Biomechanical factors associated with jump height: a comparison of cross-sectional and pre-to-post training change findings

ABSTRACT

Previous studies investigating the biomechanical factors associated with maximal countermovement jump height have typically utilised cross-sectional data. An alternative but less common approach is to use pre-to-post training change data, where the relationship between an improvement in jump height and a change in a factor is examined more directly. Our study compared the findings of these approaches. Such an evaluation is necessary because cross-sectional studies are currently a primary source of information for coaches when examining what factors to train to enhance performance. The countermovement jump of forty four males was analysed before and after an eight week training intervention. Correlations with jump height were calculated using both cross-sectional (pre-training data only) and pre-to-post training change data. Eight factors identified in the cross-sectional analysis were not significantly correlated with a change in jump height in the pre-to-post analysis. Additionally, only six of eleven factors identified in the pre-to-post analysis were identified in the cross-sectional analysis. These findings imply that: (a) not all factors identified in a cross-sectional analysis may be critical to jump height improvement, and (b) cross-sectional analyses alone may not provide an insight into all of the potential factors to train to enhance jump height. Coaches must be aware of these limitations when examining cross-sectional studies to identify factors to train to enhance jump ability. Additional findings highlight that while exercises prescribed to improve jump height should aim to enhance concentric power production at all joints, a particular emphasis on enhancing hip joint peak power may be warranted.

KEYWORDS: vertical jump, performance, training

INTRODUCTION

Vertical countermovement jump ability (maximal jump height) is an important contributor to successful performance in many sports (30,12). In order to most effectively enhance jump height, it is important for strength and conditioning professionals to have an understanding of the biomechanical factors that produce higher jumps. Establishing a true cause-effect relationship between a biomechanical factor and jump height would require a training intervention that caused only a single biomechanical factor to be enhanced, and then determine the extent to which this enhancement was related to an increase in jump height. However, it is not possible to isolate and enhance a single kinetic or kinematic variable in human subjects. Therefore, researchers have typically used correlation and regression techniques on acute cross-sectional data to obtain a greater understanding of the factors to train to enhance athletes' jump height (1,9,25,31).

An alternative but much less common approach to identify factors associated with jump height is to utilise a training intervention, and examine the relationship between changes in the underlying biomechanical factors and the change in jump height (27). This approach will be referred to herein as a pre-to-post analysis. A benefit of this method is that a direct relationship between training induced changes and performance is examined (27). The use of pre-to-post analyses are supported by the deterministic argument that if a factor is causative of jump height then a meaningful training induced change in that factor should be related to a change in jump height. Conversely, if a factor is appropriately enhanced with training, but does not relate to the associated change in jump height, it is less likely to be a causative factor. This reasoning is in line with a probabilistic approach to causation (28,29).

To the best of our knowledge, no studies have compared the results of a cross-sectional analysis with a pre-to-post analysis in countermovement jumping. Such an evaluation is necessary because results from cross-sectional analyses are currently a primary source of information in detailing factors that may be trained to enhance performance. If the findings of a cross-sectional and pre-to-post analysis are similar, it would lend further support to the former and suggest that training interventions are not essential in the identification of such factors.

Only one previous study appears to have used a pre-to-post analysis in the examination of factors associated with countermovement jump height (27), and they did not compare their results to a cross-sectional analysis. Sheppard et al. (27) found a significant ($P < .05$) correlation between a post-training change in jump height and a change in both peak whole body force ($r = 0.55$) and velocity ($r = 0.48$). However, this study only examined three biomechanical variables, and did so only at a whole body level; no individual joint measures were examined. Therefore, despite a pre-to-post analysis being considered a more direct means of identifying potential factors to train to enhance performance (27), a comprehensive application of this technique in countermovement jumping has yet to be undertaken. Such an analysis should provide pertinent information in the design of future training interventions.

The primary aim of this study is to compare factors associated with countermovement jump height in a pre-training cross-sectional analysis with those identified in a pre-to-post training change analysis. It is hypothesized that the findings of these distinct analyses will not be fully comparable due to the fact that the cross-sectional analysis relies on data from a single testing session only. As this will be the first study to undertake an in depth pre-to-post analysis of the countermovement jump, the factors identified in this analysis will be discussed to add to current knowledge on the key biomechanical factors associated with jump height.

METHODS

Experimental Approach to the Problem

Similar to previous studies that have examined the key biomechanical factors of jumping (25), the current study used bi-variate correlations to identify factors associated with higher jumps. Two distinct bi-variate correlation analyses, which differed from each other based on the data used, were undertaken. Firstly, factors associated with jump height in an acute pre-training testing session were identified (cross-sectional analysis). Secondly, pre- to post-training change data (following an eight week drop jump training intervention) were used to calculate factors whose post-training change was associated with a change in jump height (pre-to-post analysis).

