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Original article

Integrating biomechanical and motor control principles in elite high jumpers: A transdisciplinary approach to enhancing sport performance

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Abstract

Background: In recent years, there has been a proliferation of technology and sport science utilized within an athlete's training, especially at the elite level. However, the sport science is a broad field, encompassing disciplines such as biomechanics, motor control and learning, exercise physiology, sports medicine, sport psychology to name a few. Rarely are these disciplines applied in an integrated manner. The purpose of this study was to document the effectiveness of an integrated biomechanics and motor control protocol for improving athlete's performance in the high jump.
Methods: Four elite high jumpers performed baseline jumps under normal conditions and then jumps using a specific external focus of attention cue designed to improve their running posture. Three-dimensional biomechanical analysis was used to quantify the upright posture throughout the approach as well as horizontal velocity at plant and vertical velocity at takeoff.
Results: The results showed that when using the external focus of attention cue, the jumpers were significantly more upright during the approach, had significantly higher horizontal velocities at plant, and generated significantly greater vertical velocities during the takeoff.
Conclusion: The results of this study lay the foundation for future work examining how integrating sport science disciplines can improve performance of elite level athletes.

Keywords: Biomechanics; High jump; Motor control; Sport performance

1. Introduction

In recent years the integration of sport science and technology within training environments of professional and amateur athletes has become increasingly common. The sub-disciplines of sport science are diverse and constitute a breadth of scientific disciplines including strength and conditioning, sports medicine, exercise physiology, nutrition, biomechanics, motor control and learning, psychology, and sociology. While training for sport has come a long way from relying on tradition and belief systems, the integration of sub-disciplines within sport science is severely lacking. Often times, practitioners try to enhance sport performance while utilizing just one sub-discipline creating a singular or modular approach. However, truly optimizing sport performance requires integrating multiple of the sport science sub-disciplines into one training program. This study documents an approach to integrate biomechanical and motor control principles to enhance performance in elite high jumpers.

From a biomechanical perspective, the high jump consists of an approach phase, takeoff, and flight phase. Of the three, the approach phase is the most critical for jump success. The approach phase is composed of a straight portion consisting of four to seven steps run perpendicular to the bar, followed by a curved portion consisting of five steps. The goals of the approach are two-fold. First, the jumper seeks to arrive at takeoff with the highest tolerable horizontal velocity as this will help them generate the necessary vertical velocity during the takeoff.[1,2] Second, the jumper seeks to arrive at the plant of the takeoff foot in a posture which facilitates the generation of angular momentum, ultimately leading to an effective bar clearance during the flight phase. The posture adopted by the jumper during the approach phase plays a critical role in their ability to accomplish these goals.

During the initial steps of the approach the athlete uses acceleration mechanics which are marked by a forward lean of the body, long ground contact times, and large movements of the free limbs. However, a step before they begin the curved portion of the approach the athlete should have achieved an upright erect posture, as it allows the athlete to smoothly transition from the

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straight to curved portions of the approach, and will facilitate proper force application during the curved portion of the approach.[3] An erect posture is also critical during the last two steps of the approach. The athlete must facilitate the development of appropriate amounts of angular momentum without sacrificing horizontal velocity. The ability to do this is dependent on the athlete being upright as their penultimate foot contacts the ground. The takeoff foot touches down well in front of the hips and shoulders. This position is set up during the penultimate step and is accomplished by the athlete thrusting the hips forward during the second half of the penultimate step.[4] If the athlete is not upright as the penultimate step touches down, it will be more difficult for them to achieve the desired posture at plant and will require more time to thrust the hips forward of the shoulders. This means the athlete spends more time on the penultimate step resulting in a greater loss of horizontal velocity.

