***Journal of Applied Biomechanics*, 2017, 33, 153-159**
https://doi.org/10.1123/jab.2016-0179

Human Kinetics
ORIGINAL RESEARCH

Vertical Jump Biomechanics Altered With Virtual Overhead Goal

Kevin R. Ford, Anh-Dung Nguyen, Eric J. Hegedus, and Jeffrey B. Taylor
High Point University

Virtual environments with real-time feedback can simulate extrinsic goals that mimic real life conditions. The purpose was to compare jump performance and biomechanics with a physical overhead goal (POG) and with a virtual overhead goal (VOG). Fourteen female subjects participated (age: 18.8 ± 1.1 years, height: 163.2 ± 8.1 cm, weight 63.0 ± 7.9 kg). Sagittal plane trunk, hip, and knee biomechanics were calculated during the landing and take-off phases of drop vertical jump with different goal conditions. Repeated-measures ANOVAs determined differences between goal conditions. Vertical jump height displacement was not different during VOG compared with POG. Greater hip extensor moment ($P < .001$*) and hip angular impulse ($P < .004$*) were found during VOG compared with POG. Subjects landed more erect with less magnitude of trunk flexion ($P = .002$*) during POG compared with VOG. A virtual target can optimize jump height and promote increased hip moments and trunk flexion. This may be a useful alternative to physical targets to improve performance during certain biomechanical testing, screening, and training conditions.

Keywords: biomechanics, externally focused attention, drop vertical jump, female athletes

Vertical jump tasks are routinely performed in many team and individual sports. For example, women's basketball players jump between 41–49 times, depending on their position, during each game.[1] Additionally, greater jump height is advantageous for improved performance in these sports. Therefore, training programs are often designed with the aim to improve vertical jump performance. Plyometric training has been identified as an effective modality that improves vertical jump performance.[2–4] While different measurement devices are used to assess jump height, the use of extrinsic (externally focused) motivation often results in improved performance.[5–7] However, some devices or feedback that could be used to motivate improved performance may result in altered mechanics. For instance, when a target is positioned directly overhead as an extrinsic motivator, the focused attention or reaching for the target may modify joint kinematics and kinetics.[7] Additionally, some devices may result in a more erect trunk position that alters lower extremity joint moments and performance.[8,9]

The use of an extrinsic physical overhead goal improves drop vertical jump (DVJ) performance in female athletes by promoting greater knee extensor moments.[10] Ford et al[10] concluded that a goal or target should be considered not only during testing but also during training protocols to encourage maximal jump height. An external attentional focus has also been explored by Wulf and Dufek[5] during a maximum vertical jump, with instructions to focus on the rungs of a device placed above the subjects compared with an internal focus of the height of their fingers. Greater vertical jump height was identified during external focused compared with internal focused trials.[5]

Ford, Hegedus, and Taylor are with the Department of Physical Therapy, Congdon School of Health Sciences, High Point University, High Point, North Carolina. Nguyen is with the Department of Athletic Training, Congdon School of Health Sciences, High Point University, High Point, North Carolina. Address author correspondence to Kevin R. Ford at kford@highpoint.edu.

As the use of technology in healthcare continues to evolve, the use of virtual environments and biofeedback may be an efficient and useful technique in sports performance and rehabilitation applications to both simulate immersive environments and provide detailed physiological or biomechanical data to the individual.[11,12] Modifications of environment with simulated targets and goals may provide improved ability to deliver externally focused motivation. However, maximum performance with external feedback, simulated virtually, has not previously been compared with physical external feedback motivation. Therefore, the first purpose of this study was to compare center of mass displacement during drop vertical jumps during 2 external feedback goal conditions: with a physical overhead goal (POG) and with a virtual overhead goal (VOG). We hypothesized that jump height would not be different during the 2 goal conditions. The second purpose was to determine the biomechanical differences of lower extremity joints and trunk kinematics during the goal conditions. We hypothesized that differences would exist between conditions.

