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Review

The effect of reduced ankle dorsiflexion on lower extremity mechanics during landing: A systematic review

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ABSTRACT

Objectives: To examine the evidence for effect of restricted ankle dorsiflexion range of motion on lower-extremity landing mechanics.
Design: Literature review.
Methods: Systematic search of the literature. Articles critiqued by two reviewers.
Results: Six studies were identified that investigated the effect of restricted DF ROM on landing mechanics. Overall, results suggest that landing mechanics are altered with restricted DF ROM, but studies disagree as to the particular mechanical variables affected.
Conclusions: There is evidence that restricted dorsiflexion range of motion may alter lower-extremity landing mechanics in a manner, which predisposes athletes to injury. Interpretation of results was made difficult by the variation in landing tasks investigated and the lack studies investigating sport-specific landing tasks. The focus of studies on specific mechanical variables rather than mechanical patterns and the analysis of pooled data in the presence of different compensation strategies between participants also made interpretation difficult. These areas require further research.

1. Introduction

Many lower-limb injuries are associated with restricted ankle dorsiflexion (DF) range of motion (ROM)[1–8] such as ACL,[7] Achilles,[4] and patellar tendon injuries.[1,8] In New Zealand from July 2012–June 2013, the Accident Compensation Corporation (ACC) received 172,461 new claims for lower-extremity injuries incurred during sport with costs exceeding $15 million NZD.[9] Ankle injury sustained during sports participation may contribute to injury risk as reduced DF ROM has been reported following ankle sprain,[10] ankle ligament reconstruction,[11] chronic ankle instability,[12,13] and with ankle bracing.[12,13]

There are a number of theories as to the mechanics behind the association between DF restriction and injury. Reduced DF may restrict the ability to pass the leg forwards over the foot[6,14–16] and to lower the centre of mass during squat-type movements.[17] This may be compensated for via subtalar and midfoot pronation[6,14,15] or knee valgus[6,18] both of which have been linked to chronic and acute injury.[19–23] This theory is supported by studies reporting increased knee valgus during squat movements in participants with reduced DF ROM.[16,18]

DF restriction may also increase injury risk by altering lower-extremity stiffness and landing forces. Decreased stiffness on landing results in greater lower-extremity joint-excursion and thereby reduces loading-rate (LR) and ground-reaction forces (GRFs).[24,25] Restricted DF and the associated reduction in hip and knee flexion[24,26] could therefore increase GRFs or LRs as the reduced joint excursion causes increased stiffness.[26,27] Increased injury risk has been reported with both higher GRFs[28–30] and higher LRs.[27,31,32] A further possibility is that DF loss is linked to injury via one of a number of compensatory mechanical patterns rather than through a single compensatory movement at a particular joint. Dynamical Systems theory approaches goal-directed movement from the perspective that there are multiple biomechanical degrees of freedom (DOF), which work in different patterns to achieve a consistent outcome.[33,34] This variation in biomechanical patterns is termed 'coordinative variability' and the pattern used for a given task can vary widely both within and between individuals.[33,34] Restricted DF may represent a loss of DOF and force individuals into one of a number of alternative movement patterns that may be associated with various injuries. A measure such as stiffness which captures a number of variables into a single measure may be more beneficial for identifying changes in movement patterns than individual mechanical variables.

Identifying predisposing factors to injury and the mechanical factors linked to increased injury risk will assist clinicians in

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Table 1
Categorisation of quality index scores.

Total modified downs and black checklist score (/28)	Percentage	Quality index
21+	75% +	Strong
14–20	50–74%	Moderate
7–13	25–49%	Limited
<7	<25%	Poor

Adapted from Hartling, Brison, Crumley et al.,[39] Hignett,[40] and Hing et al.[41]

prevention and treatment of injury. Given the above variation in rationale for a link between reduced dorsiflexion and injury incidence, the purpose of this review is to examine the evidence for the effect of DF ROM on peak DF angle, ankle, knee, and hip kinematics, peak vGRF, LR, time-to-peak (TTP) vGRF, and stiffness during landing.

