THE INFLUENCE OF ENERGY RETURN AND MINIMALIST FOOTWEAR ON THE KINETICS AND KINEMATICS OF DEPTH JUMPING IN RELATION TO CONVENTIONAL TRAINERS

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Abstract:

Limited research has examined the influence of different footwear on depth jump performance. The current study aimed to examine the influence of minimalist, energy return and conventional footwear on the kinetics, 3-D kinematics and temporal aspects of depth jump performance. Ten male participants performed depth jumps onto a force platform in each footwear condition. 3-D kinematics of the lower extremities were also quantified using an eight camera infra-red motion capture system, and tibial accelerations were measured using an accelerometer. Differences in kinetic, 3-D kinematic and temporal aspects between footwear were tested using one-way repeated measures ANOVA. The results indicate that peak tibial accelerations were significantly reduced in the minimalist footwear (7.74 g) compared to the conventional (10.32 g) and energy return footwear (10.06 g). Both average and instantaneous loading rates were significantly reduced in the minimalist (82.94 and 240.92 B·W·s) footwear compared to the conventional (108.93 and 289.45 B·W·s) and energy return footwear (132.23 and 292.70 B·W·s). However, it was also shown that jump height was significantly lower in the minimalist footwear (0.34 m) in comparison to the conventional (0.41 m) and energy return shoes (0.42 m). This suggests that whilst minimalist footwear may be associated with parameters that reduce injury risk, they are also linked to a reduction in depth jump performance. This suggests that a potential trade-off may exist between performance and susceptibility to injury when selecting appropriate footwear for sports involving jumping.

Key words: *depth jump, biomechanics, kinematics, kinetics*

Introduction

Plyometric training refers to a specific type of exercises which are associated with a rapid and forceful eccentric stretch of the muscle followed by a similarly rapid concentric muscle action for the purpose of producing a forceful high velocity motion (Gehri, Ricard, & Kleiner, 1998; Chmielewski, Myer, Kauffman, & Tillman, 2006; Markovic, 2007). Plyometric movements are utilized to enhance explosive power through stimulation of the stretch-shortening cycle (Hof & van den Berg, 1986). One of the fundamental plyometric activities is the depth jump (McClenton, Brown, Coburn, & Kersey, 2008). Depth jumping involves dropping from boxes of varying heights and then immediately performing a maximal vertical jump on landing (Hortobagyi, Havasi, & Varga, 1990). Depth jump training interventions have been shown to mediate significant increases in vertical jump height (Gehri, et al., 1998; Hedrick & Anderson, 1996). The mechanism by which depth jumping serves to augment vertical jump performance is related to a reduction in the duration of the amortization phase: the electromechanical phase shift between the eccentric and concentric aspects of the movement (Steben & Steben, 1981).

Whilst the effects of different depth jump training modalities have received considerable attention, the influences of extrinsic parameters such as athletic footwear on depth jump performance have received little attention. In recent years there has been a trend towards athletes performing their plyometric activities barefoot or in minimalist footwear. Training barefoot has received considerable attention in biomechanics research and taking into account this popularity, minimalist footwear have been conceived in order to replicate the perceived advantages of barefoot training in a shod condition (Sinclair, Greenhalgh, Edmundson, Brooks, & Hobbs, 2013a; Sinclair, Hobbs, Currigan, & Taylor, 2013b). In addition to this, new ‘energy return’ footwear have been designed utilizing thermoplastic polyurethane midsole materials which are claimed to be associated with reduced energy loss in comparison to the traditional footwear (Worobets, Tomarasa, Wannopa, & Stefanyshyn, 2013). During each ground contact, an athlete performs work on the shoe which results in deformation energy being input into the shoe midsole that is a function of the contact force (Stefanyshyn & Nigg, 2003). If some of this energy can be reclaimed, through energy return from the shoe, it could be hypothesized that performance in dynamic activities may be enhanced.