Methods

Subjects

Fourteen female subjects participated in this study (age 19.3 ± 1.2 years, height 163.2 ± 8.1 cm, mass 63.0 ± 7.9 kg). Informed written consent was obtained from each subject in accordance with the protocol approved by the institutional review board. Inclusion criteria consisted of current or past participation on a competitive basketball, soccer, or lacrosse team at the high school level or higher. Subjects were excluded if they had current injuries that would limit sport participation.

Instrumentation

Data were collected on a 3-dimensional motion analysis system consisting of 14 digital high-resolution cameras positioned throughout the laboratory (Raptor-12, Motion Analysis Corporation, Santa

Rosa, CA). Cameras were calibrated based on manufacturer's recommendations. Two oversized force platforms were embedded level to the laboratory floor and time-synchronized to the motion analysis system (BP600900, AMTI, Watertown, MA).

Procedures

Subjects wore standard athletic apparel that allowed for 43 retroreflective markers[11] to be placed directly on the skin with double-sided tape. Markers were secured to the sternum, sacrum, left PSIS, C7, 3 locations on the upper back, and bilaterally on the shoulder, upper arm, elbow, wrist, anterior superior iliac spine (ASIS), greater trochanter, midthigh, medial and lateral knee, tibial tubercle, midshank, distal shank, medial and lateral ankle, heel, posterior lateral foot, anterior lateral foot, and toe. A static trial was collected in which the subject was instructed to stand still in the anatomical position with foot placement standardized. The static trial was used to model the segment coordinate systems and define each tracking marker. The mass and inertial properties for each segment were based on sex-specific parameters from de Leva.[13] The subject's height and body mass were included in each model.

Each subject performed standing countermovement vertical jumps to define the target jump height used during the DVJ trials.[10] Countermovement jumps were repeated and the height of the overhead goal was adjusted until the maximum standing countermovement jump allowed the subject to touch the target with only their fingertips. This target height was used for the physical target and programmed as the height of the virtual target. Each subject performed 3 trials of the DVJ. The DVJ consisted of the subject starting on top of a 31-cm box with their feet positioned 35 cm apart and arms held comfortably at their side. They were instructed to drop directly down off the box, land on both feet, and immediately perform a maximum vertical jump, raising both arms as if they were jumping for a basketball rebound.[14] Overhead goal conditions were randomized between subjects. During the POG condition (Figure 1), the DVJ was performed with a physical target (fitLight trainers,

Figure 1 — Drop vertical jump was performed with a physical overhead goal (top) and virtual overhead goal (bottom). Note: Screen image was simulated to illustrate actual display.

FITLIGHT Sports Corp., Ontario, Canada) mounted at the previously determined maximum countermovement height that illuminated green if touched. Participants were instructed to jump as high as possible while focusing on hitting the physical target. The VOG condition involved a DVJ with subjects watching a real-time model of their reflective markers which formed a virtual stick figure within the motion analysis software as they performed the task (Figure 1). A round virtual target was programmed within the motion analysis scene and positioned at the same previously determined maximum countermovement height. Subjects were instructed to view the 95 ft^2 screen directly in front of them and, when jumping, reach upward toward the target. The wrist marker vertical position was tracked in real-time and if it reached the same height as the virtual ball, a green light was illuminated on the screen, indicating the target height was achieved in a similar manner to the physical goal condition (Cortex/Biofeedtrak, Motion Analysis Corp., Santa Rosa, CA).

Data Analysis

Marker trajectories were filtered at a cutoff frequency of 12 Hz with a low-pass fourth-order Butterworth filter (Visual3d, C-Motion, Inc., Germantown, MD).[15] Hip, knee, and ankle sagittal plane joint angles were calculated for the nondominant side.[16] Trunk sagittal plane flexion and extension was calculated based on the 3-marker cluster positioned on the posterior thorax and calculated referenced to the laboratory coordinate system.[17] Data were analyzed during the stance phase of the initial DVJ landing. Stance phase was defined from initial contact (unfiltered vertical ground reaction force first exceeded 10N) to toe-off (unfiltered vertical ground reaction force fell below 10N). The vertical position of the body center of mass (COM) was used to further subdivide the stance phase into a landing phase (COM moving downward) and takeoff phase (COM moving upward until takeoff).[18] Joint angles were calculated for trunk, hip, and knee at initial contact and maximum during the landing phase. By convention, joint flexion was defined as a positive angular value.

