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ORIGINAL RESEARCH

THE INFLUENCE OF HEEL HEIGHT ON VERTICAL GROUND REACTION FORCE DURING LANDING TASKS IN RECREATIONALLY ACTIVE AND ATHLETIC COLLEGIATE FEMALES

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ABSTRACT

Purpose: To determine if heel height alters vertical ground reaction forces (vGRF) when landing from a forward hop or drop landing.

Background: Increased vGRF during landing are theorized to increase ACL injury risk in female athletes.

Methods: Fifty collegiate females performed two single-limb landing tasks while wearing heel lifts of three different sizes (0, 12 & 24 mm) attached to the bottom of a athletic shoe. Using a force plate, peak vGRF at landing was examined. Repeated measures ANOVAs were used to determine the influence of heel height on the dependent measures.

Results: *Forward hop task*- Peak vGRF (normalized for body mass) with 0 mm, 12 mm, and 24 mm lifts were 2.613 ± 0.498, 2.616 ± 0.497 and 2.495 ± 0.518% BW, respectively. Significant differences were noted between 0 and 24 mm lift ($p < .001$) and 12 and 24 mm lifts ($p = .004$), but not between the 0 and 12 mm conditions ($p = .927$). *Jump-landing task*- No significant differences were found in peak vGRF ($p = .192$) between any of the heel lift conditions.

Conclusions: The addition of a 24 mm heel lift to the bottom of a sneaker significantly alters peak vGRF upon landing from a unilateral forward hop but not from a jumping maneuver.

Key Words: ACL, heel lift, ground reaction force, landing

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INTRODUCTION

Anterior cruciate ligament (ACL) injuries remain among the most common knee injuries, with 100,000 tears occurring per year in the United States.[1,2] It has been well established that non-contact ACL tears are more common in female versus male athletes.[3-9] Researchers have divided the potential factors associated with a female's risk for ACL injury into four categories: environmental, anatomical, hormonal, or biomechanical.[10] However, given the limitations in the ability to alter most of these factors, many investigators have focused on defining the biomechanical strategies used by females during athletic activities.[9-21] Videotape analysis of ACL injuries in female athletes has demonstrated that these injuries typically occur during deceleration tasks such as landing from a jump.[9-11] Additionally, a common characteristic observed at the time of injury is a knee posture close to full extension.[9-11] The ramifications of landing in a more extended knee posture include decreased hamstring activity,[12, 16-18] increased quadriceps femoris muscle group activity,[12] increased anterior tibial translation,[17-20] and increased ground reaction forces (i.e. impact forces).[13,21]

ACL injury prevention programs have focused on attempting to favorably influence such kinematic and kinetic patterns during landing tasks in female athletes. Preventative exercise programs designed for female athletes participating in a variety of sports typically consist of plyometric activities and have demonstrated the ability to positively affect lower extremity kinematics and kinetics[20-22] in laboratory settings,[18,23,24] as well as decrease injury rates on the field.[25] However, given the large amount of time[18,22,24,25] and potential cost[26] associated with these programs, researchers are exploring alternative methods of influencing landing mechanics.[27]

Evidence exists that increased heel height alters lower extremity biomechanics, including sagittal plane knee postures. Both static-standing and dyna–mic gait analyses have demonstrated increased knee flexion angles with increased heel height.[28-33] Researchers demonstrated that a 24 mm heel lift significantly increased knee flexion at initial contact and peak knee flexion when landing during a forward hop maneuver.[27] However, no research exists that demonstrates if increased heel height will favorably influence other risk factors associated with ACL injury.

Many studies have documented a relationship between knee flexion angle and ground reaction force during landing activities.[13,21,34,35] Prapavessis and McNair[34] demonstrated that landing with increased knee flexion decreased vertical ground reaction force. This would be a favorable response when considering knee injury risk factors. However, the findings of Yu et al[36] failed to support this relationship.