2. Methods

A preliminary database search (keywords: ankle, dorsiflex*, land*, mechanic*) was conducted on EBSCO Health Databases to identify keywords (see supplementary search strategy table online). A comprehensive search of the literature was then conducted on EBSCO Health Databases on 17/09/2014 using the following search strategy: (dorsiflex* OR ankle OR talocrural) N8 (range OR ROM OR flex*) AND mechanic* OR biomechanic* OR kinetic* OR kinematic* OR move* OR "ground-reaction force*" OR GRF* OR (force* AND (land* OR load)) OR stiff* AND jump* OR land* OR hop* NOT orthos* OR orthot* OR prosthet* OR prosthes* OR stroke OR "traumatic brain injury" OR "multiple sclerosis" OR disease OR surg* OR repair*. Reference lists were scanned to identify further articles.

Studies were included if they clinically assessed DF ROM goniometrically or via a standing lunge test, or investigated peak DF angle during a landing task. Studies were also required to include at least one of GRF, LR, time-to-peak (TTP) GRF, stiffness, or lower-extremity kinematics during landing included as an outcome. Studies were excluded if participants were injured, or if participant grouping introduced an important confounder such as comparing between genders, different landing-tasks, or in varying states of fatigue. Studies were also excluded if DF restriction was induced by bracing or strapping. Articles were restricted to full text in the English language, no publication date restrictions were imposed.

Data was tabulated under the headings study design, intervention, outcome measures, and conclusions (Table 2). The terms 'knee abduction', 'medial knee deviation', 'knee valgus', and 'knee frontal plane motion' were considered synonymous. As not all studies reported confidence intervals (CIs) 90% CIs were calculated for mean differences and correlations where possible using an Excel spreadsheet.[35] For studies that did not report exact p-values, the threshold value was used (e.g. $p \leq 0.05$) to calculate the CI.

Articles were assessed for quality by two reviewers using the modified Downs and Black checklist which is a reliable tool for assessing RCTs and non RCTs[36] (Table 3). Question 27 of the Downs and Black scale was altered to score 1 for sufficient sample size based on power calculation and score 0 for insufficient sample size or power not calculated.

After each study was critiqued, a Quality Index was derived to categorise methodological score. The Quality Index enables studies to be categorised as being of poor, limited, moderate, or strong quality (Table 1). This measure has been used by several systematic reviews that have rated methodology using the modified Downs and Black checklist[37–39] (Table 2).

Levels of evidence were determined as outlined by van Tulder et al.[40] (see supplementary levels of evidence table online). Evidence was considered to be 'strong' where there were consistent findings among multiple strong-quality RCTs, 'moderate' were there were consistent findings among multiple moderate quality RCTs and/or one strong-quality RCT, 'poor', where there were consistent findings among multiple low-quality RCTs and/or controlled clinical trials (CCTs) and/or one moderate quality RCT, and 'Limited' were there was support from one low-quality RCT and/or CCT. Evidence was classified as 'conflicting' where there were inconsistent findings among multiple trials (RCTs and/or CCTs). Evidence was considered to be 'consistent' when at least 75% of articles agreed on the key outcomes.[41]

3. Results

The database search yielded 268 articles of which six met the inclusion criteria (see supplementary search results flow chart online). Scores ranged from 17–21/28 on the Downs and Black checklist (Table 3). The major quality issues were a lack of power calculations, not stating source populations, not stating the percentage of those approached who agreed to participate, and a lack of researcher and participant blinding.

Overall, there is strong evidence that restricted DF ROM alters landing mechanics. There is moderate evidence that restricted DF ROM does not reduce peak DF angle on landing and poor evidence for altered frontal plane ankle kinematics. There is moderate evidence that restricted DF ROM alters knee kinematics and poor evidence for altered hip kinematics. Evidence is conflicting regarding the effect of restricted DF ROM on peak vGRF and there is poor evidence for no effect on TTP vGRF. No studies investigated the effect of restricted DF ROM on LR or stiffness.