The ground reaction force was filtered through a low-pass fourth-order Butterworth filter at a cutoff frequency of 12 Hz to minimize possible impact peak errors.[19,20] Motion and force data were used to calculate lower extremity joint moments using inverse dynamics.[21] By convention, internal sagittal plane knee and hip moments are described in this article as positive extensor moments. Peak extensor moments were calculated during the landing phase of each trial and averaged.

Angular impulses were calculated for the hip and knee as the integral of the moment curves during the entire stance phase. Angular impulse was used as an indicator of joint moment magnitude and duration. Joint power was also calculated for each lower extremity joint as the joint moment times the angular velocity.[22] Specifically, the power curves were integrated during the landing phase to represent energy absorption (negative joint work) through eccentric muscle contractions.[22]

The participant's COM was used to calculate vertical jump displacement following take-off. Specifically, the vertical jump displacement was computed as the difference between the body COM maximum vertical jump height and the standing height COM.

A repeated-measures ANOVA ($P < .05$) was used to determine differences in vertical jump height, trunk angular kinematics, and nondominant hip and knee kinematics and kinetics between goal conditions (POG, VOG). An adjusted *p*-value technique was used with the multiple comparisons.[23,24] Briefly, the Benjamini and Hochberg technique utilizes a sequential Bonferroni type procedure to control for false discovery rate (* indicates statistically significant difference following adjustment to *p*-value). Cohen's *d* effect sizes were calculated for each statistical comparison. Interpretations of effect sizes were operationally defined as trivial (< 0.20), small (≥ 0.20 to < 0.50), medium (≥ 0.50 to < 0.80), and large (≥ 0.80).[25]

Results

Performance measures of maximum jump height during the DVJ were not statistically different between the virtual and physical target conditions ($P = .733$, effect size 0.018). Specifically, the COM displacement from standing to maximum vertical displacement was 40.8 ± 5.7 cm and 40.7 ± 5.6 cm during VOG and POG conditions, respectively.

Peak hip extensor moment (Figure 2) was significantly greater during the virtual target condition compared with the physical target (Table 1, P < .001*, effect size 0.457). Similarly, the joint moment impulse at the hip was also significantly greater during the VOG compared with POG ($P = .004$*, effect size 0.313). Hip energy absorption was not statistically different between conditions following the adjusted *p*-value procedure but had a similar small effect size as the joint moment impulse (Table 1, P = .047, effect size 0.357). Knee kinetic variables were not different between goal conditions (Table 1).

Greater trunk flexion was found, at both initial contact ($P = .018$*, effect size 0.374) and maximum ($P = .002$*, effect size 0.832) during the VOG compared with POG condition (Figure 3, Table 2). In addition, increased hip flexion (Figure 2) at initial contact was found during VOG compared with POG ($P = .014$*, effect size 0.268). Maximum hip flexion angle was not statistically different between conditions (Table 2). Furthermore, kinematic differences between goal conditions were not statistically significant at the knee (Table 2).

Discussion

The purpose of this study was 2-fold: to compare the COM displacement during jumping with 2 types of external goal conditions and to determine biomechanical differences between the goal conditions. We supported our first hypothesis and found that differences in vertical jump height were not present when subjects jumped with the extrinsic motivation of either a physical or virtual target. This finding is important when considering that an external goal has been previously determined to increase performance of a vertical jump task.[10]

External focus is characterized by attention to the outcome of the task, as opposed to internal focus, where attention is shifted to the body movements necessary to complete a task. In this study, both the POG and VOG served as external foci, as participants were given an external goal and received immediate feedback on the success of their performance. This is consistent with recent studies that clearly support the use of an external focus for both task instructions and feedback. Specifically, both vertical jump and horizontal jump performance have been improved with externally focused attention.[5,6,26] Improved performance through adoption of externally-focused attention relates to the constrained-action hypothesis.[27] An internal focus of attention may constrain or interfere with complex movements and reduce performance while an external focus may allow self-organization of motor tasks through automatic control processes.[27] Additionally, an external focus may enhance movement efficiency, as muscle activation is decreased in lifting and jumping tasks while performance either remains the same or increases compared with an internal focus.[28,29] External focus has also been used in rehabilitation following injury to elicit