Heel lift height has been shown to increase knee flexion at landing;[27] however, given the discrepancy in the literature regarding the relationship between knee angles and impact forces during landing it is necessary to investigate whether heel lift height will also alter impact forces. Therefore, the purpose of this study was to investigate the influence increased heel height has on peak vertical ground reaction forces sustained during landing tasks. It was hypothesized that increased heel height would decrease peak vertical ground reaction force.

METHODS

Subjects

Fifty female subjects between the ages of 18 and 25 (age = 20.6 ± 1.5 years, height = 166.2 ± 6.1 cm, weight = 64.3 ± 9.3 kg) were recruited from the university community via consecutive sampling procedures. Selection criteria for all subjects included: 1) at least recreationally active; 2) no history of knee surgery; 3) no acute lower extremity injury within the past six months that required the use of an assistive device for more than one day; 4) no use of foot orthotics; 5) the ability to perform required jumping tasks without limitation. Recreationally active was defined as being engaged in aerobic and/or anaerobic exercise for an average of four to five hours per week. However, this study did not exclude those who participated in more exercise, such as the levels that intercollegiate athletes would engage in. Sixteen of the participants were NCAA athletes participating in the sports of volleyball, lacrosse, soccer, or tennis. The 34 non-NCAA athletes participated in activities such as weight lifting, running, exercise classes, and Pilates based exercise for a self-reported average of 5.5 hours per week. Neither group reported having participated in any form of ACL-specific prevention activities in their past. All subjects were asked to read and sign an informed consent form approved by the University's Institutional Review Board.

EXPERIMENTAL DESIGN & SETTING

The methods and pilot testing (including power analysis) for this study were previously described and utilized by Lindenberg et al.[27] All data were collected in a laboratory setting. A randomized block design was used to evaluate the effect of heel lift height on sagittal plane knee joint kinematics of subjects participating in two unilateral landing activities: a drop-landing from a 40 cm high platform and a forward hop over an obstacle. Previous authors[37,38] have utilized similar tasks to those presented here to analyze lower extremity kinematics in female athletes. The dependent variable was peak vertical ground reaction force. The independent variable was heel height, with 3 different conditions studied: no lift (0 mm - control), 12 mm, and 24 mm. The lift sizes were chosen based on published heel lift research[39-41] and pilot testing.[27] The application of the varying heel lifts was completed in random order. The subjects were not told which heel lift was being utilized in an effort to minimize bias.

Instrumentation

A force plate (Bertec Corporation, Columbus, OH) securely mounted in the sub-floor (such that the top surface of the force plate was level with the laboratory floor) was utilized to determine ground reaction forces with landing. Initial contact was determined to be when 10 N of force was applied to the force plate as detected by the acquisition software above a quiet baseline measured 100 ms prior to the event. A total of 1000 ms was recorded: 300 ms pre-contact and 700 ms post-contact for each trial.

The force plate was connected to an analog-to-digital conversion board and a desktop computer (Dell; Austin, TX). Raw data were acquired at 2000 hertz and subsequently filtered with a software acquisition and analysis system (Run Technologies; Laguna Hills, CA).

Procedures

Identical procedures were followed for each subject. Data collection was completed during one session. Demographic data including height, weight, age, and the level and type of sport or activity was collected. All testing was performed on the dominant lower extremity. Dominance was determined by having the subject jump off a 20 cm wooden box and land on one leg. The lower extremity upon which the subject landed two out of three trials was considered the dominant lower extremity.[42] The subjects were asked to demonstrate an ability to perform the landing task to be utilized in this study. Each task was described and the potential participant completed each activity. If an individual was unable to perform both landing tasks without restriction they were excused from participation in the study.

Next, subjects donned a standardized shoe (NewBalance, Model 600; Boston, MA) that was neutrally balanced (neither a supination or pronation biased design) for the testing procedures. Subjects chose their own shoe size. Prior to donning the shoes, the investigator determined the order of the application of the heel lifts by randomly pulling papers labeled with the 3 different height measurements out of a hat. The subject was not told which heel height was being used for each trial. The heel lifts (G&W Heel Lift Incorporated; Cuba, MO) were injection-molded polyvinyl chloride (PVC) lifts 12 mm in height. Two heel lifts were combined with double-sided tape provided by the manufacturer to achieve the 24 mm height. The investigator then affixed the appropriate heel lift to the under-surface of the subject's shoe with carpet tape (Ace Hardware Corp.; Oak Brook, IL).

