University of Wollongong

Research Online

Faculty of Science, Medicine and Health -
Papers: part A

Faculty of Science, Medicine and Health

1-1-2012

Lower extremity kinematics and kinetics when landing from unloaded and loaded jumps

Ina Janssen

University of Wollongong, ij915@uowmail.edu.au

Jeremy M. Sheppard

Edith Cowan University

Andrew A. Dingley

Australian Institute of Sport

Dale W. Chapman

Australian Institute of Sport

Wayne Spratford

Australian Institute of Sport

Follow this and additional works at: <https://ro.uow.edu.au/smhpapers>

Part of the [Medicine and Health Sciences Commons](#), and the [Social and Behavioral Sciences Commons](#)

Recommended Citation

Janssen, Ina; Sheppard, Jeremy M.; Dingley, Andrew A.; Chapman, Dale W.; and Spratford, Wayne, "Lower extremity kinematics and kinetics when landing from unloaded and loaded jumps" (2012). *Faculty of Science, Medicine and Health - Papers: part A*. 122.
<https://ro.uow.edu.au/smhpapers/122>

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

Lower extremity kinematics and kinetics when landing from unloaded and loaded jumps

Abstract

Countermovement jumps loaded with a weighted vest are often used for the training of lower body power to improve jump performance. However, it is currently unknown how this added load affects the lower extremity kinematics and kinetics, in particular whether this results in an increased injury risk. Therefore, the purpose of this investigation was to determine how lower extremity kinematics and kinetics during landing are affected by loaded jumps as demonstrated in a volleyball block jump landing. Ten elite male volleyball players performed block jump landings in an unloaded and loaded (9.89 kg) condition. Kinematic and kinetic landing data from the three highest jumps were collected and assessed. Paired samples t test was used to establish whether load condition had a significant effect on lower extremity kinematics and kinetics. Hip flexion was significantly greater in the unloaded condition compared with the loaded condition ($p = .004$). There was no significant difference in any other kinematic or kinetic variables measures between the unloaded and loaded conditions. These results suggest that landing from loaded volleyball block jumps does not increase injury risk compared with unloaded jumps in elite male volleyball players.

Keywords

loaded, unloaded, landing, jumps, when, lower, kinetics, kinematics, extremity

Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details

Janssen, I., Sheppard, J. M., Dingley, A. A., Chapman, D. W. & Spratford, W. 2012, 'Lower extremity kinematics and kinetics when landing from unloaded and loaded jumps', *Journal of Applied Biomechanics*, vol. 28, no. 6, pp. 687-693.

Lower Extremity Kinematics and Kinetics When Landing From Unloaded and Loaded Jumps

Ina Janssen,^{1,2} Jeremy M. Sheppard,³ Andrew A. Dingley,¹ Dale W. Chapman,^{1,3}
and Wayne Spratford¹

¹Australian Institute of Sport; ²University of Wollongong; ³Edith Cowan University

Countermovement jumps loaded with a weighted vest are often used for the training of lower body power to improve jump performance. However, it is currently unknown how this added load affects the lower extremity kinematics and kinetics, in particular whether this results in an increased injury risk. Therefore, the purpose of this investigation was to determine how lower extremity kinematics and kinetics during landing are affected by loaded jumps as demonstrated in a volleyball block jump landing. Ten elite male volleyball players performed block jump landings in an unloaded and loaded (9.89 kg) condition. Kinematic and kinetic landing data from the three highest jumps were collected and assessed. Paired samples *t* test was used to establish whether load condition had a significant effect on lower extremity kinematics and kinetics. Hip flexion was significantly greater in the unloaded condition compared with the loaded condition ($p = .004$). There was no significant difference in any other kinematic or kinetic variables measures between the unloaded and loaded conditions. These results suggest that landing from loaded volleyball block jumps does not increase injury risk compared with unloaded jumps in elite male volleyball players.