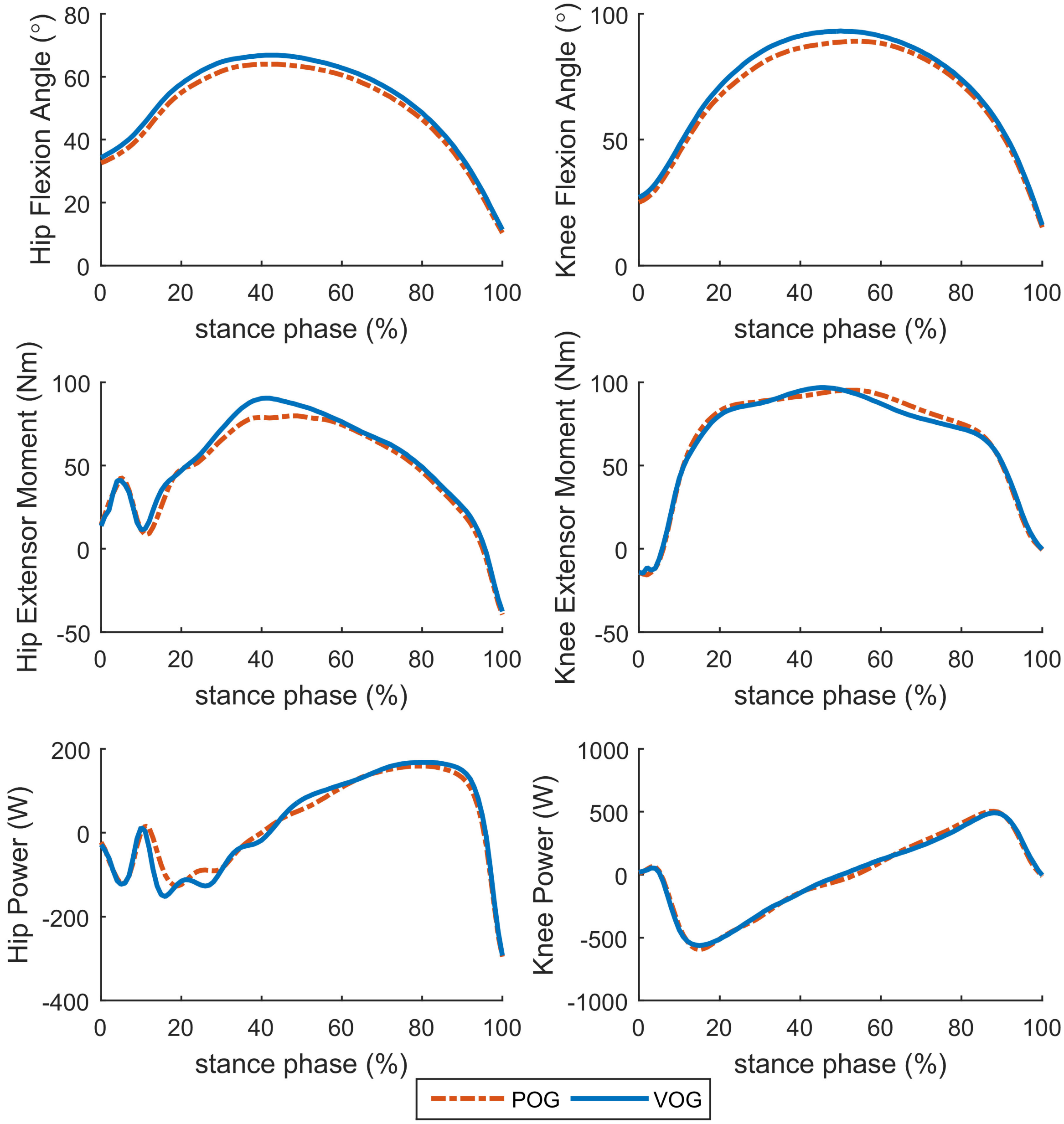

Figure 2 — Hip and knee joint angles, moments, and powers during the ground contact phase of the drop vertical jump for the physical overhead goal (POG) and virtual overhead goal (VOG) conditions.