There were a total of 267 participants across all studies (112 female, and 98 male) with an age range of 15.5 ± 1.0 to 22.5 ± 4.7 years. Kinematics were recorded via camera-based 3D motion-capture systems with the exception of Stiffler et al.[42] who used standard video cameras in two planes, and Dill et al.[43] who used an electromagnetic tracking system. Force plates were used to collect kinetic data. Kinematic variables investigated included sagittal and frontal plane ankle and knee motion, and sagittal plane hip motion. Kinetic variables included peak vGRF and TTP vGRF. All studies measured DF ROM with a standard goniometer with the exception of Dill et al. who used a digital inclinometer.[43] Dorsiflexion ROM test positions included open-chain knee-extended, open-chain knee-flexed, and standing lunge test. Three studies used a within-subject repeated-measures design,[26,44,45] two compared high and low DF ROM groups,[43,46] and Stiffler et al.[42] compared medial-knee-deviators with non-medial-knee-deviators during a squat. All landing tasks involved dropping or jumping forward from a box ranging from 30 to 72 cm in height with Malloy et al.[45] basing box height on each participant's maximal vertical jump height. Three studies used a stop-landing-style,[26,42,46] three included a subsequent jump immediately on landing,[43–45] and all landings were bilateral with the exception of Whitting et al.[46] who investigated a unilateral landing.

Five[26,42,44–46] of six studies found changes in landing kinematics. Four studies found no effect of DF ROM on peak DF angle[26,43,45,46] while Whitting et al.[46] reported altered frontal plane ankle motion in association with reduced DF range. Malloy et al.[45] found reduced peak knee flexion angle and Fong et al.[26] found reduced sagittal knee excursion with DF restriction, while a third study[43] found no effect of DF ROM on knee sagittal knee kinematics. Two studies[42,45] found greater peak knee valgus and another[44] found greater frontal plane knee excursion in association with reduced DF ROM, while other authors found no effect of DF ROM on frontal plane knee kinematics.[43,26] Dill et al.[43] also found no effect of DF ROM on transverse plane knee peak angle or excursion. Fong et al.[26] found reduced sagittal plane hip excursion with DF restriction.

Table 2
Effect of DF ROM on landing kinematics and kinetics.

Article	Participants	Groups	Measurement			Landing-Task	Results		Conclusions
			Kinematics	Kinetics	DF		Kinematics	Kinetics	
Stiffler et al. [42]	Gender, no.: M: 28 F. 69 Age (y): CON = 20.3 ± 1.5 MKD = 20.2 ± 1.4 Sport: Recreationally active	Participants grouped based on presence (MKD) or absence (CON) of medial knee deviation during an overhead squat	Standard video cameras in frontal and sagittal planes Videos used to score participants on the Landing Error Scoring System (LESS)	–	Open-chain pROM and aROM with knee extended and in 30° flexion using standard goniometer	Forward jump from 30 cm box to a distance equal to 50% of participants' height, bilateral landing	Greater extended-knee DF pROM and aROM in CON than MKD group Mean difference (pROM) = 2.62°, CI = 0.48–4.8 Mean difference (aROM) = 3.58°, CI = 1.1–6 Significantly greater number of MKD participants displayed knee valgus at or medial to the great toe than CON participants Difference = 17.7% (29 participants) No significant difference in flexed-knee DF ROM orLESS score for IC KF or IC knee valgus angles between groups	–	Greater knee valgus displacement associated with reduced extended-knee DF aROM and pROM No difference in LESS score for IC knee flexion or IC knee valgus angles with extended-knee DF aROM or pROM No difference in LESS score for knee valgus displacement, IC knee flexion, or IC knee valgus angles with reduced flexed-knee DF ROM
Whitting et al. [46]	Gender, no.: M, 33 Age (y): 22.5 ± 4.7 Sport: Physically active	Participants separated into high DF ROM (HDF) and low DF ROM (LDF) groups	3D motion capture (data used to create virtual ankle models from which sagittal and frontal plane joint angles and TTP angles were calculated)	Force platform (Peak vGRF, TTP vGRF)	Measured with a goniometer during standing lunge test	Unilateral drop-landing onto dominant leg from heights of 32 and 72 cm	No significant difference in peak DF angle or IC PF angle between groups Greater EV angle at time of peak Achilles tendon force in LDF than HDF group Mean difference = 3.8°, CI = 0.67–6.9 Greater EV angle at time of peak DF in LDF than HDF group Mean difference = 4.2°, CI = 0.88–7.5 No significant difference in peak EV angle or EV angle at time of peak PF moment between groups	No significant difference in peak vGRF or TTP vGRF between groups	Greater ankle eversion angle at some time-points during landing with DF restriction No effect of DF restriction on peak ankle EV angle, peak vGRF, or TTP vGRF
Sigward et al. [44]	Gender, no.: F, 39 Age (y) 15.5 ± 1.0 Sport: Soccer	Within-subject design	6-camera 3D motion capture (knee frontal plane kinematics)	–	pROM with knee flexed to 30° using a standard goniometer	Drop-jump from 46 cm platform bilateral landing, immediately perform maximal vertical jump	DF ROM correlated with frontal plane knee excursion (r = -0.27), CI = -0.5–0	–	Increased frontal plane knee excursion with DF restriction