Keywords: trunk, load bearing, volleyball, range of motion

In sports where jump height is an important performance criterion, loaded training modalities such as loaded countermovement jumps are often employed (Sheppard, Cormack, Taylor, McGuigan, & Newton, 2008; Sheppard, et al., 2007). Loaded training may assist in developing force characteristics such as explosiveness and is, therefore, commonly used for training in sports such as volleyball (Baker, 1996; Carlock, Smith, & Hartman, 2004). In accordance with the overload training principle, loaded countermovement jumps provide an emphasis on rapid force production by providing an increased load for the athlete to overcome. This added load can be applied to the athlete by use of a weighted vest, holding dumbbells, or using a barbell placed across the shoulders during the

performance of a countermovement jump. The use of added load is thought to increase the number of muscle fibers recruited compared with an “unloaded” jump and therefore is thought to require increased neural activation (Faccioni, 1995). Consequently, increasing the power of the knee extensors is thought to contribute to improved jump performance (Dugan, Doyle, Humphries, Hasson, & Newton, 2004; Newton, Kraemer, & Hakkinen, 1999; Stone, et al., 2003). In addition, using added resistance (10% of body mass) during a dynamic warm-up has been shown to significantly improve jumping performance in male and female athletes (Burkett, Phillips, & Ziuraitis, 2005; Thompsen, Kackley, Palumbo, & Faigenbaum, 2007). For these reasons, loaded countermovement jumps are often incorporated in the strength and conditioning environment for sports such as volleyball.

Injuries at the knee, particularly overuse injuries of the knee extensor mechanism, are common in sports involving a high frequency of jumping, such as volleyball, due to the high forces that are required to be attenuated during the jump-landing sequence (Solgard, et al., 1995). The most common overuse injury in volleyball is patellar tendinopathy (Kujala, Kvist, & Osterman, 1986). The etiology of patellar tendinopathy is not fully understood; however, a combination of the high forces that the knee extensor mechanism is exposed to and the frequency of landings are believed to be the main causative factors (Dufek & Bates, 1990; Lian, Holen, Engebretsen, & Bahr,

Ina Janssen (*Corresponding Author*) is with the Movement Science Department, Australian Institute of Sport, Canberra, ACT, Australia, and with the Biomechanics Research Laboratory, School of Health Sciences, University of Wollongong, Wollongong, NSW, Australia. Jeremy M. Sheppard is with Edith Cowan University, Joondalup, WA, Australia. Andrew A. Dingley is with the Physiology Department, Australian Institute of Sport, Canberra, ACT, Australia. Dale W. Chapman is with Edith Cowan University, Joondalup, WA, Australia, and with the Physiology Department, Australian Institute of Sport, Canberra, ACT, Australia. Wayne Spratford is with the Movement Science Department, Australian Institute of Sport, Canberra, ACT, Australia.

1996; Richards, Ajemian, Wiley, & Zernicke, 1996). The high loads that act on a joint result from both external forces applied to the body and the internal forces and moments acting within a body, which are contributing factors to injury (Bahr & Krosshaug, 2005). Eccentric contraction during landing can load the patellar tendon beyond its tensile strength and repeated tensile overload may cause micro-tearing and degeneration of tendon fibers leading to tendinitis (Cook, Kiss, Khan, Purdam, & Webster, 2004; Lian, Refsnes, Engebretsen, & Bahr, 2003). Therefore, repetitive loading of the patellar tendon may lead to overuse injuries at the knee in sports that involve repeated jumping and landing movements (McNitt-Gray, 2000; Richards, et al., 1996; Roels, et al., 1978). Thus in a counterproductive manner, loaded countermovement jumps may lead to improvements in vertical jump height, a key performance indicator, but potentially could increase the risk of developing patellar tendinopathy.

Recently, Kulas et al. (2010) investigated changes in landing strategies to assess how increased trunk load and trunk adaptations affected knee anterior shear and muscle forces during landing. Male and female participants performed a double-leg drop landing off a 0.45 m box in which they were instructed to roll forward and land in a natural and coordinated style in a no-load condition and a 10% increase in load condition using a fitted weighted vest. Participants were then categorized into a trunk-flexor or trunk-extensor group based on their trunk adaptation compared with the no load condition. The researchers concluded that participants who landed more upright after wearing the weight vest employed a quadriceps-dominant landing strategy that increased anterior shear forces and muscle forces at the knee. While drop landings are commonly used to investigate knee mechanics during landing as the landing phase can be carefully controlled (Blackburn & Padua, 2008; Coventry, O'Connor, Hart, Earl, & Ebersole, 2006; Decker, Torry, Wyland, Sterett, & Steadman, 2003; A. Kulas, Zalewski, Hortobagyi, & DeVita, 2008; Lawrence, Kernozek, Miller, Torry, & Reuteman, 2008; McNitt-Gray, 1991), these results may not transfer to more dynamic movements which include a takeoff and landing phase such as block jump-landings in volleyball. The block jump-landings include a propulsive jump phase before the landing movement and therefore some researchers have adopted this movement to assess dynamic movements (Dufek & Zhang, 1996; Hughes, Watkins, & Owen, 2010; Tillman, Criss, Brunt, & Hass, 2004). In these studies, participants commenced their blocking movement when standing still on the force plates and then performed a standing vertical jump.