Table 1 Hip and knee kinetic variables

Variable	Goal Condition		*P*-value	Effect Size
	POG	VOG		
Peak joint moment (Nm)				
Hip	83.6 ± 15.3	90.7 ± 15.8	< .001*	0.457
Knee	98.7 ± 25.9	99.6 ± 20.1	.862	0.039
Joint moment impulse stance phase (Nm·s)				
Hip	24.4 ± 8.5	27.2 ± 9.4	.004*	0.313
Knee	33.9 ± 11.6	34.3 ± 11.5	.679	0.035
Energy absorption (J)				
Hip	–13.0 ± 9.6	–16.5 ± 10.0	.047	0.357
Knee	–65.6 ± 22.5	–66.5 ± 22.1	.673	0.040

Abbreviations: POG = physical overhead goal; VOG = virtual overhead goal.

* Statistically significant difference following adjusted *p*-value (Benjamini and Hochberg technique).

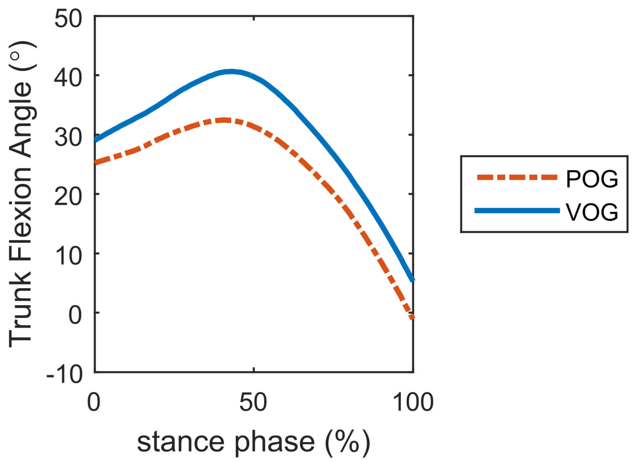

Figure 3 — Trunk flexion/extension angle during the ground contact phase of the drop vertical jump for the physical overhead goal (POG) and virtual overhead goal (VOG) conditions.

Table 2 Joint angles

Variable	Goal Condition POG	Goal Condition VOG	*P*-value	Effect Size
Initial contact (°)				
Trunk	25.2 ± 11.2	29 ± 9.1	.018*	0.374
Hip	32.6 ± 6.9	34.3 ± 5.8	.014*	0.268
Knee	25.1 ± 8.9	27.1 ± 10.2	.278	0.209
Maximum (°)				
Trunk	36.0 ± 7.8	42.7 ± 8.3	.002*	0.832
Hip	65.2 ± 9.8	67.7 ± 9.7	.079	0.256
Knee	88.7 ± 11.0	93.3 ± 15.6	.146	0.346

Abbreviations: POG = physical overhead goal; VOG = virtual overhead goal.

* Statistically significant difference following adjusted *p*-value (Benjamini and Hochberg technique).

safer movement patterns by modifying hip and knee kinematics.[12,30] However, improvements from externally focused attention may not translate to all tasks. In a recent 9-week plyometric training study, the externally focused group improved countermovement performance but not drop jump performance compared with participants that trained with an internal focus of attention.[26]

Our use of a virtual target was developed to determine if modifications in performance and biomechanics would exist specifically between the physical target and virtual target. Vertical jump height was not statistically different between the 2 externally focused targets, which may warrant further research on the use of virtual targets and feedback. Previous studies indicate that virtual environments and real-time biofeedback have direct implications for both rehabilitation and injury prevention.[11,31–34] Ford et al[11] recently used real-time biofeedback through externally focused attention to modify knee abduction angle and moment during double leg landings. Specifically, a decreased knee abduction angle and moment were found with a single bout of targeted biofeedback that used a double leg squat task. In addition, virtual environments have been used in patients to create real-life scenes that intentionally influence lower extremity movement biomechanics.[31]