Given the importance of an upright posture, an appropriate question to consider is: “how can practitioners help athletes change their posture during the approach?” The answer to this question can be obtained through the motor control and learning literature. Recently, there has been much research on how the attentional focus of a performer affects the control and learning of new movement patterns or the refinement of existing ones. According to Wulf,[5] performers can allocate their attention in two different ways prior to or during the performance of a motor skill. When a performer adopts an internal focus of attention, he or she is thinking about the movements of their body. In contrast, an external focus of attention is utilized when a performer thinks about the effects of their movements on the environment. The focus of attention literature overwhelmingly suggests that compared to an internal focus of attentions, when performers adopt an external focus of attention, they demonstrate better outcome and performance production measures.[5–9] The literature also suggests that high level performers benefit more from using an external focus of attention than novice performers.[10–12] Therefore, using appropriate focus of attention cues is critical for optimizing elite level sport performance.

When reviewing the biomechanical literature on the high jump and the current findings within the attentional focus literature of motor control, one can see the natural relationship between biomechanics and motor control/learning. One addresses “what” athletes are supposed to do, while the other addresses “how” practitioners get them do it. In an effort to demonstrate the effectiveness of integrating principles of biomechanics and motor control, this study investigated the effects of an external focus of attention on running posture during high jump approach in elite high jumpers. It was hypothesized that an external focus of attention targeted at improving posture during the curve approach would enhance high jump performance compared to athlete’s normal performances.

2. Methods

2.1. Participants and data collection environment

Participants in this study were four elite female high jumpers participating in an USA Track and Field Sport Performance Workshop. The workshop environment is specifically designed for sports science staff to work with athletes one-on-one directly on the track to address performance limiting factors in their technique. These four jumpers were identified based on previous data suggesting that their posture during the approach was a limiting factor in their performance. Participants were classified as elite performers based on their high finishes at recent USA Track and Field National Championships. Specific information regarding each athlete is shown in Table 1. All procedures were done in accordance with the Declaration of Helsinki and all participants provided informed consent prior to participation.

Table 1
Participant characteristics.

	Age (year)	Height (m)	Personal best (m)
Jumper 1	24	1.67	1.74
Jumper 2	22	1.80	1.90
Jumper 3	24	1.82	1.86
Jumper 4	23	1.80	1.92

2.2. Experimental protocol

Each participant completed their own individual warm-up prior to jumping. This was followed by each athlete completing a baseline jump using their normal approach. The bar was set to a height the participants would routinely use in a practice setting. Following the baseline jump the intervention was introduced. For the intervention a small piece of athletic tape was placed on the athlete’s shirt, approximately at the level of the navel. In an effort to ensure that the athlete adopted an upright posture prior to entering the curve, while also focusing their attention externally, the participants were instructed to “*lead with the tape*” as they transitioned from the 4th to 5th steps of the approach. Participants completed two practice runs while being verbally cued between the 4th and 5th steps, and then completed a second jump for analysis.

2.3. Data collection and analysis

Each jump was recorded with two video cameras (GC-PX10; JCV Corp., Wayne, NJ, USA) sampling at 60 frames per second with a shutter speeds of 1/1000 s. A volume encompassing the curved portion of the approach was calibrated using a 68-point calibration structure and the multiphase calibration technique described by Challis.[13] Twenty individual body landmarks were manually digitized over the last six steps of the approach, takeoff, and flight. The two cameras were synchronized based on the frames of foot contact and toe off[14] and a Direct Linear Transformation[15] reconstruction was used to obtain three-dimensional (3D) coordinates. The *X*-*Y*-*Z* coordinates of individual body landmarks were smoothed using quintic spine functions.[16] The location of the whole body center of mass (COM) was calculated as the weighted sum of the individual segments based on Dempster’s data[17] and the quantic spline equations were used to calculate the instantaneous velocity of the COM throughout the approach. The forward lean of the torso at each instant during the approach was calculated based on the orientation of the torso relative to the global *X* (parallel to the bar, pointing in the direction of approach), *Y* (perpendicular to the bar), and *Z* (vertical) axes.