As greater knee extensor moments have the potential to injury the knee joint (Lian, et al., 1996), performing loaded volleyball block jumps may increase this risk during landing. The effects of added load on lower extremity joint kinematics and kinetics in block landings, as often used in the strength and conditioning environment, has not been investigated. Therefore, the aims of this study were to investigate sagittal plane lower

extremity joint kinematics and kinetics when landing from unloaded and loaded jumps.

Methods

Participants

Ten junior national team male volleyball players (mean $\pm$ SD; age: 17.10 ± 0.99 years; height: 2.02 ± 0.06 m; mass: 86.45 ± 10.18 kg) from the Australian Institute of Sport volleyball program participated in the study. Participants were recruited as they compete in a sport where jump height is an important performance criterion and they had prior experience in wearing weighted vests during resistance training. Approval for the study was granted by the Australian Institute of Sport Ethics Committee and informed written consent was obtained from the participants before testing.

Landing Protocol

Soft weights were fitted into a standard weight vest made of nylon and adjustable through the waist strap for a secure fit (Figure 1). The total mass of the weight vest and added load was 9.89 kg which is comparable to previous studies investigating the effects of weighted vests on training (Burkett, et al., 2005; Thompson, et al., 2007). The same vest with added load was used for each participant and this encompassed an average of $10.34 \pm 0.89\%$ of each subject's body weight with a range of 8–12%. The same weighted vest was used for each participant as this scenario is commonly found in the strength

Figure 1 — Experimental setup with the participant in the static position, showing the weighted vest (9.89 kg) used for the loaded block jump condition.

and conditioning environment and was considered comparable to the percentage of body weight in previous research (Burkett, et al., 2005; Thompson, et al., 2007).

Participants were led through a standardized dynamic warm-up of approximately 15 min comprising jogging, multidirectional lunges, squat movements, and practice block jumps until they felt comfortable with the required task. Following the practice trials, each participant performed five successful simulated volleyball block jump landings for each condition; no weight vest (unloaded) and while wearing a weight vest (loaded) using an arm swing for takeoff if desired. Jump technique such as depth and duration of the countermovement were not standardized, however, participants were instructed to perform maximum block jumps and pretend to block a volleyball for each trial. A trial was considered successful when the participant performed the block jump and landed bilaterally with each foot placed on a separate force plate. However, participants were not made aware that they were required to land with one foot on each force plate to prevent targeting of the force plates potentially altering their landing strategy. Participants were provided with a 20–30 s rest between each trial. The order of test condition for each participant was randomized to reduce any order effects.

Instrumentation

Two synchronized force plates (0.60×0.90 m; Model Z12697, Kistler Instrument Corporation, Amherst NY, USA), embedded side by side into the floor captured ground reaction force (GRF) at 1,500 Hz. Three-dimensional kinematics were collected using 15 infrared cameras (250 Hz, Vicon; Oxford Metrics Ltd, Oxford, UK). Thirty-two retroreflective markers (14 mm in diameter) were applied on the skin over the following bilateral anthropometric landmarks based on Vicon's Plug-in-Gait Marker set: second metatarsal, calcaneus, lateral malleolus, lateral epicondyles of knee, lateral thigh, posterior superior iliac spine, anterior superior iliac spine, second metacarpal, lateral epicondyle of elbow, medial and lateral wrist, acromioclavicular joint, xyphoid process, jugular notch, 10th thoracic vertebra, 7th cervical vertebra, and four on a headband. These markers identified the joint centers of the ankle, knee, hip, as well as the trunk segment. Vicon incorporated the anthropometric data of Dempster (1955) to determine whole body center of gravity (CG) location based on a 15-segment model defined by the marker set as reported by Winter (1990). Lower body kinetic data were calculated on a three-segment model containing the foot, shank, and thigh based on previously defined algorithms (Davis, Ounpuu, Tyburski, & Gage, 1991; Ramakrishnan, Kadaba, & Wootten, 1987). The motion analysis system was calibrated before each testing session using a static calibration frame to orient the cameras to the laboratory coordinate system and a dynamic wand to fine tune camera positions (Ford, Myer, & Hewett, 2007). As the xyphoid and 10th thoracic vertebral markers were placed over the weight vest, each

participant completed a calibration trial in the anatomical position before the unloaded and loaded conditions.

