Does This Paper Add?

This study demonstrates the important role of the counter-movement as a contributor to differences in jumping performance in children. Generally, the differences in performance among children of the same age are correlated to differences in size caused by variations in growth rates. By controlling for age and size, this study shows that the differences in jumping performance can be explained by how effectively the children use the stretch shortening cycle. The results suggest that during the fundamental movement phase the counter-movement has a critical role in the improvement of the vertical jump performance and this should be the focus for improvement during the learning of the vertical jump and other similar activities in children. This study has also demonstrated that an analysis of the pattern of force-, velocity-, displacement-, and RFD-time curves can be used to distinguish biomechanical differences in performance between homogeneous groups.

References

Aragón-Vargas, L. F., & Gross, M. M. (1997). Kinesiological factors in vertical jump performance: Differences among individuals. *Journal of Applied Biomechanics*, *13*, 24–44.

Barrett, U., & Harrison, A. J. (2002). Comparing muscle function of children and adults: Effects of scaling for muscle size. *Pediatric Exercise Science*, *14*(4), 369–376.

Bobbert, M. F., Gerritsen, K. G. M., Litjens, M. C. A., & Van Soest, A. J. (1996). Why is counter-movement jump height greater than squat jump height? *Medicine and Science in Sports and Exercise*, *28*(11), 1402–1412.

Bobbert, M. F., & Van Ingen Schenau, G. J. (1988). Coordination in vertical jumping. *Journal of Biomechanics*, *21*(3), 249–262.

Clark, J. E., Phillips, S. J., & Petersen, R. (1989). Developmental stability in jumping. *Developmental Psychology*, *25*(6), 929–935.

Cohen, J. (1977). *Statistical power analysis for the behavioral sciences*. New York, NY: Academic Press.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2008). Power-time, force-time, and velocity-time curve analysis during the jump squat: Impact of load. *Journal of Applied Biomechanics*, *24*(2), 112–120.

Cormie, P., McBride, J. M., & McCaulley, G. O. (2009). Power-time, force-time, and velocity-time curve analysis of the counter-movement jump: Impact of training. *Journal of Strength and Conditioning Research*, *23*(1), 177–186.

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Medicine and Science in Sports and Exercise*, *42*(9), 1731–1744.

Ebben, W., Flanagan, E., & Jensen, R. (2007). Gender similarities in rate of force development and time to takeoff during the counter-movement jump. *Journal of Exercise Physiology Online*, *10*(6), 10–17.

Floría, P., & Harrison, A. J. (in press). The influence of range of motion versus application of force on vertical jump performance in prepubescent girls and adult females. *European Journal of Sport Science*. doi:10.1080/17461391.2012.679316

Gallahue, D. L., & Ozmun, J. C. (2006). *Understanding motor development: Infants, children, adolescents, adults* (p. 524). New York, NY: McGraw-Hill.

Gerodimos, V., Zafeiridis, A., Perkos, S., Dipla, K., Manou, V., & Kellis, S. (2008). The contribution of stretch-shortening cycle and arm-swing to vertical jumping performance in children, adolescents, and adult basketball players. *Pediatric Exercise Science*, *20*(4), 379–389.

González-Badillo, J. J., & Marquez, M. C. (2010). Relationship between kinematic factors and counter-movement jump height in trained track and field athletes. *Journal of Strength and Conditioning Research*, *24*(12), 3443–3447.

Harrison, A. J., & Gaffney, S. (2001). Motor development and gender effects on stretch-shortening cycle performance. *Journal of Science and Medicine in Sport*, *4*(4), 406–415.

Hopkins, W. G. (2004). How to interpret changes in an athletic performance test. *Sportscience*, *8*, 1–7.

Ingen Schenau, G. J. van, Bobbert, M. F., & Haan, A. de. (1997). Does elastic energy enhance work and efficiency in the stretch-shortening cycle? *Journal of Applied Biomechanics*, *13*, 389–415.

Jensen, J. L., Phillips, S. J., & Clark, J. E. (1994). For young jumpers, differences are in the movement's control, not its coordination. *Research Quarterly for Exercise and Sport*, *65*(3), 258–268.

Kibele, A. (1998). Possibilities and limitations in the biomechanical analysis of counter-movement jumps: A methodological study. *Journal of Applied Biomechanics*, *14*, 105–117.

Linthorne, N. P. (2001). Analysis of standing vertical jumps using a force platform. *American Journal of Physics*, *69*(11), 1198–1204.

Malina, R., Bouchard, C., & Bar-Or, O. (2004). *Growth, maturation, and physical activity* (p. 728). Champaign, IL: Human Kinetics.

O'Brien, T. D., Reeves, N. D., Baltzopoulos, V., Jones, D. a, & Maganaris, C. N. (2009). Strong relationships exist between muscle volume, joint power and whole-body external mechanical power in adults and children. *Experimental Physiology*, *94*(6), 731–738.

Sheppard, J. M., Cronin, J. B., Gabbett, T. J., McGuigan, M. R., Etxebarria, N., & Newton, R. U. (2008). Relative importance of strength, power, and anthropometric measures to jump performance of elite volleyball players. *Journal of Strength and Conditioning Research*, *22*(3), 758–765.

Street, G. M., McMillan, S., Board, W., Rasmussen, M., & Heneghan, J. M. (2001). Sources of error in determining counter-movement jump height with the impulse method. *Journal of Applied Biomechanics*, *17*, 43–54.

Taylor, M. J. D., Cohen, D., Voss, C., & Sandercock, G. R. H. (2010). Vertical jumping and leg power normative data for English school children aged 10–15 years. *Journal of Sports Sciences*, *28*(8), 867–872.

Temfemo, A., Hugues, J., Chardon, K., Mandengue, S.-H., & Ahmaidi, S. (2009). Relationship between vertical jumping performance and anthropometric characteristics during growth in boys and girls. *European Journal of Pediatrics*, *168*(4), 457–464.

Vanezis, A., & Lees, A. (2005). A biomechanical analysis of good and poor performers of the vertical jump. *Ergonomics*, *48*(11-14), 1594–1603.

Wang, L.-I., Lin, D.-C., & Huang, C. (2004). Age effect on jumping techniques and lower limb stiffness during vertical jump. *Research in Sports Medicine*, *12*(3), 209–219.