The following dependent variables describing the participants' posture were then calculated: the forward lean of the torso during mid-stance of the 6th, 7th, and 8th steps, and at touchdown of the penultimate step. Performance related variables included: the time spent on the penultimate step, percent decrease in horizontal velocity from touchdown of the penultimate step to touchdown of the takeoff step, horizontal velocity at touchdown of the takeoff step, and vertical velocity of the COM at takeoff.

Paired *t* tests were used to evaluate differences between baseline jumps and post-intervention jumps for all dependent variables. While this study used a small sample size, simulation studies have suggested that the use of paired *t* tests can be appropriate with extremely small sample sizes while not artificially inflating risk of a Type I error as long as certain precautions are taken.[18] Therefore prior to performing statistical analyses, data were checked for violation of assumptions required for a parametric test. Specifically, box-plot and normal probability plots were used to identify the presence of any outliers in the data and Shapiro–Wilk test was employed to examine the normality of distribution of the paired differences. For each dependent variable, Pearson product correlations between pre- and post-intervention measurements were calculated. Where statistically significant differences were observed based on group means, plots of individual subject responses were created. Finally, effect sizes (Cohen's *d*) were calculated to aid in interpreting the meaningfulness of any statistically significant differences. All statistical analyses were completed using SPSS (v. 22.0; IBM SPSS Statistics, Chicago, IL, USA). All correlations were statistically significant at the $p < 0.05$ level.

3. Results

After the intervention, participants demonstrated decreased forward lean during mid-stance on the 6th and 7th steps, and at touchdown of the penultimate foot. However, forward lean on the 8th step was not different before and after the intervention (Fig. 1).

Effect sizes for the differences between conditions were 0.85, 1.20, 0.39, and 0.58 for the 6th, 7th, 8th steps, and touchdown of penultimate step, respectively. Box-plots and normal probability plots for these variables suggested that no outliers were present. The Shapiro–Wilk test suggested that the distribution of paired differences did not violate the assumptions of normality with *p* values of 0.506, 0.081, 0.225, and 0.940 for differences in forward lean on the 6th, 7th, 8th steps, and touchdown of penultimate step, respectively. Correlations between pre- and post-intervention measurements were 0.943, 0.995, 0.929, and 0.994 for forward leans on the 6th, 7th, 8th steps, and penultimate step, respectively. Individual subject responses showed the direction of change and magnitude of change was similar for all subjects (Fig. 2).

The duration of time spent on the penultimate step was not different between pre- and post-intervention; however, the percentage of horizontal velocity lost during the penultimate step

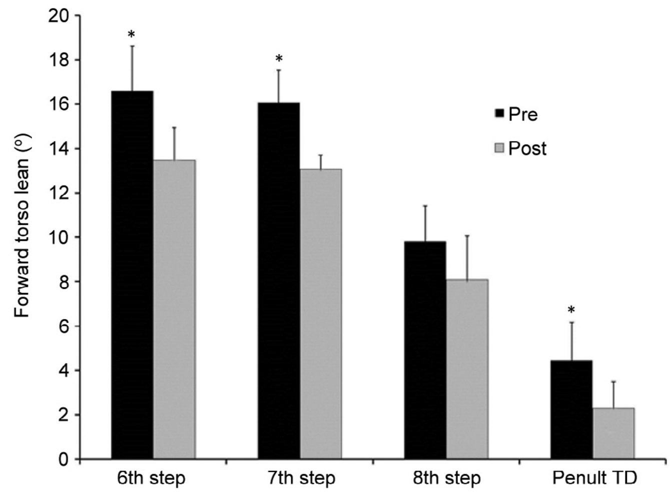

Fig. 1. Forward torso lean on the 6th, 7th, and 8th steps and at touchdown of the penultimate step (penult TD). * $p < 0.05$, compared with the post values.

was reduced after the intervention. Moreover, the horizontal velocity brought onto the plant step was higher after the intervention and the vertical velocity at the end of the takeoff was also higher after the intervention (Table 2). Effect sizes for these dependent variables ranged from small to large (Table 2).