Data Analysis

Jump height was calculated as the displacement between the standing position and highest position of the sacrum, calculated as the average of the left and right posterior superior iliac spine markers. Marker trajectories were filtered using a low-pass 4th-order Butterworth filter with a cut-off frequency of 12 Hz, chosen after conducting a residual analysis as described by Winter (1990). The following angles were measured in the sagittal plane: ankle (between the tibia and the foot), knee (between the femur and the tibia axis), hip (from the femur axis and the sagittal pelvic axis), and trunk flexion (between the thorax axis and the sagittal laboratory axis) (Figure 2). Ankle dorsiflexion, knee flexion, hip flexion, and forward trunk tilt were positive with zero degrees indicating extension of the knee and hip. Sagittal plane joint range of motion (ROM) was calculated as the difference between initial ground contact (IC) and peak flexion angles (maximum) attained during the landing cycle.

The IC of the landing phase was defined as the instant where the force plate reported values greater than 20 N. A data analysis cut-off filter frequency was chosen following a residual analysis as described by Winter (1990) and kinetic data were filtered using a low-pass 4th order Butterworth filter with a cut-off frequency of 90 Hz. Peak vertical GRF (vGRF) was normalized to body weight (BW) and loading rate of the vertical GRF (LR vGRF)

Figure 2 — A pictorial representation of the angles measured based on VICON's Plug-in-Gait Marker set.

was defined as the ratio of the peak vGRF to the time from IC to the peak vGRF. Leg stiffness provides an indication of the dynamic stability and may reveal whether landing with increased load alters the dynamic stability of the leg (Granata, Padua, & Wilson, 2002). Leg stiffness (k_{leg}) was calculated as the ratio of the change in vGRF to the change in vertical displacement of the CG between IC and the maximum vGRF (Δz) (Hughes & Watkins, 2008):

$$k_{\text{leg}} = \frac{\Delta \text{vGRF}}{\Delta z}$$

Using standard inverse dynamics methods, external joint moments were computed using filtered position and external ground reaction force data using numerical differentiation to calculate segmental accelerations. External peak ankle, knee, and hip moments were analyzed and reported such that an external knee flexion load will tend to flex the knee. Moments were normalized to the participant's height and weight to reduce any anthropometric differences, expressed as $\text{BW} \times \text{Ht}$.

Statistical Analysis

For each condition, the three highest jumps were further analyzed with the average values used in the statistical analysis. Statistical analysis was performed using SPSS Statistics 15.0 (SPSS Inc., Chicago, IL). Paired t tests were conducted to examine the differences between jump

conditions for hip, knee, and ankle angle at IC, maximum, and ROM. Significance was accepted when $p \leq .05$. The effect size (ES) statistics for unloaded compared with loaded jump conditions were calculated using Cohen's d (1992) criteria of small 0.2, moderate 0.5, and large 0.8.

Results

Hip flexion angle at IC during the unloaded condition was significantly greater than the loaded condition (unloaded = $32.33^\circ \pm 5.19$; loaded = $30.00^\circ \pm 4.68$; $p = .004$) (Table 1; Figure 3). There were no other significant differences observed for the ankle, knee, hip, or trunk kinematics at IC, maximum, or ROM between the unloaded and loaded conditions (Table 1). Jump height was significantly greater during the unloaded jumps than the loaded jumps (0.57 m vs. 0.51 m; $p = .000$).

No significant lower limb landing kinetic differences were found between the load conditions (Table 2). There were no significant differences in peak vGRF and the LR vGRF between the unloaded and loaded conditions at $p = .412$ and $p = .770$, respectively. There was no significant effect of load condition on leg stiffness ($p = .794$). Furthermore, no significant difference was revealed between jump condition and peak joint moments during landing with peak ankle, knee, and hip flexion moment values observed to be similar ($p = .370$, $p = .501$, $p = .594$) between the load conditions (Figure 4).

Table 1 Group mean ($\pm$ SD) values for ankle plantar / dorsiflexion, knee flexion, hip flexion, and trunk flexion angles at initial ground contact (IC), maximum angle, and range of motion (ROM) for landing in the unloaded and loaded (9.89 kg) conditions

	Ankle Plantar / Dorsiflexion ($^\circ$)	Knee Flexion ($^\circ$)	Hip Flexion ($^\circ$)	Trunk Flexion ($^\circ$)
Unloaded				
IC	-27.05 (6.62)	27.93 (5.44)	32.33 (5.19)*	13.58 (10.67)
Maximum	39.40 (8.67)	94.72 (14.20)	81.23 (21.19)	40.90 (17.61)
ROM	66.45 (9.12)	66.78 (12.94)	48.90 (18.63)	28.35 (12.40)
Loaded				
IC	-26.43 (9.25)	27.02 (6.18)	30.00 (4.68)*	14.12 (9.44)
Maximum	39.32 (7.46)	94.78 (13.94)	80.36 (20.38)	40.66 (17.00)
ROM	65.75 (10.72)	67.76 (14.47)	50.35 (18.25)	26.54 (12.60)

*Indicates significant difference from the other condition ($p \leq 0.05$).