However, despite the potential efficacy of different footwear during plyometric activities, the majority of current research has examined their effects on running biomechanics (Lieberman, et al., 2010; Squadrone & Gallozzi, 2009; Sinclair, et al., 2013a,b). There is currently a paucity of research which has investigated the influence of different footwear during plyometric movements. Laporta et al. (2013) examined the influence of barefoot, minimalist and tennis footwear on vertical, depth and Bosco jump performance. It was demonstrated that the barefoot condition was associated with greater jump height and power production during the vertical jump. The Bosco test also revealed a greater peak power and jump height when performing barefoot, although no differences were found in jump height or power production when performing the depth jump movement. However, this study did not examine the 3-D kinematics of the jump movements or the temporal aspects of the kinetic parameters. Therefore, the aim of the current investigation was to examine the influence of minimalist, energy return and conventional footwear on the kinetics, 3-D kinematics and temporal aspects of the depth jump. A study of this nature may provide insight into the influence of different footwear from the contexts of both injury aetiology and performance.

Methods

Participants

A sample of ten male participants (age 22.38±4.47 years; height 1.73±0.07 m; body mass 67.83±5.65 kg) volunteered to take part in the current investigation. Participants were university-level athletes from activities that habitually utilize explosive jumping. Each participant was currently involved in plyometric conditioning as part of their training regime. Ethical approval for this project was obtained from the University Ethics Committee, and each participant provided written consent in accordance with the Declaration of Helsinki.

Procedure

The current investigation measured kinetic and kinematic parameters during the contact phase, i.e. the time over which the foot was in contact with the ground. The contact phase was considered to begin at foot contact and end at the point of foot take-off. This was quantified as the time period in which >20 N of vertical force was applied to the force platform (Sinclair, Hobbs, Protheroe, & Greenhalgh, 2013c). Prior to data collection each participant completed a thorough warm-up at a self-selected pace which consisted of 90 seconds of cycling on bicycle ergometer (Monark 828E, Monark Exercise AB, Sweden) and 90 seconds of step-ups onto a 30-cm high box (Smith, Kernozek, Kline, & Wright, 2011). Following the warm-up, participants completed five depth jumps in each of the three footwear conditions (minimalist, energy return and conventional), landing onto a piezoelectric force platform (Kistler, Kistler Instruments Ltd., Alton, Hampshire) from a 40-cm high box placed 30 centimetres in front of the platform (Smith, et al., 2011). The force platform captured data at 1000 Hz. The order in which participants performed depth jumps in each footwear condition was randomized. Participants were instructed to jump for maximum height, and fifteen seconds of rest were allowed between each jump to allow recovery (Read & Cisar, 2001). Kinematic data was captured at 250 Hz via an eight camera motion analysis system (Qualisys Medical AB, Goteburg, Sweden). Calibration of the system was performed before each data collection session.

The calibrated anatomical systems technique (Cappozzo, Catani, Leardini, Benedet, & Della, 1995) was utilized to define the anatomical frames of the right foot, shank and thigh. Retroreflective markers (19 mm in diameter) were positioned unilaterally to the calcaneus, 1st and 5th metatarsal heads, medial and lateral malleoli and medial and lateral epicondyles of the femur. To define the pelvic segment, additional markers were placed on the anterior (ASIS) and posterior (PSIS) superior iliac spines. The right side was selected for analysis as it was dominant for all participants. The hip joint centre was determined using regression equations based on the ASIS markers (Sinclair, Taylor, Currigan, & Hobbs, 2013d). Rigid tracking clusters used to define a technical frame were positioned on the shank and thigh segments. The pelvic and foot segments were tracked using the ASIS and PSIS markers, and the calcaneus, 1st and 5th metatarsal markers, respectively. Static trials were conducted for each footwear condition with the participant in the anatomical position in order for the positions of the anatomical markers to be referenced in relation to the tracking markers. Following acquisition of the static trial the femoral epicondyle and malleoli markers were removed as they were not required for tracking.

Tibial accelerations were also quantified using a uni-axial accelerometer (Biometrics ACL 300, Cwmfelinfach, Gwent, United Kingdom). The accelerometer sampled at 1000 Hz and was mounted onto a piece of carbon-fibre material using the procedure of Sinclair et al. (2013a). The device was attached to the distal tibia 0.08 m above the medial malleolus in alignment with the longitudinal axis of the tibia.