Each participant's countermovement jump was analysed before and after the eight-week training period using standard motion capture techniques (20). The following kinetic variables were calculated at the whole body and joint (hip, knee and ankle) level: force at the start of the concentric phase, concentric peak force, concentric peak power, eccentric peak power and concentric work done. All kinetic variables were normalised with respect to body mass. The following kinematic and temporal variables were calculated at the whole body level only: eccentric peak vertical velocity, eccentric phase duration, concentric phase duration and countermovement amplitude. At the joint level, angles at joint reversal for the hip, knee and ankle were examined. These particular variables were chosen due to their potential to influence countermovement jump height (1,9), and have previously been shown to exhibit good test-retest repeatability (20).

Subjects

Forty-four athletic male students (mean ± *SD*: age, 22 ± 4 y; height, 177.8 ± 5.2 cm; mass 77.5 ± 9.3 kg) were recruited to take part in the study and all provided written informed consent as required by the Dublin City University Ethics Committee. The majority of participants played Gaelic football (47%), soccer (30%) and basketball (12%). Participants had not undertaken structured drop jump training in the previous six months.

Procedures

Prior to jump testing, participants' height and weight were recorded using an electronic scale (Seca 876) and stadiometer (Seca 213). Participants then undertook a standardised warm-up which consisted of a three minute treadmill jog at 7 $km \cdot h^{-1}$ followed by five sub-maximal (approximately 50% of maximal intensity) countermovement jumps. The testing itself consisted of five maximal countermovement jumps, separated by an adequate rest period of forty seconds (24). The countermovement jump was initiated from an upright standing position before counter-moving to a self selected depth and then jumping vertically with maximum effort. Participants placed their hands on their hips for all trials and wore their own athletic footwear. It is acknowledged that the use of different verbal instructions or the use of an overhead target may lead to altered jump performance (11, 34). However, this does not affect the ability of the vertical jump variant utilised herein to examine the primary hypothesis of interest. Testing was undertaken at the same time of day, and participants wore the same footwear, in both pre- and post-testing sessions.

A twelve camera Vicon (Oxford, Oxfordshire, England) motion analysis system in conjunction with a 60 x 90 cm AMTI (Watertown, MA, USA) force platform was used to collect the jump data. As described by Marshall & Moran (20), reflective markers were placed on both limbs at the fifth metatarsal joint, calcaneus, lateral malleolus, lateral femoral epicondyle, greater trochanter and the glenohumeral joint. The motion capture system controlled simultaneous collection of motion (250Hz) and force data (1000Hz) at an effective capture rate of 250 Hz. Data were filtered using a recursive second-order low pass Butterworth digital filter (33). The force plate data were filtered at 70 Hz (20,21) and marker position data at different values: toe 6.62 Hz, heel 6.62 Hz, ankle 7.52 Hz, knee 9.21 Hz, hip 8.50Hz and shoulder 6.64 Hz (20,21). These values were determined by minimizing the root mean square difference between the vertical acceleration of the center of mass, and the same measure derived from force plate data (21). The mean data from each individual’s best three jumps were used for further analysis.

The marker data were used to form a sagittal plane four-segment model, linked by frictionless hinge joints. Similar four segment models have also been used in previous examinations of the vertical jump (31,20,21). Bi-lateral marker data were combined in the formation of the model. The four segments were the foot, shank, thigh and head-arms-trunk separated by the ankle, knee and hip joints, respectively. Standard inverse dynamics techniques were used to calculate sagittal plane joint moments and powers (33). Jump height was calculated as the difference between the body’s centre of mass position when standing and at the apex of the jump (20). Previous research has found excellent test-retest reliability for jump height using these techniques (20). A mean difference of 1.0cm between test and re-test jump heights was observed with an intraclass correlation coefficient of 0.88.

The eccentric and concentric phases of each jump, both at the whole body and joint level, were defined with respect to power production. When negative power was being produced by the centre of mass (or joint) it was considered to be acting eccentrically, and when positive power was being produced it was considered to be acting concentrically. The instant at which a joint changed from flexion to extension (or dorsiflexion to plantarflexion at the ankle) was termed joint reversal. All measures examined in this study were calculated in the sagittal plane only; hip angle for example, refers to hip flexion.