Box-plots and normal probability plots for these variables suggested that no outliers were present. The Shapiro–Wilk test suggested that the distribution of paired differences did not violate the assumptions of normality with *p* values of 0.544, 0.449, 0.122, and 0.499 for differences in penultimate duration, horizontal velocity lost on the penultimate step, horizontal velocity at touchdown of the takeoff step, and vertical velocity at takeoff, respectively. Correlations between pre- and post-intervention measurements were 0.936, 0.977, and 0.929 for horizontal velocity lost during the penultimate step, horizontal velocity at plant, and vertical velocity at takeoff, respectively. Individual subject responses showed the direction of change and magnitude of change were similar for all subjects (Fig. 3).

4. Discussion

The purpose of this study was to examine the effects of an external focus of attention cue on posture during the high jump approach in elite female high jumpers. Specifically, the cue was designed to elicit a more upright posture which we hypothesized would result in improvement in biomechanical factors related to high jump performance. The results support this hypothesis, with jumpers demonstrating less forward trunk lean during the curve approach after the intervention when compared to the baseline performances. Moreover, decreasing forward trunk lean through the use of the "lead with the tape" cue enhanced other critical factors including less horizontal velocity lost during the penultimate step, higher horizontal velocities at touchdown of the takeoff step, and higher vertical velocities of the jumper's COM at takeoff.

The results of the current study are in agreement with a growing body of attentional focus literature which suggests that using an external focus of attention improves outcomes and

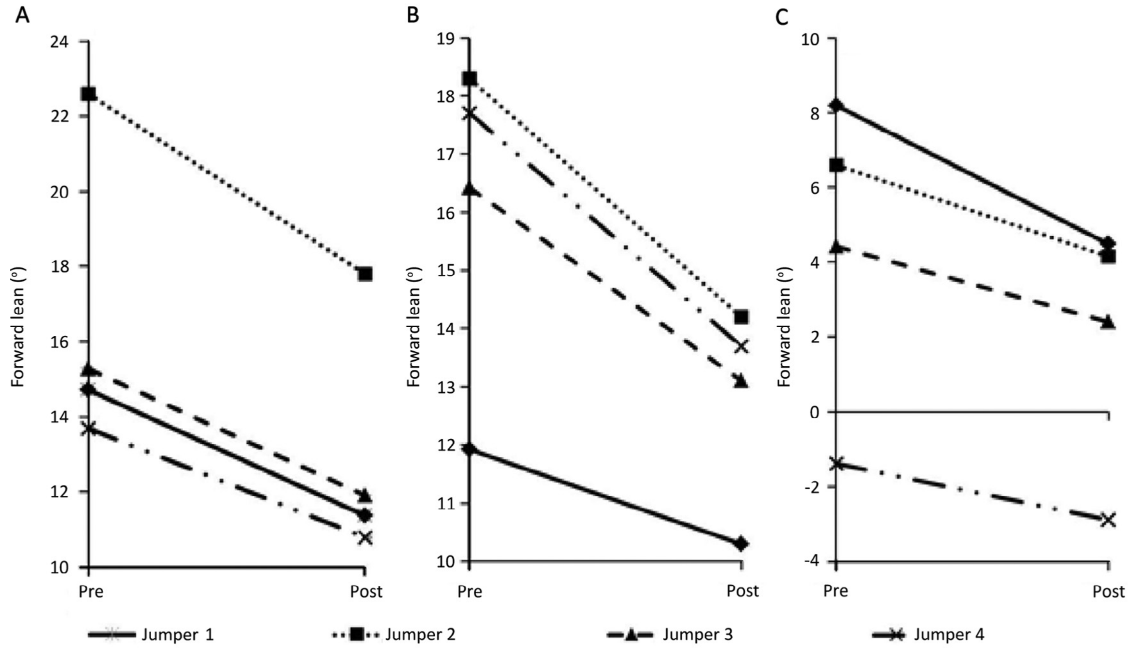

Fig. 2. Individual subject responses for change in forward torso lean on the 6th step (A), 7th step (B), and touchdown of the penultimate step (C).