Table 2 (*Continued*).

Article	Participants	Groups	Measurement			Landing-Task	Results		Conclusions
			Kinematics	Kinetics	DF		Kinematics	Kinetics	
Dill et al. [43]	Gender, no.: M, 20 F, 20 Age (y): Normal group (NWB) = 20.70 ± 1.98 Restricted group (NWB) = 19.45 ± 1.40 Normal group (WB) = 20.70 ± 1.95 Restricted group (WB) = 19.45 ± 1.43 Sport: Physically active	Participants grouped based on DF ROM during weight-bearing and non-weight-bearing tests Limited = $\leq 5^\circ$ DF Normal = $\geq 15^\circ$ DF	Electromagnetic motion-tracking system (peak ankle DF, knee sagittal, frontal, and transverse plane kinematics)	–	NWB test: Open-chain pROM measured with knee extended using a standard goniometer WB test: Range measured with a digital inclinometer during a standing lunge	Forward jump from 30 cm box to distance equal to 50% participants' height, bilateral landing, immediately perform maximal vertical jump	No significant difference in peak DF, or knee sagittal, frontal or transverse plane excursion or peak angles, between groups	–	No effect of DF ROM on peak DF, or knee sagittal, frontal or transverse excursion
Malloy et al. [45]	Gender, no.: F, 23 Age (y): 19.4 ± 0.84 Sport: College soccer	Within-subject design	14-camera 3D motion-capture (Peak ankle DF, knee frontal and sagittal plane kinematics)	Force plate (peak vGRF)	Active-assisted DF ROM with knee extended using standard goniometer	Drop-jump from height equal to vertical displacement of PSIS during participants' maximal jump height, bilateral landing, immediately perform maximal vertical jump	DF ROM correlated with: Peak KF (r = 0.385), CI = 0.04–0.65 Peak knee abduction (r = 0.355), CI = 0.00–0.63 No significant correlation between DF ROM and peak DF angle	No significant correlation between DF ROM and peak vGRF	Reduced peak knee flexion and greater knee abduction with DF restriction No effect of DF ROM on peak DF angle or peak vGRF
Fong et al. [26]	Gender, no.: M, 17 F, 18 Age (y): 20.5 ± 1.5 Sport: Physically active	Within-subject design	7-camera 3D motion-capture (knee frontal and sagittal plane kinematics; hip and ankle sagittal plane kinematics)	Force plate (peak vGRF)	Open-chain pROM with knee extended and in 90° flexion using standard goniometer	Forward jump from 30 cm box to a distance equal to 40% of participant's height, bilateral landing, dominant foot on force plate	Extended-knee DF ROM correlated with: KF excursion (r = 0.464), CI = 0.21–0.66 HF excursion (r = 0.357), CI = 0.08–0.58 No significant correlation between extended-knee DF ROM and KV excursion or DF excursion No significant correlation between flexed-knee DF ROM and KF excursion or KV excursion	Extended-knee DF ROM correlated with: Peak vGRF (r = -0.411), CI = -0.62–-0.15 No significant correlation between flexed-knee DF ROM and peak vGRF	Reduced hip and knee sagittal excursion, and increased peak vGRF with DF restriction (measured with extended-knee) No effect of DF range on knee frontal plane excursion