Training Protocol

Training consisted of four sets of eight drop jumps, from a 30 cm drop height, three times a week for eight weeks. Participants were instructed to undertake a 'countermovement' style drop jump (5). The warm-up for the training sessions consisted of a three minute 7 km.hr^{-1} treadmill jog. One rest day was allocated between training days, and each session was supervised to ensure completion of all sets and repetitions. The recovery time between sets and repetitions was two minutes and fifteen seconds, respectively (24). Participants did not undertake other lower body plyometric or resistance training over the course of the training period. A jump height of 30cm was chosen as Lees & Fahmi suggested that if an optimal drop height were to exist for drop jump training it would be at lower (< 34 cm) rather than higher drop heights (17). Neither training intensity nor training volume were altered in the present study as there is no evidence based research regarding the optimal increments by which to increase these over the course of a drop jump training period, or indeed when these increments should be introduced (4,19). The drop jump training protocol utilised in this study was chosen as similar protocols have previously resulted in significant improvements in countermovement jump height (4,13).

Statistical Analyses

Variables were checked for normality of distribution using Shapiro-Wilks tests (10). Pearson bi-variate correlations were used to identify factors significantly correlated with jump height. Factors correlated with jump height in the acute pre-training testing session were identified (cross-sectional analysis) as were factors whose post-training change were correlated with a change in jump height (pre-to-post analysis). Regression techniques were not employed due to the likely presence of multicolinearity (20). In order to examine if a factor had significantly changed following the training intervention, pre versus post data was analysed using paired sample t-tests. All statistical analyses were carried out using SPSS for Windows (version 15.0, SPSS Inc., U.S.A) and statistical significance was set at $P < .05$.

RESULTS

All variables exhibited normal distribution as evidenced by non-significant ($P > 0.05$) Shapiro-Wilks tests (mean [95 % confidence intervals]: 0.964 [0.958, 0.969]).

Fourteen factors were related to jump height in the cross-sectional analysis but only six of these were subsequently found to be related to jump height in the pre-to-post analysis (Table 1). In addition, five factors identified in the pre-to-post analysis were not identified in the cross-sectional analysis (Table 1).

Table 1 about here

Countermovement jump height increased significantly (*P* < .001) by 2.9 cm (6 %) following training (Table 2). Post-training changes in 11 biomechanical factors were significantly correlated with this increase in jump height (Table 1). The strongest correlations at the whole body level included whole body concentric work done (r = 0.62) and peak power (r = 0.60). At the joint level, several hip related factors demonstrated noticeably strong correlations, including hip concentric peak power (r = 0.61), work done (r = 0.57), and angle at joint reversal (r = -0.56).

The post-training changes exhibited in all biomechanical variables are detailed in Table 2. Salient findings included significant (*P* < .001) increases in concentric peak power (3 %), eccentric peak power (19 %), countermovement amplitude (14 %) and reductions in concentric ankle peak moment (14 %) and ankle concentric work done (13 %) (Table 2).

Table 2 about here

DISCUSSION

The majority of previous studies that have identified potential biomechanical factors to train to enhance countermovement jump height have done so using cross-sectional data (1, 9,25,31). Another approach is to use pre-to-post training change data, where the relationship between a change in a factor and an improvement in jump height can be examined more directly (27). The current study appears to be the first to compare the findings of these distinct approaches. Our findings illustrate that factors associated with jump height in a cross-sectional analysis are not necessarily those same factors associated with a post-training increase in jump height.

There was a 6% increase in jump height following the eight weeks of drop jump training which is comparable to the 8.7% improvement typically seen following plyometric training interventions (19).

In total, eight of fourteen factors identified in the cross-sectional analysis were not subsequently identified in the pre-to-post analysis. For example, ankle concentric peak moment was positively correlated with jump height prior to training ($r = 0.53$, $P < .001$) but the pre- to post-training change in this variable was not related to the increase in jump height ($r = -0.07$, $P = 0.658$). Indeed there was actually a significant 17 % reduction ($P < .001$) in ankle concentric peak moment at the end of the eight week training period (Table 2). These findings demonstrate that a cross-sectional analysis may identify factors that are not necessarily critical to an improvement in jump height. This is of particular importance to coaches who utilise the findings of cross-sectional analyses to identify factors to train to enhance jump height.

There are several potential explanations as to why the majority of factors identified in the cross-sectional analysis, were not subsequently found to be related to the post-training increase in jump height:

(a) Some variables (e.g. knee peak moment) may have only been identified in the pre-training cross-sectional analysis by virtue of their contributory relationship to other variables that were more strongly related to jump height (e.g. knee peak power).