performance production measures. An external focus of attention has been documented to improve performance in activities involving whole body movements such as standing long jump,[9] vertical jump and reach,[19] baseball batting,[12] golf swing,[10,11] swimming,[20] and in activities involving small movements and fine motor control such as dart throwing[8] and playing of musical instruments.[21] The benefits of an external focus of attention compared to an internal focus of attention can be explained

Table 2
Changes in performance related variables from baseline to post-intervention trial (mean ± SD).

Variable	Pre-intervention	Post-intervention	p	Effect size
Duration of penultimate step (ms)	126.5 ± 12.7	126.2 ± 16.7	0.955	0.016
Percent horizontal velocity lost during penultimate step (%)	−4.7 ± 2.2	−2.1 ± 1.2	0.018	1.32
Horizontal velocity at touchdown of plant foot (m/s)	6.32 ± 0.41	6.74 ± 0.32	0.045	0.67
Vertical velocity at takeoff (m/s)	3.31 ± 0.14	3.63 ± 0.11	0.014	1.57

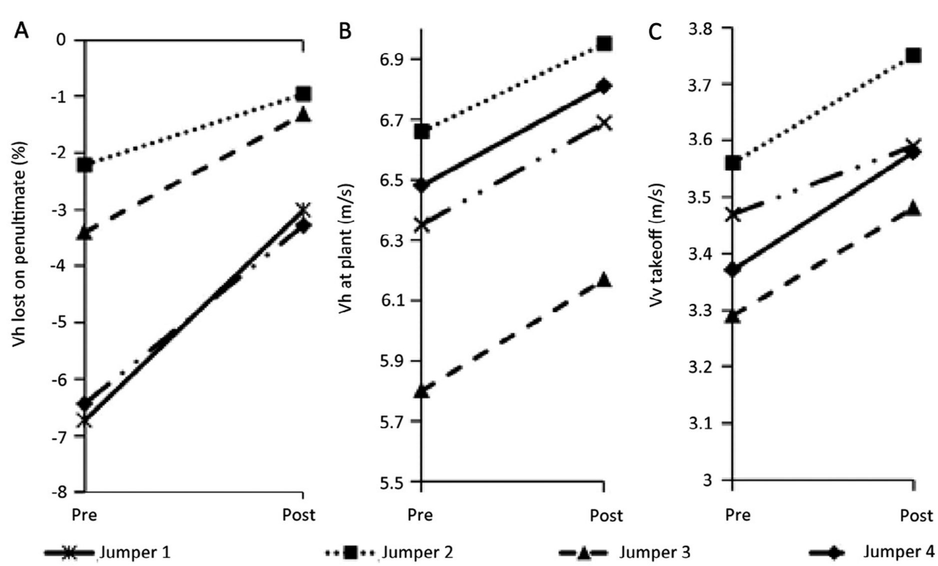

Fig. 3. Individual subject responses for percentage horizontal velocity lost on the penultimate step (A), horizontal velocity on at plant of the takeoff step (B), and vertical velocity at takeoff (C). Vh = horizontal velocity; Vv = vertical velocity.

using the constrained action hypothesis. According to the constrained action hypothesis, an internal focus of attention causes performers to intervene in control processes that regulate the coordination of movements, inadvertently overriding processes that allow for efficient movement. In essence, an external focus of attention allows more efficient movement.