IC = Initial Contact; DF = Dorsiflexion; PF = Plantarflexion;, EV = Eversion; KF = Knee flexion; KV = Knee valgus; HF = Hip flexion; ROM = Range of motion; pROM = Passive range of motion; GRF = Ground reaction force; vGRF = Vertical ground reaction force; LR = Loading rate; TTP = Time-to-peak, WB = Weight-bearing; NWB = Non-weight-bearing.

Table 3
Downs and black scores for articles on mechanical effect of dorsiflexion restriction (≥21 = strong-quality, 14–20 = moderate-quality, 7–13 = limited quality, <7 = poor-quality).

Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	Total/28	Quality
Stiffler et al. [42]	1	1	1	1	2	1	1	0	1	1	1	0	n/a	0	0	1	1	1	1	1	1	1	0	n/a	1	1	1	21	Strong
Whitting et al. [46]	1	1	1	1	2	1	1	0	1	1	1	0	n/a	0	0	1	1	1	1	1	1	1	n/a	n/a	1	1	0	20	Moderate
Sigward et al. [44]	1	1	1	1	2	1	1	0	1	1	0	0	n/a	0	0	1	1	1	1	1	1	1	n/a	n/a	1	1	0	19	Moderate
Dill et al. [43]	1	1	1	1	2	1	1	0	1	1	0	0	n/a	0	0	1	1	1	1	1	1	1	0	n/a	1	1	0	19	Moderate
Malloy et al. [45]	1	1	1	1	2	1	0	0	1	1	0	0	n/a	0	0	1	1	0	1	1	1	1	n/a	n/a	1	1	0	17	Moderate
Fong et al. [26]	1	1	1	1	1	1	1	0	1	1	0	0	n/a	0	0	1	1	0	1	1	1	1	n/a	n/a	0	1	0	16	Moderate

Three studies investigated the effect of DF ROM on landing kinetics.[26,45,46] Fong et al.[26] found increased vGRF with DF restriction, while Whitting et al.[46] and Malloy et al.[45] found no effect of DF ROM on peak vGRF and Whitting et al.[46] found no effect on TTP vGRF.

4. Discussion

Although five of the six reviewed studies found a significant association between DF range of motion and landing mechanics, results for each measured variable were inconsistent. This inconsistency may be due in part to variations in landing tasks investigated in each study and to variability in landing strategy within and between participants.

Studies by Whitting et al.,[46] Fong et al.,[26] Dill et al.,[43] and Malloy et al.[45] found that peak DF angle on landing was unaffected by DF ROM. Although these results call into question the impact of DF range on landing kinematics, all studies except Dill et al.[43] found an association between DF range and other kinematic variables indicating that some degree of kinematic compensation was necessary. Fong et al.[26] and Malloy et al.[45] suggest that the lack of correlation is due to individual variations in landing technique and suggest that PF angle at initial contact (IC) may be adjusted in order to maintain adequate DF range in the presence of restricted mobility. Fong et al.[26] noted wide variation in IC ankle angle between participants ($SD = \pm 15^{\circ}$; $range = 60^{\circ}$) with some landing in a highly plantarflexed position and thus maximising available DF range while others landed in more dorsiflexion. This coordinative variability may have resulted in a non-significant correlation between mean values while on an individual level there were important changes.