Deterministic models illustrate this phenomenon through the inter-related yet hierarchical nature of the factors influencing several sporting tasks including jumping (7).

(b) Training induced technique changes may have reduced the role played by some factors in influencing jump height performance following training. A post-training decrease in ankle concentric peak moment and ankle concentric work done ($P < .001$) would suggest that the ankle joint was contributing less actively (more passively) to propulsion following the training period. This finding may be explained by greater force production about the knee (Table 2) generating a greater inertia of the body's centre of mass, and in effect 'pulling' the ankle joint into plantar flexion. This is in accordance with the inter-segmental biomechanical constraint which states that a muscular action at one joint can act to accelerate another joint it does not span due to inertial forces being transmitted from one segment to another (35).

(c) While an increase in some eccentric variable magnitudes may be expected to enhance jump height (through stimulating an enhanced stretch shortening cycle utilisation) any increases beyond a certain magnitude may not necessarily produce concomitant improvements in jump height. This may explain why the large 18 % increase in whole body eccentric peak power was not related to the post-training change in countermovement jump height.

Several of the biomechanical factors associated with an increase in jump height following training (pre-to-post analysis) were not identified in the pre-training cross-sectional analysis (Table 1). Hip flexion angle at joint reversal, for example, was significantly related to the post training increase in jump height ($r = -0.56$, $P < .001$) but was not related to jump height prior to training ($r = -0.14$, $P = 0.360$). These findings suggest that a reliance on cross-sectional data alone may not facilitate an identification of all potential factors to train to enhance jump height. This lends support to the use of training interventions to aid in the identification of factors associated with performance outcome (27).

As far as the current authors are aware this is the first study to utilise a pre-to-post analysis to identify both whole body *and* joint level biomechanical factors associated with jump height. The identification of joint level factors may be particularly useful in providing more specific information to guide the design and implementation of targeted training interventions. Four of the eleven factors identified in this study pertained to power development in the concentric phase, namely: whole body, hip, knee and ankle concentric peak power. While several previous studies have found significant and strong correlations between whole body peak power and jump height (1,9,14), our study appears to be the first to do so using pre-to-post data. Peak hip power had a notably larger association with the post-training increase in jump height (r = 0.61) than either peak ankle (r = 0.32) or knee power (0.33). Previous studies have also highlighted the relative importance of the hip in vertical jumping. Vanrenterghem et al. (31) and Aragon-Vargos & Gross (1), for example, both found significant correlations between hip concentric peak power and jump height (r = .0.68 and 0.66, respectively), albeit in a cross-sectional analysis. Moreover, Pandy and Zajac (23) found the gluteus maximus muscle, a hip extensor, to be a major contributor to energy production during vertical jumping. Together, these findings highlight that exercises prescribed to enhance jump ability should aim to enhance concentric power output, but do so with a particular focus on enhancing hip power. This is not to suggest a focus on concentric muscle action alone when training jump ability. On the contrary, a likely mechanism of the increased concentric power output in the present study was an improvement in stretch shortening cycle function, driven by training related improvements in eccentric muscle action (8). Significant increases in eccentric phase velocity and eccentric peak power, and a reduction in eccentric phase duration, provide evidence for this (Table 2). Cormie et al. (8) also cited enhanced stretch shortening cycle function as a contributor to improved jumping ability following training interventions.

Despite the strong correlation between peak hip power and jump height in the pre-to-post training correlation analysis, peak hip power did not enhance at a group level following training (Table 2). However, and as apparent from figure 1, several individuals within the group did experience concomitant increases in peak hip power and jump height, while others experienced concomitant declines. These individual level changes were masked in the overall group analysis (3).

Figure 1 about here

Variability in the adaptation of jump mechanics to the training regime may be due to differences in how individuals undertake the training exercise (drop jump) or the task of interest (countermovement jump). Bobbert et al. (6) found that when drop jumping there appears to be a jump technique continuum between ‘high speed - low range of motion’ jumps and ‘low speed - high range of motion’ jumps. This can influence the training load placed on the system, as well as the muscles surrounding individual joints, and in turn the training outcome (20). Variability in how individuals undertake the countermovement jump itself may also influence the training effect of a given exercise. Samozino et al. (26) found that maximal jump performance is dependent, at least in part, on an optimal force-velocity relationship. Individuals can have different optimal levels of force and velocity due to inter-individual differences in anthropometrics or training history (3,26). Variability may be further increased when the degrees of freedom are considered (16). For example, some individuals may have enhancements induced at the hip joint, while others at the knee joint; thereby increasing inter-participant variability. Thus the drop jump in the current study may have induced training related changes that were not optimal for each individual. This may explain why significant increases in variables, such as knee concentric peak moment (table 2), were not related to an improvement in jump height.