Our second hypothesis was partially supported. Differences were present among several biomechanical variables, primarily at the trunk and hip in the different jumping conditions. Clearly, the trunk is in a more erect posture (large effect size) with a physical overhead goal, compared with a virtual goal. Considering that the placement of the physical overhead goal was directly overhead, this likely forced participants to modify their trunk and hip kinematics compared with the VOG condition, where the virtual external target was displayed on a screen in front of them. Whether a mirror or additional type of video system would elicit similar alterations should be investigated. Similar hip kinematic alterations were found with decreased hip flexion in male athletes during a countermovement with the trunk inclination angle manipulated experimentally to limit trunk flexion.[9] Likewise, greater jump height has been shown to be related to an increase in trunk flexion during the countermovement phase of a vertical jump.[35]

Greater trunk and hip flexion at initial contact appears to provide a more optimal posture to absorb the landing with the hip musculature, as hip moments were greater during virtual compared with physical target condition. In addition, while not statistically different, a trend toward greater hip energy absorption ($P = .047$, effect size 0.357) was also present during virtual compared with physical target conditions. Previous studies have generally reported increased hip energy absorption during soft compared with stiff landings.[36,37] Furthermore, greater hip extensor moments during landings have been observed with the trunk in a more flexed position compared with a more upright trunk position.[38] This is consistent with the current study where the hip joint moment peak and impulse were increased 8.5% and 11.5%, respectively, between the 2 target conditions. This result highlights the potential to use virtual environments to promote kinematic and kinetic changes during landing activities.

Kinetic changes throughout stance (during the landing and takeoff phases) in the hip are likely a result of increased activation of the hip musculature. During the takeoff phase of a DVJ, individuals typically use a proximal to distal muscle activation pattern to generate energy. This is based on evidence[39] that reports a proximal to distal muscle activation pattern during a countermovement jump, with lower extremity muscle activation initiated at the hip, followed by the knee and then ankle during the takeoff phase. This is a result of the role of the hip to first decelerate the trunk and then get the trunk in a more vertical position before the knee extensors can activate. Furthermore, the timing pattern between the hip and knee was greater during a countermovement jump compared with a squat jump, where the hip and trunk were more in a flexed position.[39] This suggests that greater hip muscle activation is needed during tasks that position the trunk and hip in a flexed position. The positive relationship between greater trunk flexion and greater hip extensor muscle activation was also observed in studies that examined other functional tasks including a forward lunge[40] and running.[41] Greater hip muscle activation and hip extensor energy generation were consistently observed with greater trunk and hip flexion.

In conclusion, jump height was not different during both externally focused conditions. Importantly, the results indicate that with an optimized jump height, the virtual target also promoted increased hip moments and trunk flexion. Increased trunk flexion and hip extensor activation is typically encouraged during knee injury prevention training. The use of a virtual target may be a useful alternative to physical targets to improve performance during certain biomechanical testing, screening, and training conditions, and should be further investigated.