Drop-landing activity. The subject stepped onto the 40 cm high platform and stood facing the force plate with her feet shoulder width apart and toes aligned with the edge of the platform. The platform was located 11 cm from the force plate. The subject then leaned and fell forward off the platform and landed in the middle of the force plate on her dominant lower extremity. The subject was instructed to maintain her balance on the single limb until cued by the investigator to place the other lower extremity on the floor. Failure to land in the middle of the force plate or to maintain single limb balance following the jump resulted in negation of that trial from the data set and the subject was asked to repeat the jump.

Forward hop activity. The subject stood with both lower extremities on the floor and feet shoulder width apart 45% of her height away from the center of the force plate. A 30 cm × 17 cm × 12 cm box was placed halfway between the subject and the force plate. The purpose of the box was to ensure the subject achieved a minimum of 12 cm in height during the forward hopping maneuver. These procedures were similar to those found in previous studies investigating lower extremity kinematics in landing.[37] The subject hopped forward from a static, two-legged stance over the box and landed in the middle of the platform on the dominant lower extremity. The subject was instructed to maintain her balance on the single limb until cued by the investigator to place the other lower extremity on the floor. Failure to land in the middle of the force plate or to maintain single limb balance following the jump resulted in negation of that trial from the data set and the subject was asked to repeat the hop.

Each subject completed five trials of each landing task in each of the heel lift conditions for a total of 30 jumps or trials. Most subjects were able to complete successful trials without the need to repeat additional jumps. In subjects who required an additional jump, on average only one negated trial occurred. The order of the landing activities was counterbalanced between each subject with the initial subject's order being determined by flipping a coin. The subject was given a 30-second rest period between each jump to minimize the effect of fatigue. All data were gathered consecutively with a five-minute break between each condition to allow time to affix the heel lift and to give the subject a longer rest period.

Data Reduction

Force plate data were signal averaged over all five trials of each task using the features available in the acquisition software. The acquisition software capabilities were used to report the values of the dependent measures. Research has suggested that ACL injuries occur within 50 ms of foot contact,[43] and it is unlikely that forces occurring after 250 ms impact an athlete's susceptibility to injury. Therefore, the data collection was restricted to a timeframe of 0 to 250 ms. Data were filtered with a linear smoothing function with a 10 ms time constant. All identified dependent measures for each subject were exported from the acquisition software as an ASCII text file and then imported into a spreadsheet program (Microsoft Excel) to be pooled and organized. The data were then transferred to SPSS (Version 18.0) for analysis.

STATISTICAL METHODS

Statistical analysis was completed with a commercially available software package (SPSS; Chicago, IL). In order to better establish the homogeneity of our sample population an unpaired t-test was utilized to compare the performance of the athletes and the recreationally active females during the forward hop task, 0 mm condition. Separate repeated measures (randomized block) analysis of variance tests (ANOVA) were utilized to determine the influence of heel height on peak ground reaction force. The within subject variable was heel lift height with 3 levels: 0 mm, 12 mm, and 24 mm. The block factor was the individual subjects. When appropriate, post hoc testing using one-tailed paired t-tests with Bonferroni correction were performed to identify any significant differences in the dependent variables between the heel lift conditions. Alpha levels were set a-priori at $p < 0.05$. The corrected p-value used for each post hoc test was $p < 0.017$.