Table 2 Group mean ($\pm$ SD) and effect size (ES) for jump height, peak vGRF, loading rate of the vGRF, and leg stiffness for the unloaded and loaded (9.89 kg) conditions

	Unloaded	Loaded	p -value	ES
Jump Height (m)	0.57 (0.09)*	0.51 (0.08)*	0.000	0.74
Peak vGRF (BW)	4.43 (0.58)	4.55 (0.86)	0.412	0.17
LR vGRF (kN/s)	30.62 (14.31)	29.57 (10.10)	0.770	0.09
Leg Stiffness (kN/m)	13.62 (10.08)	12.95 (5.09)	0.794	0.09

*Indicates significant difference from the other load condition ($p \leq 0.05$).

Figure 3 — Hip flexion angle for unloaded (left) and loaded (right) condition at initial contact was found to be the only significant variable between the conditions ($p = .004$).

Discussion

Vertical jump training with loaded weight vests are commonly used in strength and conditioning environments. During landing, contraction of the knee extensor muscles generates a knee extensor moment which is vital to prevent the knee “collapsing” (Richards, et al., 1996; van Eijden, De Boer, & Weijs, 1985). This study reports no significant difference in sagittal lower extremity kinetics between landings from an unloaded and an approximate additional 10% body weight loaded jump-landings. This suggests that loaded countermovement jump training may not increase the risk of knee injury during landing as the knee extensor mechanism contracted at a similar magnitude during the two load conditions. The absence of a significant difference between the two conditions is a novel finding suggesting that trained athletes may perform loaded jump training without increased risk. This is an important finding for injury prevention and rehabilitation efforts, especially for volleyball players who are prone to sustaining injuries such as patellar tendinopathy.

With the increased mass in the loaded condition, greater trunk inertia was present making it more difficult

Figure 4 — Mean values (+ *SD*) of the peak ankle, knee, and hip moment during landing in the unloaded (solid bars) and loaded (open bars) (9.89 kg) conditions.

to flex the trunk during landing. Therefore, trunk flexion during a loaded condition will be more difficult to produce compared with an unloaded landing condition. This may explain the findings of this study as landing from a loaded jump exhibited significantly decreased hip flexion at IC compared with an unloaded condition. Our data demonstrates that participants landed with a more vertical trunk at IC during the loaded jumps. Furthermore, participants landed from a greater height during the unloaded condition. Previous research has observed increased hip flexion with increased landing height (Bisseling, Hof, Bredeweg, Zwerver, & Mulder, 2007), which may explain the increased hip flexion angle at IC observed in the current study.

Trunk position is related to the tilt of the pelvis and this tilting of the pelvis may change the active length of the hamstring. Therefore, less hip flexion may be an injury prevention motor control strategy inherently aiming to keep the primary acting muscle working on the ascending portion of its length tension relationship. As the hamstring muscle group is working concentrically during the landing phase to stabilize the knee (Newham, Jones, Ghosh, & Aurora, 1988), the kinematic data would seem to indicate that the inherent strategy employed would place the hamstring muscles at a shorter length and thus at a lower chance of muscle strain or injury. It has previously been shown that greater muscle damage and strain is seen at longer muscle length (Child, Saxton, & Donnelly, 1998; Newham, et al., 1988). Future examinations using surface electromyography during the landing should further elucidate the characteristics of the motor control strategy and any impact of increased load.

Given the sizeable mass of the trunk, it is speculated that trunk biomechanics will also affect lower limb peak joint moments; however, this was not found in the current study. A shorter time to peak force (high LR), measured

as LR vGRF, is associated with greater mechanical loads on the knee compared with a longer time to peak force (low LR), indicating lower force applied over a longer duration (van Eijden, et al., 1985). A high LR has been attributed to increased degeneration in anatomical structures such as the patellar tendon (Nigg & Bobbert, 1990). As this study found no difference in LR vGRF between the two load conditions, this supports the hypothesis that performing block jumps with a weighted vest does not increase the risk of injury to the knee joint.