References

1. Ben Abdelkrim N, El Fazaa S, El Ati J. Time-motion analysis and physiological data of elite under-19-year-old basketball players during competition. *Br J Sports Med*. 2007;41(2):69–75, discussion 75. PubMed doi:10.1136/bjsm.2006.032318
2. Perez-Gomez J, Calbet JA. Training methods to improve vertical jump performance. *J Sports Med Phys Fitness*. 2013;53(4):339–357. PubMed
3. Harries SK, Lubans DR, Callister R. Resistance training to improve power and sports performance in adolescent athletes: a systematic review and meta-analysis. *J Sci Med Sport*. 2012;15(6):532–540. PubMed doi:10.1016/j.jsams.2012.02.005
4. Ziv G, Lidor R. Vertical jump in female and male basketball players–a review of observational and experimental studies. *J Sci Med Sport*. 2010;13(3):332–339. PubMed doi:10.1016/j.jsams.2009.02.009
5. Wulf G, Dufek JS. Increased jump height with an external focus due to enhanced lower extremity joint kinetics. *J Mot Behav*. 2009;41(5):401–409. PubMed doi:10.1080/00222890903228421
6. Porter JM, Ostrowski EJ, Nolan RP, Wu WF. Standing long-jump performance is enhanced when using an external focus of attention. *J Strength Cond Res*. 2010;24(7):1746–1750. PubMed doi:10.1519/JSC.0b013e3181df7fbf
7. Smith JP, Kernozek TW, Kline DE, Wright GA. Kinematic and kinetic variations among three depth jump conditions in male NCAA division III athletes. *J Strength Cond Res*. 2011;25(1):94–102. PubMed doi:10.1519/JSC.0b013e3181b6041c
8. Kopper B, Ureczky D, Tihanyi J. Trunk position influences joint activation pattern and physical performance during vertical jumping. *Acta Physiol Hung*. 2012;99(2):194–205. PubMed doi:10.1556/APhysiol.99.2012.2.13
9. Vanrenterghem J, Lees A, Clercq DD. Effect of forward trunk inclination on joint power output in vertical jumping. *J Strength Cond Res*. 2008;22(3):708–714. PubMed doi:10.1519/JSC.0b013e3181636c6c
10. Ford KR, Myer GD, Smith RL, Byrnes RN, Dopirak SE, Hewett TE. Use of an overhead goal alters vertical jump performance and biomechanics. *J Strength Cond Res*. 2005;19(2):394–399. PubMed
11. Ford KR, DiCesare CA, Myer GD, Hewett TE. Real-time biofeedback to target risk of anterior cruciate ligament injury: a technical report for injury prevention and rehabilitation. *J Sport Rehabil.* 2015;Technical Notes(13).
12. Gokeler A, Benjaminse A, Hewett TE, et al. Feedback techniques to target functional deficits following anterior cruciate ligament reconstruction: implications for motor control and reduction of second injury risk. *Sports Med*. 2013;43(11):1065–1074. PubMed doi:10.1007/s40279-013-0095-0
13. de Leva P. Joint center longitudinal positions computed from a selected subset of Chandler's data. *J Biomech*. 1996;29(9):1231–1233. PubMed doi:10.1016/0021-9290(96)00021-8
14. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc*. 2003;35(10):1745–1750. PubMed doi:10.1249/01.MSS.0000089346.85744.D9
15. Ford KR, Myer GD, Hewett TE. Reliability of landing 3D motion analysis: implications for longitudinal analyses. *Med Sci Sports Exerc*. 2007;39(11):2021–2028. PubMed doi:10.1249/mss.0b013e318149332d
16. Cole GK, Nigg BM, Ronsky JL, Yeadon MR. Application of the joint coordinate system to three-dimensional joint attitude and movement representation: a standardization proposal. *J Biomech Eng*. 1993;115(4A):344–349. PubMed doi:10.1115/1.2895496
17. Ford KR, Taylor-Haas JA, Genthe K, Hugentobler J. Relationship between hip strength and trunk motion in college cross-country runners. *Med Sci Sports Exerc*. 2013;45(6):1125–1130. PubMed doi:10.1249/MSS.0b013e3182825aca
18. Ford KR, Myer GD, Melson PG, Darnell SC, Brunner HI, Hewett TE. Land-jump performance in patients with juvenile idiopathic arthritis (JIA): a comparison to matched controls. *Int J Rheumatol*. 2009; 478526. doi:10.1155/2009/478526. PubMed
19. Bisseling RW, Hof AL. Handling of impact forces in inverse dynamics. *J Biomech*. 2006;39(13):2438–2444. PubMed doi:10.1016/j.jbiomech.2005.07.021
20. McCaw ST, Gardner JK, Stafford LN, Torry MR. Filtering ground reaction force data affects the calculation and interpretation of joint kinetics and energetics during drop landings. *J Appl Biomech*. 2013;29(6):804–809. PubMed doi:10.1123/jab.29.6.804
21. Winter DA. *Biomechanics and Motor Control of Human Movement.* 3rd ed. New York: John Wiley & Sons, Inc.; 2005.
22. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Richard Steadman J. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech (Bristol, Avon)*. 2003;18(7):662–669. PubMed doi:10.1016/S0268-0033(03)00090-1
23. Glickman ME, Rao SR, Schultz MR. False discovery rate control is a recommended alternative to Bonferroni-type adjustments in health studies. *J Clin Epidemiol*. 2014;67(8):850–857. PubMed doi:10.1016/j.jclinepi.2014.03.012
24. Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *J R Stat Soc B*. 1995;57(1):289–300.
25. Cohen J. *Statistical power analysis for the behavioral sciences. Vol*. 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates; 1988.
26. Makaruk H, Porter JM, Czaplicki A, Sadowski J, Sacewicz T. The role of attentional focus in plyometric training. *J Sports Med Phys Fitness*. 2012;52(3):319–327. PubMed
27. Wulf G, McNevin N, Shea CH. The automaticity of complex motor skill learning as a function of attentional focus. *Q J Exp Psychol A*. 2001;54(4):1143–1154. PubMed doi:10.1080/713756012
28. Vance J, Wulf G, Tollner T, McNevin N, Mercer J. EMG activity as a function of the performer's focus of attention. *J Mot Behav*. 2004;36(4):450–459. PubMed doi:10.3200/JMBR.36.4.450-459
29. Wulf G, Dufek JS, Lozano L, Pettigrew C. Increased jump height and reduced EMG activity with an external focus. *Hum Mov Sci*. 2010;29(3):440–448. PubMed doi:10.1016/j.humov.2009.11.008
30. Gokeler A, Benjaminse A, Welling W, Alferink M, Eppinga P, Otten B. The effects of attentional focus on jump performance and knee joint kinematics in patients after ACL reconstruction. *Phys Ther Sport*. 2015;16(2):114–120. PubMed
31. Gokeler A, Bisschop M, Myer GD, et al. Immersive virtual reality improves movement patterns in patients after ACL reconstruction: implications for enhanced criteria-based return-to-sport rehabilitation. *Knee Surg Sports Traumatol Arthrosc*. 2016;24(7):2280–2286. PubMed
32. Noehren B, Scholz J, Davis I. The effect of real-time gait retraining on hip kinematics, pain and function in subjects with patellofemoral pain syndrome. *Br J Sports Med*. 2011;45(9):691–696. PubMed
33. Barrios JA, Crossley KM, Davis IS. Gait retraining to reduce the knee adduction moment through real-time visual feedback of dynamic knee alignment. *J Biomech*. 2010;43(11):2208–2213. PubMed doi:10.1016/j.jbiomech.2010.03.040
34. Willy RW, Buchenic L, Rogacki K, Ackerman J, Schmidt A, Willson JD. In-field gait retraining and mobile monitoring to address running biomechanics associated with tibial stress fracture. *Scand J Med Sci Sports*. 2016;26(2):197–205. PubMed
35. Lees A, Vanrenterghem J, De Clercq D. The energetics and benefit of an arm swing in submaximal and maximal vertical