Dill et al.[43] suggest that the lack of correlation between DF ROM and peak DF angle may have been due to their landing-task incorporating a jump immediately upon landing. They note that recoiling quickly in preparation for a second jump may reduce the amount of DF range utilised. This is supported by Arampatzis et al.[47] who found that as ground-contact time between landing and a subsequent jump decreased sagittal displacement at the ankle decreased. Malloy et al.[45] and Sigward et al. [44] also investigated a landing-task with a subsequent jump, potentially contributing to the non-significant correlation.

The majority of studies measured DF range in the open-chain position although, it has been suggested that this technique underestimates true maximal DF range during functional tasks.[48] Studies comparing DF ROM measurement in closed and open-chain positions have found significantly greater ranges during functional tests such as the standing lunge.[43,48] Underestimating the DF range available as a result of landing-forces may further explain the lack of correlation found between DF range and peak angle in these studies. However, Dill et al.[43] and Whitting et al.[46] measured DF range during a standing lunge and although the authors found that the standing lunge test did yield greater DF range than an open-chain measurement, neither study found a correlation between DF ROM and peak DF angle on landing. It is possible that the standing lunge may still underestimate the DF range available during landing as landing-forces may allow greater DF angle to be achieved.

Excessive ankle eversion (i.e. frontal plane ankle motion) has been linked to Achilles tendon injury[19,20] and is mechanically linked to other movements associated with lower-extremity injury risk such as pronation[49] and knee valgus.[50] Whitting et al.[46] found that participants with low DF exhibited greater ankle eversion angle at peak Achilles tendon force (calculated by dividing internal PF moment by Achilles tendon moment arm) and at peak DF angle during a unilateral drop-landing. The authors speculated that increased eversion at times of greatest Achilles load and triceps surae end-range will further increase Achilles loading and predispose to tendon injury.

Reduced knee sagittal excursion on landing may increase lower-extremity stiffness and increase injury risk.[24,25,27] Although greater hip stiffness has not been found to increase GRFs or LRs,[24] hip stiffness is a contributor to leg stiffness.[51] Hip stiffness may therefore have a bearing on injury risk as excessive leg stiffness is associated with greater GRFs and LRs and is speculated to increase injury-risk.[52] Reduced extended-knee DF ROM was found to be moderately correlated with sagittal hip and knee excursion[26] and with peak knee flexion angle,[45] suggesting that sagittal knee and hip displacement may have been restricted by reduced DF range. Although Fong et al.[26] found that the correlation between knee excursion and 90°-flexed-knee DF ROM was non-significant the CI suggests a small-to-moderate[53] correlation which may be important ($r = 0.33$, CI = 0.05–0.56). The limited size of these correlations may reflect movement variability as outlined by Dynamic Systems theory and the wide range of potential consequences of restricted joint range.[33,34] In contrast, Dill et al.[43] found no significant difference in knee sagittal plane excursion, peak angle, or IC angle between high and low DF groups. It is possible that the incorporation of a vertical jump on landing contributed to the non-significant result, in a similar manner to that described above regarding peak DF angle. Stiffler et al.[42] also found no difference in IC knee angle between the low-DF MKD group and high-DF control group, although the authors suggested this may have been due to the study not being sufficiently powered.

Increased knee frontal plane excursion has been implicated in a number of lower-extremity injuries[22,23,54] and has been proposed to occur in compensation for restricted knee and ankle sagittal excursion.[16–18,55] This theory is supported by the greater number of medial knee deviators in the low DF group reported by Stiffler et al.[42] and the correlations between DF ROM and peak knee valgus and knee frontal plane excursion found by Malloy et al.[45] and Sigward et al.[44] respectively. The authors of all three studies theorised that DF restriction directly restricted knee flexion by limiting forward progression of the tibia and suggest that participants compensated via increased medial knee deviation. This theory is supported by the reduced knee sagittal excursion found by Fong et al.[26] and increased ankle eversion found by Whitting et al.[46] However as noted previously, Stiffler et al.[42] found no reduction in peak knee flexion in the reduced DF group, possibly due to the study being underpowered for this variable. This study also grouped participants based on the presence or absence of medial knee deviation (MKD) during an overhead squat introducing the possibility that the MKD group might naturally prefer a valgus movement strategy during landing tasks. It is therefore possible that the knee valgus demonstrated by the MKD group was due to factors other than the lower DF range found in this group. It should also be noted that the correlations found by Malloy et al.[45] and Sigward et al.[44] were moderate and weak respectively, highlighting the large number of possible compensations for restricted joint range.