RESULTS

Subjects: Fifty females, 16 athletes and 32 recreationally active individuals participated in this study. In order to better establish the homogeneity of our sample population we compared the performance of the athletes and the recreationally active females for the forward hop tasks. No significant differences ($p = 0.46$) in peak vertical ground reaction force (vGRF) were found between the NCAA (2.54 ± 0.47) and recreational athletes (2.65 ± 0.51) during the forward hop task at the 0 mm heel lift level. (Figure 1)

Peak vGRF during the forward hop task were found to be significantly different ($F_{2,98} = 7.040$, $p < 0.001$,

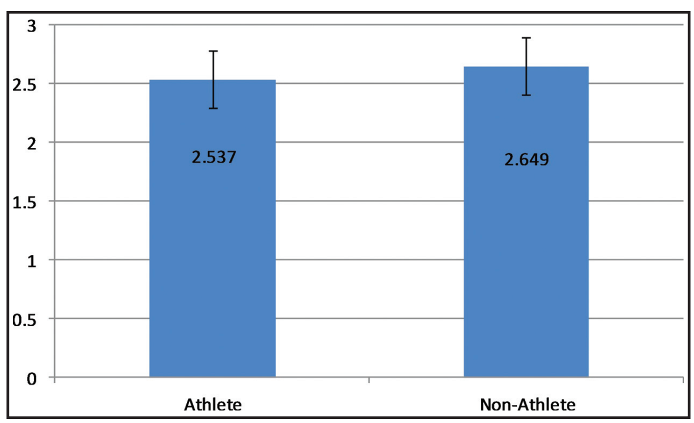

Figure 1. *Graphic representation of means and standard deviations comparing the vGRF of the athletes versus non-athletes during the forward hop task with 0 mm lift. ($p = 0.46$).*

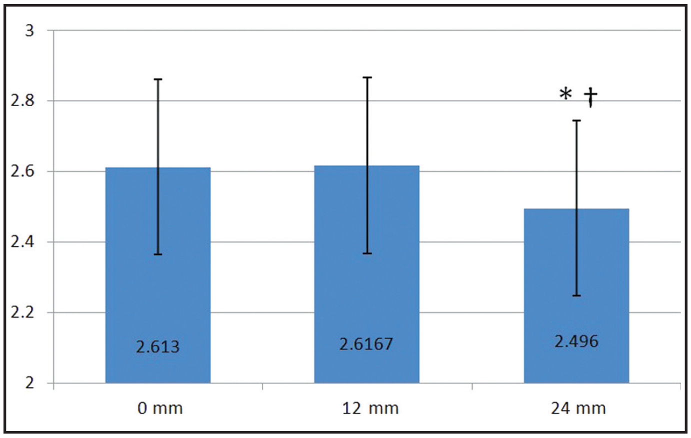

Figure 2. *Graphic representation of means and standard deviations for peak vGRF during forward hop task. Key: *, significantly different between 0 mm and 24 mm; †, significantly different between 12 mm and 24 mm.*

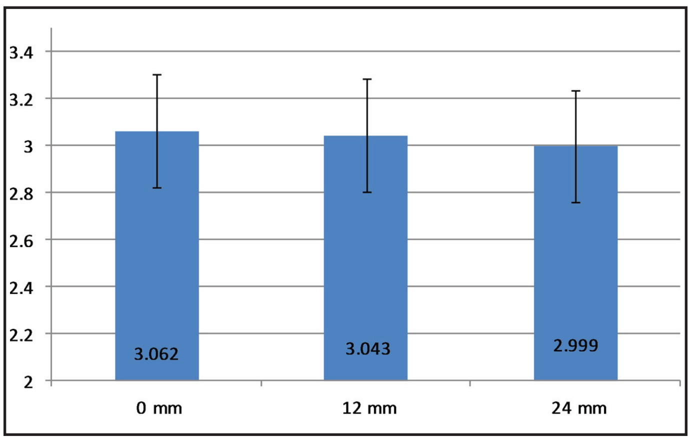

Figure 3. *Graphic representation of means and standard deviations for peak vGRF during drop landing task.*

$eta^2 = 0.126$) between lift conditions. The peak vGRF when normalized by mass (% of body weight, or BW) for each condition were 2.61 $\pm$ 0.50 BW at 0 mm, 2.62 $\pm$ 0.50 BW at 12 mm, and 2.49 $\pm$ 0.52 BW at 24 mm. Post-hoc analyses revealed significant differences between the 0 and 24 mm lifts ($p = .004$) and the 12 and 24 mm lifts ($p \leq .001$), but not between the 0 and 12 mm conditions ($p = .927$). (Figure 2) Peak vGRF during the drop-landing task were not found to be significantly different ($F = 1.68$, $p = .192$, $eta^2 = .033$) between conditions. (Figure 3)