Support for the more efficient movement suggested by the constrained action hypothesis can be found in studies examining electromyography in combination with joint torque production during movement. Using a bicep curl exercise, Marchant et al.[6] demonstrated that participants could generate greater joint torques with reduced electromyographic (EMG) activity when using an external focus condition compared to an internal focus. Similarly, a study by Wulf and colleagues[22] reported greater knee extension torques, greater jump heights, and reduced EMG activity of the quadriceps muscles when using an external focus of attention compared to an internal focus of attention. A separate study by Zachry et al.[7] demonstrated not only more efficiency with an external focus but also greater accuracy. In their study, participants that focused on the rear of a basketball rim produced less EMG activity and greater shooting accuracy scores than the internal condition that focused on wrist flexion.

The participants in the current study were all elite high jumpers. In this regard, the types of focus of attention cues used are even more important as it has been previously demonstrated that high level performers benefit more from using an external focus of attention than do novice performers.[11,12] A recent study by Porter et al.[23] revealed that coaches and athletes competing at the USA Track and Field Championship primarily utilized an internal focus of attention. This suggests that there is room for even these high level athletes to further improve their performances with the proper attentional focus strategies. Unfortunately, the results of Porter et al.'s[23] study also suggest that high level coaches are actively using methods that are not consistent with the motor control and learning literature. According to Williams and Ford,[24] the exclusion of motor control and learning principles is likely due to coaches having the view that instruction is solely the domain of the coach and not the sport scientist. In addition, the authors attribute the lack of evidence-based learning principles to the fact that researchers are often more concerned with theory rather than application. The results of the current study suggest that coaching cues drawn from evidence in the motor control and learning literature is an effective method for improving biomechanical factors related to performance.

There are a few limitations to this study which should be considered, especially when trying to apply the results to other track and field events or other sports. First, this study used a small sample size, which means caution must be used when generalizing the results of this study to a larger population. From a statistical perspective, statistically significant results with moderate to large effect sizes were observed for most variables. Since the individual responses of the subjects were similar (Figs. 2 and 3) and none of the assumptions for using a parametric test were violated, the likelihood of committing a Type I error is small, despite the small sample size.[18] This study specifically used elite female high jumpers. Based on the personal bests of the jumpers (Table 1), there were only 14 individuals in the entire United States who performed at this level in 2014,[25] and of those only seven were post-collegiate athletes who would have been eligible for the workshop where this study was carried out. Thus, the small sample used in this study actually represents 57% of the entire population being studied.

A second limitation which must be considered involves timing of the intervention. The intervention jumps were always performed after the baseline jumps. Therefore, we cannot rule out some type of order effect. However, most jumpers will take between eight and 16 jumps in a training session, so any effects of fatigue are likely to be minimal. Additionally, this order was required as the baseline jumps were meant to see what the athlete's "normal" biomechanics looked like without any outside influence. If the baseline jump had been performed after the intervention, one would not be able to rule out any lingering effects from the intervention and therefore would not obtain a "true" baseline.

Finally, the specific type of intervention used in this study must be considered. The goal of the "lead with the tape" intervention was to use an external focus of attention cue specifically designed to achieve an upright running posture. However, this posture could be obtained in different ways. For example, the athletes could simply hyperextend their spine and have the perception of an upright torso. However, their pelvis would likely remain severely anteriorly tilted which would not allow optimal running mechanics. By placing tape at the level of the navel, it was hypothesized that this would yield the best compromise between an upright torso while also obtaining a neutrally aligned pelvis. It is likely that the location will vary depending on the specific activity and biomechanical flaw being corrected. For example, the location and cue used in this study may work well for a sprinter transitioning from the acceleration phase to maximal velocity phases of a sprint or a long jumper transitioning to an upright posture prior to takeoff but would likely not work for throwing events. Additional research is required to investigate the influence of placing the tape in different locations depending on both activity and biomechanical flaws being addressed to determine a "best practice" for this type of intervention.

In summary, the results of this study have demonstrated the utility of integrating the sub-disciplines of sport science rather than instituting each individually. In the case of movement refinement or correction, biomechanics and motor control/learning play a symbiotic role in optimizing movement patterns. Future studies should look at the long term retention effects of external focus of attention cues on performance production and outcome.

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