Data processing

Trials were digitized using Qualisys Track Manager in order to identify anatomical and tracking markers then exported as C3D files into Visual 3-D (C-Motion Inc, Gaithersburg, USA). Kinematic parameters were quantified using Visual 3-D after marker data was smoothed using a low-pass Butterworth 4th order zero-lag filter at a cut-off frequency of 10 Hz. Kinematics of the hip, knee and ankle were quantified using an XYZ Cardan sequence of rotations (where X is flexion-extension; Y is ab-adduction and Z is internal-external rotation). All kinematic data graphs were normalized to 100% of the contact phase. For the 3-D kinematic analysis the contact phase was split into the landing and jump phases. The landing phase was identified from foot contact to peak knee flexion, and the jump phase was identified from peak knee flexion to take-off (Shultz, Schmit, Nguyen, & Levine, 2010). 3-D kinematic measures during the landing and contact phases from the hip, knee and ankle which were extracted for statistical analysis were 1) angle at foot contact, 2) angle at the termination of the landing phase (peak knee flexion), 3) landing phase range of motion which represents the angular displacement from foot contact to termination of the landing phase, and 4) jump phase range of motion which represents the angular displacement from the termination of the landing phase to take-off. The parameters were extracted and averaged within participants for statistical analysis.

From the force platform vertical force parameters of impact peak, time to impact peak, average loading rate and instantaneous loading rate were calculated in accordance with Sinclair et al. (2013b). The impact peak was taken as the vertical ground reaction force peak that occurred during the first 50 ms of the contact phase. The average loading rate was calculated by dividing the impact peak magnitude by the duration over which the impact peak occurred, i.e. from foot contact to impact peak. The instantaneous loading rate was calculated as the maximum increase between adjacent data points. The acceleration signal was filtered using 60 Hz low-pass Butterworth 4th order zero-lag filter. Peak tibial acceleration was defined as the highest positive acceleration peak measured during the contact phase. Tibial acceleration slope was quantified by dividing the peak tibial acceleration magnitude by the duration over which the acceleration occurred. The duration over which the peak acceleration occurred was taken from footstrike to the instance of peak tibial acceleration.

Jump height which occurred following the contact phase was quantified using the technique adopted by Read and Cisar (2001), via the vertical rise of the iliac crest marker. The vertical height rise of the iliac crest was determined as the difference between iliac crest during the standing static trial and the height attained at the peak of the flight phase.

Experimental footwear

The experimental training shoes used during the current investigation consisted of conventional footwear (New balance 1260 v2), minimalist footwear (Vibram five-fingers, ELX) and commercially available shoes which claim to enhance energy return (Adidas energy boost 2.0 ESM), (shoe size 8-10 UK men's).

Statistical analyses

Mean kinetic, temporal and 3-D kinematic and kinetic parameters (outlined previously) were calculated for each footwear condition for each participant and an ensemble mean and standard deviation were calculated for the group. Differences between footwear were examined using one-way repeated measures ANOVA with the significance accepted at the $p \leq .05$ level. *Post-hoc* pairwise comparisons were conducted on all significant main effects using a Bonferroni adjustment. Effect sizes were calculated for each significant main effect using partial eta^2 ($p\eta^2$). The normality assumption was calculated using the Shapiro-Wilk test, which confirmed that all data were normally distributed. All statistical procedures were conducted using SPSS v21.0 (SPSS Inc, Chicago, USA).

Results

Figure 1 and Tables 1-4 present the mean± standard deviation of kinetics, temporal and 3-D kinematic parameters observed during the depth jump movement as a function of footwear.

Jump height

A significant main effect ($p<.01$, $p\eta^{2=.42}$) was shown for jump height. *Post-hoc* analysis showed that jump height was significantly greater in the energy return (0.42±0.03 m) and conventional shoes (0.41±0.03 m) compared to the minimalist footwear (0.34±0.05 m).