DISCUSSION

The purpose of this study was to determine if a heel lift had the ability to alter vGRF during landing. These data demonstrated a decrease in peak vGRF with an addition of a 24 mm heel lift compared to the control condition during a forward hop task. A 12 mm heel lift did not have a similar effect on peak vGRF. For the drop-landing task, no significant changes in peak vGRF were observed between conditions. When sub-group comparison data were examined, no differences in the results were found between athletes and recreationally active individuals in our study. Subjects' landing forces responded similarly to added heel height despite any differing level of activity or training.

Investigation of the utilization of heel lifts to influence the properties of landing tasks is novel research. Thus, there is a paucity of literature to directly compare the results of this study. One study was found that investigated the influence of different shoe-types on vGRF during gait. The investigators demonstrated a significant decrease in impact forces during the foot-flat phase of gait in shoes with 36 mm (294.4 N) and 41 mm (298.8 N) heel thickness when compared to an 18 mm (317.3 N) heel thickness.[44] The data gathered during the forward hop task paralleled these findings in demonstrating a significant decrease in peak vGRF when landing with a 24 mm heel lift in comparison with both 0 mm and 12 mm conditions. Min-Chi et al[44] also found that the 36 mm and 41 mm heel thickness had no effect on impact forces during the toe off portion of the gait cycle (when the heel is no longer in contact with the ground). The authors of the current study failed to demonstrate any effect of heel height on knee vGRF while performing a drop-landing task. This could be attributed to a more forefoot biased landing style during the drop-landing. It has been demonstrated in other research that subjects landing from a more vertically oriented jump demonstrate a larger degree of ankle plantarflexion and utilize a forefoot landing strategy.[45-47] Thus, our subjects may not have had heel contact with the ground early enough in their landing pattern to utilize the effects of the increased heel height.

Factors related to heel height that could impact vGRF include an enhancement of knee flexion at landing and the promotion of greater ankle dorsiflexion excursion. A number of studies[19,13,21,34,35] have demonstrated an inverse relationship between knee angle during landing and vGRF. Specifically, as knee flexion angle increases during landing, vertical ground reaction forces decrease. Salci et al[35] investigated biomechanical characteristics of landing from various heights in male and female volleyball players. They demonstrated that the female volleyball players consistently landed with less knee flexion and higher peak vGRF values as compared to the male subjects. Other investigators have found that instructing subjects in "soft landing" techniques, such as increased knee flexion, can successfully decreased vGRF in a pre-test to post-test comparison.[34,48] The addition of a heel lift of 24 mm height demonstrated similar influences on landing characteristics. Lindenberg et al[27] previously found an increase in knee flexion at initial contact and peak knee flexion during a forward hop landing. The data in this current study further demonstrated that peak vGRF was significantly lessened with the same lift height and landing maneuver.

Other investigators[19,49,50] have described a significant relationship between ankle range of motion during landing and vGRF. Kovacs et al[50] investigated the influence of foot position on landing characteristics and found that landing styles with less sagittal plane excursion at the ankle were associated with less joint excursion at the knee and higher vGRF. Johanson et al[40] investigated the influence of heel lifts during normal gait and found that ankle dorsiflexion excursion increased with the addition of 6 mm and 9 mm heel lifts compared to no lift conditions. No research exists that has studied the influence of heel lifts on ankle kinematics or impact forces in landing.