Dynamic stability of the leg is determined by the coordination between the ankle, knee, and hip joints during landing and is reflected in the stiffness of the leg (Hughes & Watkins, 2008). In a previous volleyball block jump task, leg stiffness during landing from a volleyball block jump was reported as 15.02 kN/m (Hughes & Watkins, 2008), which is similar to the values observed in the current study (13.62 kN/m). These similarities in leg stiffness values may be due to the similar task involved. To our knowledge, this is the first study to investigate leg stiffness during unloaded and loaded block jump landings. As no difference was found in the magnitude of leg stiffness, this suggests experienced participants had similar dynamic stability when landing with an increased load. This observed result may be due to the training level of the current participants; the participants were highly trained volleyball players who had experience performing these types of jumps in the loaded and unloaded conditions and therefore may have been more stable in their technique. To confidently determine if dynamic stability does not change in the loaded condition, it would be necessary to perform the same study using novice participants.

In this investigation, we have reported only sagittal plane kinetics; however, frontal plane moments have been implicated with increased injury risk (Hughes & Watkins, 2008) and further research should investigate frontal plane moments for the lower extremity joints during unloaded and loaded jump landings. Nevertheless, outcomes from this study will assist sports scientists by providing an objective measure for prescribing loaded block jump training as a modality to improve jumping performance. It is suggested that training with a weight vest of approximately 10 kg does not increase the susceptibility for injury. However, these results do not suggest similar findings for jump landings performed using other weight values such as a 20 kg barbell (Kraska et al., 2009) or using dumbbells to increase the load (Burkett et al., 2005). In addition, future research using a standard percentage of body mass, instead of the constant weight as used in this study, may provide new insights into lower extremity peak joint moments.

Acknowledgments

The authors would like to acknowledge the Australian Institute of Sport volleyball program for their contribution to this study. This work was funded by a grant from the National Strength and Conditioning Association to J. M. Sheppard.

References

- Bahr, R., & Krosshaug, T. (2005). Understanding injury mechanisms: a key component of preventing injuries in sport. *British Journal of Sports Medicine*, 39, 324–329. [PubMed doi:10.1136/bjsm.2005.018341](#)
- Baker, D. (1996). Improving vertical jump performance through general, special, and specific strength training: A brief review. *Journal of Strength and Conditioning Research*, 10, 131–136.
- Bisseling, R.W., Hof, A.L., Bredeweg, S.W., Zwerver, J., & Mulder, T. (2007). Relationship between landing strategy and patellar tendinopathy in volleyball. *British Journal of Sports Medicine*, 41, e8. doi:10.1136/bjsm.2006.032565
- Blackburn, J.T., & Padua, D.A. (2008). Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clinical Biomechanics (Bristol, Avon)*, 23, 313–319. [PubMed doi:10.1016/j.clinbiomech.2007.10.003](#)
- Burkett, L., Phillips, W., & Ziuraitis, J. (2005). The best warm-up for the vertical jump in college-age athletic men. *Journal of Strength and Conditioning Research*, 19, 673–676. [PubMed](#)
- Carlock, J., Smith, S., & Hartman, M. (2004). The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. *Journal of Strength and Conditioning Research*, 18, 534–539. [PubMed](#)
- Child, R., Saxton, J., & Donnelly, A. (1998). Comparison of eccentric knee extensor muscle actions at two muscle lengths on indices of damage and angle-specific force production in humans. *Journal of Sports Sciences*, 16(4), 301–308. [PubMed doi:10.1080/02640419808559358](#)
- Cook, J.L., Kiss, Z.S., Khan, K.M., Purdam, C.R., & Webster, K. (2004). Anthropometry, physical performance, and ultrasound patellar tendon abnormality in elite junior basketball players: a cross-sectional study. *British Journal of Sports Medicine*, 38, 206–209. [PubMed doi:10.1136/bjsm.2003.004747](#)
- Coventry, E., O'Connor, K.M., Hart, B.A., Earl, J.E., & Eber-sole, K.T. (2006). The effect of lower extremity fatigue on shock attenuation during single-leg landing. *Clinical Biomechanics (Bristol, Avon)*, 21, 1090–1097. [PubMed doi:10.1016/j.clinbiomech.2006.07.004](#)
- Davis, R., Ounpuu, S., Tyburski, D., & Gage, J. (1991). A gait analysis data collection and reduction technique. *Human Movement Science*, 10, 575–587. doi:10.1016/0167-9457(91)90046-Z
- Decker, M.J., Torry, M.R., Wyland, D.J., Sterett, W.I., & Steadman, J.R. (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics (Bristol, Avon)*, 18, 662–669. [PubMed doi:10.1016/S0268-0033\(03\)00090-1](#)
- Dempster, W. (1955). *Space requirements of the seated operator*.
- Dufek, J.S., & Bates, B.T. (1990). The evaluation and prediction of impact forces during landings. *Medicine and Science in Sports and Exercise*, 22, 370–377. [PubMed doi:10.1249/00005768-199006000-00014](#)
- Dufek, J.S., & Zhang, S-N. (1996). Landing models for volleyball players: a longitudinal evaluation. *Journal of Sports, Medicine, and Physical Fitness*, 36(1), 35–42. [PubMed](#)
- Dugan, E., Doyle, T., Humphries, B., Hasson, C., & Newton, R. (2004). Determining the optimal load for jump squats: a review of methods and calculations. *Journal of Strength and Conditioning Research*, 18, 668–674. [PubMed](#)