In light of the observed importance of a large power output while jumping it is not surprising to find that whole body concentric peak velocity and concentric work done were also associated with the pre- to post-training increase in jump height; power being the product of force and velocity, and work done being the integral of power with respect to time. Greater concentric work done can be facilitated by using a larger countermovement amplitude and concentric phase duration, which may explain why both of these variables were also found to be related to the increase in jump height. Aragon-Vargas & Gross also found that countermovement amplitude was a key factor in maximal jump height, and was included in many of the best regression models of jump height at a group level ($R^2 = 0.88$) (1). Similarly, the duration of the concentric phase was a significant factor in jump height achievement for several subjects in Aragon-Vargas & Gross' single subject analysis (e.g. Subject A, $R^2 = 0.83$) (2).

The remaining three factors identified in the pre-to-post analysis were all at the hip joint: hip concentric work done, hip moment at joint reversal and hip angle at joint reversal. These findings reinforce the notion that neuromuscular output at the hip is a particularly important contributor to vertical jump performance (31, 32). Despite being identified in the pre-to-post analysis, hip moment at joint reversal and hip concentric peak power did not change significantly at a group level following training (Table 2). As discussed above for peak hip power, these apparent anomalies can be explained by the fact that some individuals in the group experienced post-training magnitude increases while others experienced declines; this is apparent from the relatively large standard deviation of the post-training magnitude changes in these factors (Table 2).

Due to inter-individual differences in force production capacity (e.g. joint power, joint dominance), anthropometrics (e.g. limb lengths), muscle morphology (e.g. percentage muscle fibre type) and past-training experience, all of the countermovement jump factors identified in the pre-to-post analysis may not be exactly the same for other individuals or groups. Whether core biomechanical factors exist that are relatively stable across different groups and/or individuals remains to be seen. Inter-individual differences in optimal timing of segment rotations (coordination) are also likely to exist (2) but an examination of such variables was beyond the scope of the current study.

A potential limitation of this study is that the training modality utilised, the drop jump, may not have sufficiently enhanced every factor to the extent necessary for it to be identified in the pre-to-post analysis. This might explain why Sheppard et al. (27) found that an increase in whole body concentric peak force was related to an increase in jump height following training ($r = 0.55$, $P < .05$), while the current study did not. Indeed enhancements in peak power and jump height in the current study appear to be derived from increases in peak velocity rather than peak force (Table 2). It is also acknowledged that due to the use of multiple t-tests when examining the post-training changes, there may have been an increased risk of identifying a significant difference by chance (type 1 error).

In conclusion, biomechanical factors significantly correlated with countermovement jump height in a cross-sectional analysis are not necessarily those same factors that are correlated with jump height in a pre-to-post analysis. These findings have major implications for strength and conditioning professionals who utilise cross-sectional data to identify factors to train in order to improve jump height: (a) not all factors identified in a cross-sectional analysis may be critical to the improvement of jump height, and (b) a cross-sectional analysis alone may not identify all potential factors limiting jump height. This study lends support to the use of training interventions to aid in the identification of factors associated with performance outcome.

PRACTICAL APPLICATIONS

A reliance on cross-sectional studies alone to identify factors to train to enhance jump ability will likely result in sub-optimal performance improvements.

While exercises prescribed to improve jump height should aim to enhance concentric power production at all joints, a particular emphasis on enhancing hip joint peak power may be warranted. Plyometric and ballistic (e.g. weighted jump squat) training have both been found to enhance whole body power in a countermovement jump (18,15) but the authors are unaware of any studies that have found one of these forms of exercise more effective than the other at enhancing hip power output.

Having greater hip flexion during the eccentric phase of the countermovement jump was a key factor associated with an improvement in jump height. A more optimal hip flexion angle is likely to enhance other factors that were related to jump height including countermovement amplitude, concentric phase duration, concentric work done and hip moment at joint reversal. It is suggested that coaches examine their athletes' jumping technique and identify those athletes who may benefit from a greater hip flexion angle. Augmented technique feedback (e.g. video playback combined with coaching advice) may be particularly useful with such athletes (22). It is important to acknowledge that increases in hip flexion beyond an optimal will likely lead to a performance decrement due, at least in part, to a less effective utilisation of the stretch shortening cycle.

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Figure Legend

Figure 1. Post-training change in peak hip power versus post-training change in countermovement jump height