Clinical Implications

Given the relatively low effect sizes calculated from the data (0.126 for the forward hop and 0.033 for the drop landing task), it is appropriate to further discuss the clinical relevance of the decreased vGRF that was demonstrated in this study. Many authors have described significant differences in the peak vGRF during sports maneuvers between males and females.[18,38,53] For example, Pappas et al[38] found that peak vGRF in female subjects was 1x BW higher than male subjects landing from the same height. While the current study did not investigate gender differences, past researchers have proposed increased vGRF to be a contributing factor in the gender disparity in ACL injury rates.[18,53] The application of a 24 mm heel lift was found to decrease the vGRF by 0.12 BW when compared to baseline landing forces. While this does not suggest that the 24 mm heel lift caused the subjects to land with the same landing forces as their male counterparts, it does demonstrate that the heel lift permits females to land with vGRF closer to those deemed to be less of a risk for injury in previous gender-related risk factor analysis reports.[18,38,54]

Limitations

Like all studies, the current study had several limitations. No data was gathered on ankle kinematics. Therefore, the influence of a heel lift on ankle kinematics during the selected landing tasks is unknown. Future research could delineate to what extent ankle kinematics are affected by the addition of a heel lift during landing maneuvers. Further, the authors did not monitor local muscle activity during the landing tasks. As a result it is not possible to draw conclusions on how muscle response may have changed or impacted vGRF. Kellis et al[51] demonstrated that peak vGRF decreased with a decrease in EMG activity of the knee extensors following a fatigue protocol. However, other studies have reported that muscle response often does not impact peak vGRF.[52] Despite the equivocal information available on the topic, it appears that further investigation into the relationship between heel height, muscle activity and vGRF is needed.

At this time the authors of this study are unable to predict any potential negative effects from using elevated heel heights in athletic shoe wear. There is very little information on the use of heel lifts in landing activities and, thus, there is no data suggesting whether an elevated heel could have a negative impact on performance, joint integrity, or the overall safety of the individual. Additionally, it is not possible to comment on how elevated heel height might alter other athletic activities, such as running or cutting. Again, future research and longitudinal studies would be necessary to discover if any problems would arise from the use of heel lifts.

CONCLUSION

The addition of a 24 mm heel lift decreased peak vGRF when landing from a forward hop task when compared to a 0 mm and 12 mm lift condition. However, neither a 12 mm nor 24 mm lift caused any significant change in vGRF when landing from a drop-landing task. Further research is needed to investigate the effect of heel height on ankle kinematics, muscle activity, vGRF and whether negative effects that could arise from heel lift use in athletic situations.