Kinetic and temporal parameters

A significant main effect ($p<.01$, $p\eta^{2=0.45}$) was found for the time to impact peak. *Post-hoc* analysis showed that time to impact peak was significantly greater in the minimalist footwear compared to the conventional and energy return shoes. Sig-

Table 1. Kinetic and temporal variables as a function of footwear

	Energy return		Minimalist		Conventional		
	Mean	SD	Mean	SD	Mean	SD	
Impact peak (B·W)	2.67	0.40	2.52	0.51	2.51	0.36	
Time to impact peak (s)	0.03	0.01	0.04 Ω	0.01	0.03	0.01	*
Average loading rate (B·W·s)	132.23	47.63	82.94 Ω	22.38	108.93	28.60	*
Instantaneous loading rate (B·W·s)	292.70	73.01	240.92 Ω	83.44	289.45	45.15	*
Peak tibial acceleration (g)	10.06	2.52	7.74 Ω	1.63	10.32	2.51	*
Time to tibial acceleration (s)	0.04	0.02	0.05	0.01	0.04	0.02	
Tibial acceleration slope (g·s)	311.13	158.65	193.57 Ω	79.26	353.73	194.82	*
Contact time (s)	0.46	0.07	0.41	0.10	0.46	0.08	

Notes: * = significant main effect
Ω = significantly different from conventional and energy return footwear

nificant main effects were also noted for average ($p<.01$, $p\eta^{2=0.68}$) and instantaneous ($p<.01$, $p\eta^{2=0.66}$) loading rates. *Post-hoc* analysis showed that both the average and instantaneous loading rates were significantly reduced in the minimalist footwear compared to the conventional and energy return shoes. A significant main effect ($p<.01$, $p\eta^{2=0.69}$) was found for peak tibial acceleration. *Post-hoc* analysis showed that peak tibial accelerations were significantly reduced in the minimalist footwear compared to the conventional and energy return shoes. Finally, a significant main effect ($p<.01$, $p\eta^{2=0.63}$) was also found for tibial acceleration slope. *Post-hoc* analysis showed that tibial acceleration slope was significantly reduced in the minimal footwear compared to the conventional and energy return shoes (Table 1).