- Faccioni, A. (1995). Assisted and resisted methods for speed development. In J. Jarver (Ed.), *Sprints and Relays* (4th ed., pp. 20–26). Mountain View, CA: TAFNEWS Press.
- Ford, K.R., Myer, G.D., & Hewett, T.E. (2007). Reliability of landing 3D motion analysis: implications for longitudinal analyses. *Medicine and Science in Sports and Exercise*, 39(11), 2021–2028. [PubMed doi:10.1249/mss.0b013e318149332d](#)
- Granata, K.P., Padua, D.A., & Wilson, S. (2002). Gender differences in active muscle stiffness. Part II Quantification of leg stiffness during functional hopping task. *Journal of Electromyography and Kinesiology*, 12(2), 127–135. [PubMed doi:10.1016/S1050-6411\(02\)00003-2](#)
- Hughes, G., & Watkins, J. (2008). Lower limb coordination and stiffness during landing from volleyball block jumps. *Research in Sports Medicine*, 16, 138–154. [PubMed doi:10.1080/15438620802103999](#)
- Hughes, G., Watkins, J., & Owen, N. (2010). Differences between the sexes in knee kinetics during landing from volleyball block jumps. *European Journal of Sport Science*, 10(1), 1–11. [doi:10.1080/17461390903108117](#)
- Kraska, J.M., Ramsey, M.W., Haff, G.G., Fethke, N., Sands, W.A., Stone, M.E., et al. (2009). Relationship between strength characteristics and unweighted and weighted vertical jump height. *International Journal of Sports Physiology and Performance*, 4, 461–473. [PubMed doi:10.1016/j.jbiomech.2007.06.027](#)
- Kujala, U., Kvist, M., & Osterman, K. (1986). Knee injuries in athletes - review of exertion injuries and retrospective study of outpatient sports clinic material. *Sports Medicine (Auckland, N.Z.)*, 3, 447–460. [PubMed doi:10.2165/00007256-198603060-00006](#)
- Kulas, A., Zalewski, P., Hortobagyi, T., & DeVita, P. (2008). Effects of added trunk load and corresponding trunk position adaptations on lower extremity biomechanics during drop-landings. *Journal of Biomechanics*, 41, 180–185. [PubMed doi:10.1016/j.jbiomech.2007.06.027](#)
- Kulas, A.S., Hortobagyi, T., & DeVita, P. (2010). The interaction of trunk-load and trunk-position adaptations on knee anterior shear and hamstrings muscle forces during landing. *Journal of Athletic Training*, 45(1), 5–15. [PubMed doi:10.4085/1062-6050-45.1.5](#)
- Lawrence, R.K., Kernozek, T.W., Miller, E.J., Torrey, M.R., & Reuteman, P. (2008). Influences of hip external rotation strength on knee mechanics during single-leg drop landings in females. *Clinical Biomechanics (Bristol, Avon)*, 23(6), 806–813. [PubMed doi:10.1016/j.clinbiomech.2008.02.009](#)
- Lian, O., Holen, K., Engebretsen, L., & Bahr, R. (1996). Relationship between symptoms of jumper's knee and the ultrasound characteristics of the patellar tendon among high level male volleyball players. *Scandinavian Journal of Medicine & Science in Sports*, 6, 291–296. [PubMed doi:10.1016/j.jbiomech.2007.06.027](#)
- Lian, O., Refsnes, P-E., Engebretsen, L., & Bahr, R. (2003). Performance characteristics of volleyball players with patellar tendinopathy. *American Journal of Sports Medicine*, 31(3), 408–413. [PubMed doi:10.1016/j.jbiomech.2007.06.027](#)
- McNitt-Gray, J.L. (1991). Kinematics and impulse characteristics of drop landings from three heights. *International Journal of Sports Biomechanics*, 7, 201–224.
- McNitt-Gray, J.L. (2000). Musculoskeletal Loading During Landing. In V.M. Zatsiorsky (Ed.), *Encyclopedia of Sports Medicine* (Vol. 9). Oxford, England: Blackwell Sciences.