REFERENCES

1. Boden BP, Dean GS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23(6):573-578.
2. Miyasaka KC, Daniel DM, Stone MI, et al. The incidence of knee ligament injuries in the general population. *Am J Knee Surg*. 1991;4:3-8.
3. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer. *Am J Sports Med*. 1995;23:694-701.
4. Arendt EA, Agel J, Dick R. Anterior Cruciate Ligament Injury Patterns Among Collegiate Men and Women. *J Athl Train*. 1999;34(2):86-92.
5. Chandy TA, Grana WA. Secondary school athletic injury in boys and girls: a three-year comparison. *Physician Sportmed*. 1985; 13:106-111.
6. De Loes M, Dahlstedt LJ, Thomee R. A 7-year study on risks and costs of knee injuries in male and female youth participants in 12 sports. *Scand J Med Sci Sport*. 2000;10(2):90-97.
7. Ferretti A, Papandrea P, Contenduca F, Mariani PP. Knee ligament injuries in volleyball players. *Am J Sports Med*.1992;20:203-207.
8. Gwinn DE, Wilckens JH, McDevitt ER, Ross G, Kao T. The relative incidence of anterior cruciate ligament injury in men and women at the United States Naval Academy. *Am J Sports Med*. 2000;28(1):98-102.
9. Malone TR, Hardaker WT, Garrett WE. Relationship of gender to anterior cruciate ligament injuries in intercollegiate basketball players. *J. Southern Orthop. Assoc*. 1993;2:36-39.
10. Ireland ML. Anterior cruciate ligament injury in female athletes: epidemiology. *J Athl Train*. 1999;34(2):150-154.
11. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med*. 2004;32(4):1002-1012.
12. Colby S, Francisco A, Yu B, Kirkendall D, Finch M, Garrett W. Electromyographic and kinematic analysis of cutting maneuvers. Implications for anterior cruciate ligament injury. *Am J Sports Med*. 2000;28(2):234-240.
13. Baratta R, Solomonow M, Zhou BH, Letson D, Chuinard R, D'Ambrosia R. Muscular coactivation. The role of the antagonist musculature in maintaining knee stability. *Am J Sports Med*.1988;16:113-22.
14. Li G, Rudy TW, Sakane M, Kanamori A, Ma CB, Woo SL-Y. The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. *J Biomech*. 1999;32:395-400.
15. Pandy MG, Shelburne KB. Dependence of cruciate-ligament loading on muscle forces and external load. *J Biomech*. 1997;30(10):1015-1024.
16. More RC, Karras BT, Neiman R, Fritschy D, Woo SL, Daniel DM. Hamstrings – an anterior cruciate ligament protagonist. An in vitro study. *Am J Sports Med*. 1993;21(2):231-237.
17. Renstrom P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH. Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *Am J Sports Med*. 1986;14:83-87.
18. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes – decreased impact forces and increased hamstring torques. *Am J Sports Med*. 1996;24(6):765-773.
19. DeVita P, Skelly WA. Effect of landing stiffness on joint kinematics and energetics in the lower extremity. *Med Sci Sport Exerc.* 1992;24(1):108-115.
20. Lephart SM, Abt JP, Ferris CM, et al. Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *Br J Sports Med*. 2005;39:932-938.
21. Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res*. 2005;19(1):51-60.
22. Myer GD, Ford KR, McLean SG, Hewett TE. The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *Am J Sports Med*. 2006b;34(3):445-455.
23. Irmischer BS, Harris C, Pfeiffer RP, DeBeliso MA, Shea KG. Effects of a knee ligament injury prevention exercise program on impact forces in women. *J Strength Cond Res.* 2004;18(4): 703-707.
24. Myer GD, Ford KR, Brent JL, Hewett TE. The effects of plyometric vs dynamic stabilization and balance training on power, balance, and landing force in female athletes. *J Strength Cond Res*. 2006a;20(2):345-353.
25. Hewett TE, Lindenfeld TN, Riccobene JV, Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes: A prospective study. *Am J Sports Med*. 1999;27(6):699-706.
26. Holm I, Fosdahl MA, Friis A, Risberg MA, Myklebust G, Steen H. Effect of neuromuscular training on proprioception, balance, muscle strength, and lower limb function in female handball players. *Clin J Sport Med*. 2004;14:88-94.
27. Lindenberg KM, Carcia CR, Phelps AL, Martin RL, Burrows AM. The influence of heel height on sagittal plane knee kinematics during landing tasks in recreationally active and athletic collegiate females. *Int J Sports Phys Ther*. 2011;6:186-98.