3-D kinematic parameters

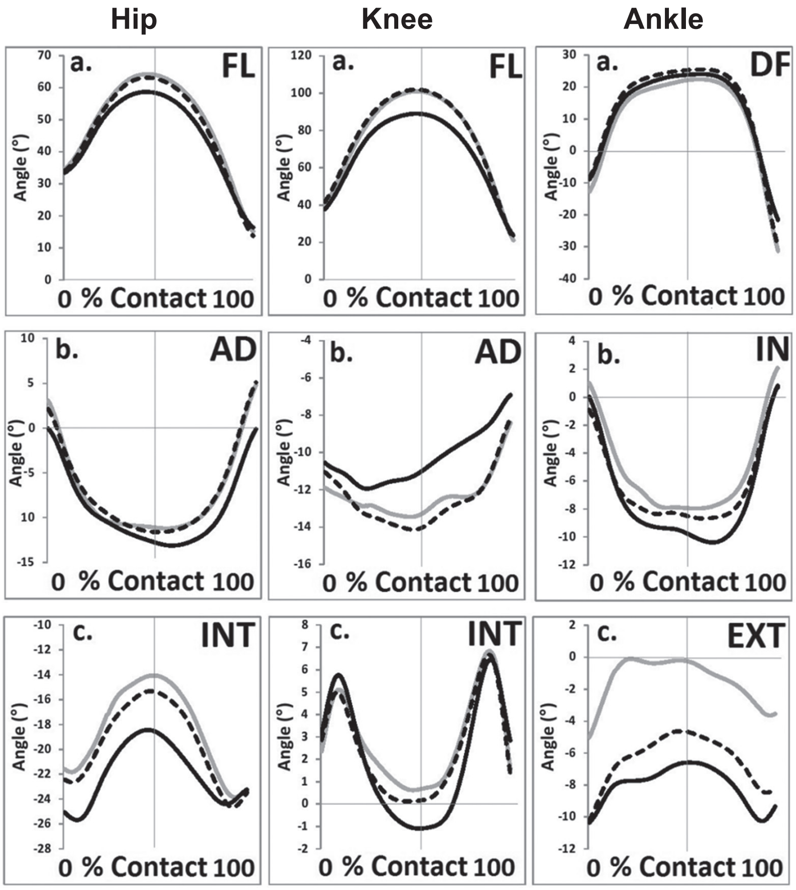

Figure 1. Hip, knee and ankle joint kinematics in the a) sagittal, b) coronal, c) transverse planes as a function of footwear; vertical line denotes termination of the landing phase. (Black = minimalist, grey = energy return, dot = conventional) (FL = flexion, DF = dorsiflexion, AD = adduction, IN = inversion, INT = internal rotation, EXT = external rotation).

Hip

A significant main effect (p<.01, $p\eta^{2=0.43}$) was found in the sagittal plane for the angle at the termination of the landing phase. *Post-hoc* analysis showed that hip flexion was significantly greater in the conventional and energy return shoes compared to the minimalist footwear. A significant main effect (p<.01, $p\eta^{2=0.46}$) was found for landing phase range of motion in the sagittal plane. *Post-hoc* analysis showed that landing phase range of motion was significantly greater in the conventional and energy return shoes compared to the minimalist footwear. Finally, a significant main effect (p<.01, $p\eta^{2=0.45}$) was found for jump phase range of motion in the sagittal plane. *Post-hoc* analysis showed that jump phase range of motion was significantly greater in the conventional and energy return shoes compared to the minimalist footwear (Table 2; Figure 1).

Knee

A significant main effect (p<.01, $p\eta^{2=0.51}$) was found in the sagittal plane for the angle at the termination of the landing phase. *Post-hoc* analysis showed that knee flexion was significantly greater in the conventional and energy return shoes compared to the minimalist footwear. A significant main effect (p<.01, $p\eta^{2=0.54}$) was found for landing phase range of motion in the sagittal plane. *Post-hoc* analysis

Table 2. Hip joint kinematics as a function of footwear

	Energy return		Minimalist		Conventional		
	Mean	SD	Mean	SD	Mean	SD	
Sagittal plane (+ = flexion/ - = extension)							
Angle at foot contact	35.42	15.00	34.88	13.03	35.05	13.09	
Angle at the termination of the landing phase	63.01	12.11	58.52 Ω	16.19	62.12	12.91	*
Landing phase range of motion	27.57	11.62	23.24 Ω	8.31	26.25	9.67	*
Jump phase range of motion	47.51	13.57	41.05 Ω	13.02	47.82	14.16	
Coronal plane (+ = adduction/ - = abduction)							
Angle at foot contact	1.06	4.39	0.40	4.56	-0.82	4.12	
Angle at the termination of the landing phase	-9.14	7.55	-10.05	6.99	-9.85	7.56	
Landing phase range of motion	10.12	4.45	10.43	5.06	10.42	5.11	
Jump phase range of motion	11.05	3.98	10.44	3.84	10.41	4.08	
Transverse plane (+ = internal/ - = external)							
Angle at foot contact	-21.47	8.01	-24.55	7.05	-22.19	8.02	
Angle at the termination of the landing phase	-13.18	10.46	-16.88	7.16	-14.67	10.30	
Landing phase range of motion	8.01	4.51	7.06	3.14	7.36	4.77	
Jump phase range of motion	7.85	3.99	7.16	4.06	7.86	4.13	

Notes: * = significant main effect
Ω = significantly different from conventional and energy return footwear