jump performance. *J Sports Sci*. 2006;24(1):51–57. PubMed doi:10.1080/02640410400023217
36. Zhang SN, Bates BT, Dufek JS. Contributions of lower extremity joints to energy dissipation during landings. *Med Sci Sports Exerc*. 2000;32(4):812–819. PubMed doi:10.1097/00005768-200004000-00014
37. Devita P, Skelly WA. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Med Sci Sports Exerc*. 1992;24(1):108–115. PubMed doi:10.1249/00005768-199201000-00018
38. Shimokochi Y, Ambegaonkar JP, Meyer EG, Lee SY, Shultz SJ. Changing sagittal plane body position during single-leg landings influences the risk of non-contact anterior cruciate ligament injury. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(4):888–897. PubMed doi:10.1007/s00167-012-2011-9
39. Kopper B, Ureczky D, Tihanyi J. Trunk position influences joint activation pattern and physical performance during vertical jumping. *Acta Physiol Hung*. 2012;99(2):194–205. PubMed doi:10.1556/APhysiol.99.2012.2.13
40. Farrokhi S, Pollard CD, Souza RB, Chen YJ, Reischl S, Powers CM. Trunk position influences the kinematics, kinetics, and muscle activity of the lead lower extremity during the forward lunge exercise. *J Orthop Sports Phys Ther*. 2008;38(7):403–409. PubMed doi:10.2519/jospt.2008.2634
41. Teng HL, Powers CM. Influence of trunk posture on lower extremity energetics during running. *Med Sci Sports Exerc*. 2015;47(3)625–630. PubMed