28. Mika A, Oleksy Ł, Mika P, Marchewka A, Clark BC. The influence of heel height on lower extremity kinematics and leg muscle activity during gait in young and middle-aged women. *Gait Posture*. 2012;35:677-80.
29. DeLateur BJ, Giaconi RM, Questad K, Ko M, Lehmann JF. Footwear and posture. Compensatory strategies for heel height. *Am J Phys Med Rehabil*. 1991;70(5):246-254.
30. Ebbling CJ, Hamill J, Crussemeyer JA. Lower extremity mechanics and energy cost of walking in high-heeled shoes. *JOSPT*. 1994;19(4):190-196.
31. Gollnick PD, Tipton CM, Karpovich PV. Electrogoniometric study of walking in high-heels. *Res Q Exerc Sport*. 1964;35:370-8.
32. Opila-Correia KA. Kinematics of high-heeled gait. *Arch Phys Med Rehabil*. 1990;71(5):304-309.
33. Opila-Correia KA. Kinematics of high-heeled gait with consideration for age and experience of wearers. *Arch Phys Med Rehabil*. 1990;71(11):905-909.
34. Prapavessis H, McNair PJ. Effects of instruction in jumping technique and experience jumping on ground reaction forces. *J Orthop Sports Phys Ther*. 1999;29:352-6.
35. Salci Y, Kentel BB, Heycan C, Akin S, Korkusuz F. Comparison of landing maneuvers between male and female college volleyball players. Clin Biomech (Bristol, Avon). 2004;19:622-8.
36. Yu B, Lin CF, Garrett WE. Lower extremity biomechanics during the landing of a stop-jump task. *Clin Biomech (Bristol, Avon)*. 2006;21:297-305.
37. Lephart SM, Ferris CM, Riemann BL, Myers JB, Fu FH. Gender differences in strength and lower extremity kinematics during landing. *Clin Ortho Rel Res*. 2002;401:163-169.
38. Pappas E, Hagins M, Sheikhzadeh A, Nordin M, Rose D. Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. *Clin J Sport Med*. 2007;17:263-268.
39. Bird AR, Bendrups AP, Payne CB. The effect of foot wedging on electromyographic activity in the erector spinae and gluteus medius muscles during walking. *Gait & Posture*. 2003;18: 81-91.
40. Johanson MA, Cooksey A, Hillier C, Kobbeman H, Stambaugh A. Heel lifts and the stance phase of gait in subjects with limited ankle dorsiflexion. *J Athl Train*. 2006;41(2):159-165.
41. Hong WH, Lee YH, Chen HC, Pei YC, Wu CY. Influence of heel height and shoe insert on comfort perception and biomechanical performance of young female adults during walking. *Foot Ankle Intern.* 2005;26(12):1042-1048.
42. Padua DA, Carcia CR, Wilson SE, Granata KP. Lower extremity stiffness and stiffness recruitment strategies between males and females during hopping. *J Motor Behav;* 37:111-125, 2005.
43. Krosshaug T, Nakamae A, Boden BP, Engebretsen L, Smith G, Slauterbeck JR, Hewett TE, Bahr R. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007;35:359-367.
44. Min-Chi C, Mao-Jiun J. Wang Professional footwear evaluation for clinical nurses. *Applied Ergonomics*. 2007;38:133-141.
45. Brown C, Padua D, Marshall SW, Guskiewicz K. Individuals with mechanical ankle instability exhibit different motion patterns than those with functional ankle instability and ankle sprain copers. *Clin Biomech*. 2008;23:822-831.
46. Cortes N, Onate J, Abrantes J, Gagen L, Dowling E, van Lunen B. Effects of gender and foot-landing techniques on lower extremity kinematics during drop-jump landings. *J Applied Biomech*. 2007;23:289-299.
47. DiStefano LJ, Padua DA, Brown CN, Guskiewicz KM. Lower extremity kinematics and ground reaction forces after prophylactic lace-up ankle bracing. *J Athl Train*. 2008;43:234-241.
48. Cronin JB, Bressel E, Fkinn L. Augmented feedback reduces ground reaction forces in the landing phase of the volleyball spike jump. *J Sport Rehabil*. 2008;17:148-59.
49. Fong C, Blackburn JT, Norcross MF, McGrath M, Padua DA. Ankle-Dorsiflexion range of motion and landing biomechanics. *J Athl Train.* 2011;46:5-10.
50. Kovacs I, Tihanyi J, Devita P, Racz L, Barrier J, Hortobagyi T. Foot placement modifies kinematics and kinetics during drop jumping. *Med Sci Sports Exerc*; 1999;31:708-716.
51. Kellis E, Kouvelioti V. Agonist versus antagonist muscle fatigue effects on thigh muscle activity and vertical ground reaction during drop landing. *J Electromyo Kinesio*. 2009;19:55-64.
52. Nikooyan AA, Zadpoor AA. Effects of muscle fatigue on the ground reaction force and soft-tissue vibrations during running: a model study. *IEEE Trans Biomed Eng*. 2012;59:797-804.
53. James CR, Sizer PS, Starch DW, Thurmon EL, Slauterbeck J. Gender differences among sagittal plane knee kinematic and ground reaction force characteristics during rapid sprint and cut maneuver. *Res Q Exerc Sport*. 2004;75:31-38.
54. Markolf K, Burchfield D, Shapiro M, Shepard MF, Finerman GA, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Ortho Res*. 1995;13:930-935.