Table 3. Knee joint kinematics as a function of footwear

	Energy return		Minimalist		Conventional		
	Mean	SD	Mean	SD	Mean	SD	
Sagittal plane (+ = flexion/ - = extension)							
Angle at foot contact	40.09	10.30	38.45	10.59	42.05	8.62	
Angle at the termination of the landing phase	100.29	14.34	90.29 Ω	16.37	101.36	15.32	*
Landing phase range of motion	60.20	14.23	51.84 Ω	12.03	59.31	13.44	*
Jump phase range of motion	79.86	16.21	71.05 Ω	15.57	78.64	15.77	
Coronal plane (+ = adduction/ - = abduction)							
Angle at foot contact	-11.58	4.58	-10.48	3.64	-10.95	3.43	
Angle at the termination of the landing phase	-15.11	5.51	-11.54	4.54	-15.27	4.98	
Landing phase range of motion	4.39	4.19	3.12	2.68	4.30	3.64	
Jump phase range of motion	5.08	4.00	4.29	3.95	5.26	4.06	
Transverse plane (+ = internal/ - = external)							
Angle at foot contact	2.22	9.21	2.12	11.85	2.72	9.84	
Angle at the termination of the landing phase	0.85	1.87	-1.24	2.06	0.26	2.41	
Landing phase range of motion	1.47	2.27	3.11	2.44	3.06	2.49	
Jump phase range of motion	0.61	1.88	3.40	2.13	1.03	2.47	

Notes: * = significant main effect
Ω = significantly different from conventional and energy return footwear

showed that landing phase range of motion was significantly greater in the conventional and energy return shoes compared to the minimalist footwear. Finally, a significant main effect ($p<.01$, $p\eta^{2=0.52}$) was found for jump phase range of motion in the sagittal plane. *Post-hoc* analysis showed that jump phase range of motion was significantly greater in the conventional and energy return shoes compared to the minimalist footwear (Table 3; Figure 1).

Ankle

No significant ($p>.05$) differences in ankle kinematics were observed (Table 4; Figure 1).

Table 4. Ankle joint kinematics as a function of footwear

	Energy return		Minimalist		Conventional	
	Mean	SD	Mean	SD	Mean	SD
Sagittal plane (+ = dorsiflexion/ - = plantarflexion)						
Angle at foot contact	-12.96	9.82	-8.60	5.03	-8.55	8.62
Angle at the termination of the landing phase	21.09	8.21	22.13	7.22	23.26	8.56
Landing phase range of motion	33.61	4.51	31.48	5.64	32.09	4.99
Jump phase range of motion	52.15	5.04	47.62	6.32	50.67	5.77
Coronal plane (+ =inversion/ - = eversion)						
Angle at foot contact	1.54	6.04	2.29	1.93	-1.55	3.04
Angle at the termination of the landing phase	-7.61	5.11	-9.64	4.56	-8.15	5.00
Landing phase range of motion	9.13	3.57	11.15	4.05	8.59	3.98
Jump phase range of motion	9.68	3.67	10.57	4.11	9.72	4.09
Transverse plane (+ =external/ - = internal)						
Angle at foot contact	-4.50	4.55	-8.70	7.88	-7.06	5.37
Angle at the termination of the landing phase	-0.37	6.87	-7.60	7.21	-5.54	6.88
Landing phase range of motion	4.20	3.66	1.11	3.77	1.50	3.87
Jump phase range of motion	3.51	3.75	2.03	3.49	2.74	4.29

Discussion and conclusions

The aim of the current research was to examine the influence of minimalist, energy return and conventional footwear on the kinetics, 3-D kinematics and temporal aspects of the depth jump. To the best of our knowledge this study represents the first to examine the effects of different footwear on these biomechanical aspects of depth jump performance.

The first key observation from the current investigation is that jump height was shown to be significantly greater in the energy return and conventional footwear in comparison to the minimalist shoes. This opposes the observations of Laporta et al. (2013) who showed that barefoot and minimalist conditions produced significantly greater jump heights during the vertical jump and Bosco test compared to tennis footwear, although it should be noted that they observed no differences in the depth jump movement. Laporta et al. (2013) suggested that reductions in jump height in the vertical jump and Bosco test were attributable to the additional cushioning properties of athletic footwear when compared to barefoot and minimalist conditions. They hypothesized that a proportion of the propulsive force that results in the vertical movement of the centre of mass was dissipated into the midsole of footwear resulting in reduced jump performance. This does not appear to be the case during the depth jump however, and may relate to the fact that contact times are much shorter during depth jump. A reduction in contact time is expected to alter both the response of the viscoelastic materials of the shoe and the soft tissues. Midsole stiffness is likely to increase, which may reduce energy dissipation, whereas the ability to store and release energy through rapid eccentric-concentric muscular contraction may be limited (Markovic, 2007).