- Newham, D., Jones, D., Ghosh, G., & Aurora, P. (1988). Muscle fatigue and pain after eccentric contractions at long and short length. *Clinical Science*, 74(5), 553–557. [PubMed doi:10.1016/j.jbiomech.2007.06.027](#)
- Newton, R., Kraemer, W., & Hakkinen, K. (1999). Effects of ballistic training on preseason preparation of elite volleyball players. *Medicine and Science in Sports and Exercise*, 31, 323–330. [PubMed doi:10.1097/00005768-199902000-00017](#)
- Nigg, B., & Bobbert, M.F. (1990). On the potential of various approaches in load analysis to reduce the frequency of sports injuries. *Journal of Biomechanics*, 23, 2–12. [PubMed doi:10.1016/0021-9290\(90\)90036-3](#)
- Pappas, E., Hagins, M., Sheikhzadeh, A., Nordin, M., & Rose, D. (2007). Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. *Clinical Journal of Sport Medicine*, 17, 263–268. [PubMed doi:10.1097/JSM.0b013e31811f415b](#)
- Ramakrishnan, H.K., Kadaba, M.P., & Wootten, M.E. (1987). Lower extremity joint moments and ground reaction torque in adult gait. In J. Stein (Ed.), *Biomechanics of normal and prosthetic gait* (Vol. BED Vol 4, pp. 87–92): American Society of Mechanical Engineers.
- Richards, D.P., Ajemian, S.V., Wiley, J.P., & Zernicke, R.F. (1996). Knee joint dynamics predict patellar tendinitis in elite volleyball players. *American Journal of Sports Medicine*, 24(5), 676–683. [PubMed doi:10.1177/036354659602400520](#)
- Sheppard, J., Cormack, S., Taylor, K., McGuigan, M., & Newton, R. (2008). Assessing the force-velocity characteristics of well trained athletes: the incremental load power profile. *Journal of Strength and Conditioning Research*, 22, 1320–1326. [PubMed doi:10.1519/JSC.0b013e31816d671b](#)
- Sheppard, J., Cronin, J., Gabbett, T., McGuigan, M., Extebarria, N., & Newton, R. (2007). Relative importance of strength and power qualities to jump performance in elite male volleyball players. *Journal of Strength and Conditioning Research*, 22, 758–765. [doi:10.1519/JSC.0b013e31816a8440](#)
- Solgard, L., Nielsen, A., Moller-Madsen, B., Jacobsen, B., Yde, J., & Jensen, J. (1995). Volleyball injuries presenting in casualty: A prospective study. *British Journal of Sports Medicine*, 29, 200–204. [PubMed doi:10.1136/bjism.29.3.200](#)
- Stone, M., O'Bryant, H., McCoy, L., Coglianese, R., Lehmkuhl, M., & Schilling, B. (2003). Power and maximum strength relationships during performance of dynamic and static weighted jumps. *Journal of Strength and Conditioning Research*, 17, 140–147. [PubMed doi:10.1519/00124278-200702000-00010](#)
- Thompson, A., Kackley, T., Palumbo, M., & Faigenbaum, A. (2007). Acute effects of different warm-up protocols with and without a weighted vest on jumping performance in athletic women. *Journal of Strength and Conditioning Research*, 21(1), 52–56. [PubMed doi:10.1519/00124278-200702000-00010](#)
- Tillman, M.D., Criss, R.M., Brunt, D., & Hass, C.J. (2004). Landing constraints influence ground reaction forces and lower extremity EMG in female volleyball players. *Journal of Applied Biomechanics*, 20, 38–50.
- van Eijden, T., De Boer, W., & Weijss, W. (1985). The orientation of the distal part of the quadriceps femoris muscle as a function of the knee flexion-extension angle. *Journal of Biomechanics*, 18(10), 803–809. [PubMed doi:10.1016/0021-9290\(85\)90055-7](#)
- Winter, D.A. (1990). *Biomechanics and Motor Control of Human Movement* (2nd ed.). New York: John Wiley & Sons.