The kinematic analysis may provide insight into mechanisms by which jump height was enhanced in the conventional and energy return footwear. Both the conventional and energy return shoes were associated with greater hip and knee landing phase range of motion compared to the minimalist footwear. This indicates that the eccentric phase from foot contact to maximum knee flexion was greater in these footwear. This also suggests that a greater pre-stretch of the hip/knee extensors occurred in the counter-movement phase. This, in conjunction with subsequent increases in jump phase range of motion, indicates the presence of a more enhanced concentric phase leading to an increased jump height (Gehri, et al., 1998; Chmielewski, et al., 2006; Markovic, 2007; Hof & van den Berg, 1986).

In addition to this, the kinetic analysis showed that the minimalist footwear were associated with significant reductions in both tibial acceleration and vertical loading rate parameters in comparison to the other experimental footwear. This observation may have relevance to the aetiology of injury in athletes who habitually undertake depth jumping as part of their training. It is proposed that a positive relationship exists between the magnitude of impact-loading magnitude and the incidence of chronic injury development (Whittle, 1999); therefore it appears, based on the findings from the current study, that performing depth jumps in minimalist footwear such as those examined in the current investigation has the potential to reduce kinetic parameters associated with the aetiology of chronic injuries.

A potential limitation to the current investigation is that no measurements of electrical recruitment were obtained from the lower extremity musculature. Therefore the influence of different footwear on overall muscular recruitment during the eccentric and concentric phases of the depth jump movement are currently unknown. Additional work may wish to determine the effects of typically utilized athletic footwear on muscle activation amplitude during plyometric activities. A further limitation of the current investigation is that only male participants were examined. Females have been shown to be associated with different landing mechanics during jumping activities (Hewett, Stroupe, Nance, & Noyes, 1996). Furthermore, Laporta et al. (2013) also demonstrated that females exhibited distinct responses to different footwear during plyometric movements. Thus the generalizability of the findings from the current study is limited. It is recommended that the current investigation be repeated using a female sample.

In conclusion, the present study adds to the current knowledge regarding the influence of different footwear on depth jump performance by providing a comprehensive kinetic and 3-D kinematic evaluation. Given that significant reductions in tibial acceleration and vertical loading rate parameters were noted in the minimalist footwear, it can be concluded that they may be associated with a reduced injury risk. However, as the minimalist footwear was associated with a reduced jump height, this suggests that a potential trade-off may exist between performance and susceptibility to injury. It is recommended, based on these findings, that those who wish to maximize performance during depth jumping should select energy return footwear. However, those utilizing depth jumping as part of their training who are susceptible to chronic injury may wish to consider minimalist footwear. However, additional research is necessary before the clinical efficacy of minimalist footwear is confirmed.

References

Cappozzo, A., Catani, F., Leardini, A., Benedet, M.G., & Della, C.U. (1995). Position and orientation in space of bones during movement: Anatomical frame definition and determination. *Clinical Biomechanics*, *10*, 171-178.

Chmielewski, T.L., Myer, G.D., Kauffman, D., & Tillman, S.M. (2006). Plyometric exercise in the rehabilitation of athletes: Physiological responses and clinical application. *Journal of Orthopaedic and Sports Physical Therapy*, *36*, 308-319.

Gehri, D., Ricard, M., & Kleiner, D.A. (1998). Comparison of plyometric training techniques for improving vertical jump ability and energy production. *Journal of Strength and Conditioning Research*, *12*, 85-89.

Hedrick, A., & Anderson, J.C. (1996). The vertical jump: A review of the literature and a team case study. *Journal of Strength and Conditioning Research, 2*, 7-12.

Hewett, T.E., Stroupe, A.L., Nance, T.A., & Noyes, F.R. (1996). Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *American Journal of Sports Medicine*, *24*, 765-773.

Hof, A.L., & van den Berg, J.W. (1986). How much energy can be stored in human muscle elasticity. *Movement Science, 5*, 107-114.

Hortobagyi, T., Havasi, J., & Varga, Z. (1990). Comparison of two stretch shortening exercise programs in 13-year-old boys: Non-specific training effects. *Journal of Human Movement Studies, 18*, 177-188.

Laporta, J.W., Brown, L.E., Coburn, J.W., Galpin, A.J., Tufano, J.J., Cazas, V.L., & Tan, J.G. (2013). Effects of different footwear on vertical jump and landing parameters. *Journal of Strength and Conditioning Research*, *27*, 733-737.

Lieberman, D.E., Venkadesan, M., Werbel, W.A., Daoud, A.I., D'Andrea, S., Davis I.S., Mangeni, R.O., & Pitsiladis, Y. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*, *463*, 531-553.

Markovic, G. (2007). Does plyometric training improve vertical jump height? A meta-analytical review. *British Journal of Sports Medicine*, *41*, 349-355.

McClenton, L.S., Brown, L.E., Coburn, J.W., & Kersey, R.D. (2008). The effect of short-term Vertimax vs. depth jump training on vertical jump performance. *Journal of Strength and Conditioning Research*, *22*, 321-325.

Read, M.M., & Cisar, C. (2001). The influence of varied rest interval lengths on drop jump performance. *Journal of Strength and Conditioning Research*, *15*, 279-283.

Shultz, S.J., Schmitz, R.J., Nguyen, A.D., & Levine, B.J. (2010). Joint laxity is related to lower extremity energetics during a drop jump landing. *Medicine and Science in Sports and Exercise*, *42*, 771-780.

Sinclair, J., Greenhalgh, A., Edmundson, C.J., Brooks, D., & Hobbs, S.J. (2013a). The influence of barefoot and barefoot-inspired footwear on the kinetics and kinematics of running in comparison to conventional running shoes. *Footwear Science*, *5*, 45-53.

Sinclair, J., Hobbs, S.J., Currigan, G., & Taylor, P.J. (2013b). A comparison of several barefoot inspired footwear models in relation to barefoot and conventional running footwear. *Comparative Exercise Physiology*, *9*, 13-21.

Sinclair, J., Hobbs, S.J., Protheroe, L., & Greenhalgh, A. (2013c). Determination of gait events using an externally mounted shank accelerometer. *Journal of Applied Biomechanics*, *29*, 118-122.

Sinclair, J., Taylor, P.J., Currigan, G., & Hobbs S.J. (2013d). The test-retest reliability of three different hip joint centre location techniques. *Movement and Sport Sciences*, *83*, 31-39.

Smith, J.P., Kernozek, T.W., Kline, D.E., & Wright, G.A. (2011). Kinematic and kinetic variations among three depth jump conditions in male NCAA division III athletes. *Journal of Strength and Conditioning Research*, *25*, 94-102.

Squadrone, R., & Gallozzi, C. (2009). Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. *Journal of Sports Medicine and Physical Fitness*, *49*, 6-13.

Stefanyshyn, D.J., & Nigg, B.M. (2003). Energy and performance aspects in sports surfaces. In B.M. Nigg, G.K. Cole & D.J. Stefanyshyn (Eds.), *Sport surfaces–biomechanics, injuries, performance, testing and installation* (pp. 31-46). Calgary: University of Calgary.

Steben, R.E., & Steben, A.H. (1981). The validity of the stretch shortening cycle in selected jumping events. *Journal of Sports Medicine*, *21*, 28-37.

Whittle, M.W. (1999). The generation and attenuation of transient forces beneath the foot: A review. *Gait and Posture*, *10*, 264-275.

Worobets, J., Tomarasa, E., Wannopa, J.W., & Stefanyshyn, D. (2013). Running shoe cushioning properties can influence oxygen consumption. *Footwear Science*, *5*, S75-S76.

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