Conversely, although Fong et al.[26] found reduced knee sagittal excursion in association with restricted DF, the correlation with frontal plane knee excursion was non-significant. This study also found a negative correlation between DF ROM and GRFs suggesting that the lack of kinematic compensation for reduced sagittal range may have led to greater GRFs. Furthermore, low power and the CIs calculated for this variable suggest there may have been a small correlation with DF ROM.[53]

Greater GRFs and LRs have been implicated in the aetiology of a number of lower-extremity injuries.[27–32] Consistent with the theory that restricted DF range increases landing stiffness and conseqently increases lower-extremity loading, Fong et al.[26] found a small negative correlation between extended-knee DF ROM and peak vGRF while the flexed-knee DF correlation was non-significant. The authors contend that as the flexed-knee measurement eliminates the influence of gastrocnemius on ankle ROM, the extended-knee measurement is a more valid representation of true DF ROM. However, the relevance of this to landing is debateable as the mean peak knee angle during landing was $80.2 \pm 13.3°$ which will similarly reduce the influence of gastrocnemius on DF ROM. Although non-significant, a small-to-moderate correlation was found between flexed-knee DF ROM and vGRF. The authors noted that p-values approached significance suggesting a trend and that statistical power for these variables was insufficient. Furthermore, the CI for vGRF suggests a trivial-to-moderate correlation.[35]

In contrast, Whitting et al.[46] and Malloy et al.[45] found no effect of DF restriction on peak vGRF with Whitting et al.[46] also reporting no difference in TTP vGRF between high and low-DF groups. The kinematic results of both studies indicate compensatory frontal plane movement with Malloy et al.[45] finding greater peak knee abduction angle and Whitting et al.[46] reporting greater ankle eversion which is mechanically associated with knee valgus.[50] The difference in kinetic results between these studies and Fong et al.[26] may be therefore due to the lack of kinematic compensation made by participants in Fong et al.[26] leading to higher GRFs while participants in the other two studies[45,46] may have altered landing kinematics in order to attenuate forces. However, this is speculative as Whitting et al.[46] did not measure hip or knee kinematics.

Differences in landing tasks between studies make comparisons difficult and may contribute to inconsistent results. There is evidence that the mechanical demands of a landing task change with varying height, distance, goals (e.g. catching a ball), and landing style (e.g. unilateral vs bilateral), and result in participants utilising different landing strategies.[56,57] Caution must therefore be taken when comparing studies investigating different landing tasks. Although all studies investigated sagittal plane landings from a platform, Stiffler et al.,[42] Whitting et al.[46] and Fong et al.[26] investigated stop-landings, while all other studies included a subsequent jump immediately upon landing. This may contribute to the inconsistent results as the shorter ground-contact time and need to recoil and prepare for a second jump may cause reduced joint excursion and increased stiffness compared with stop-landings.[47] Furthermore, landings in Stiffler et al.,[42] Dill et al.,[43] and Fong et al.[26] were from a 30 cm height while Whitting et al.[46] investigated heights of 32 cm and 72 cm and Sigward et al.[44] investigated 42 cm. Greater forces associated with greater height may have resulted in participants adopting kinematic compensation strategies in the frontal plane to attenuate landing forces, while participants in Dill et al.[43] and Fong et al.[26] were not motivated to do so as forces were not sufficiently high. Malloy et al.[45] based platform height on the maximal jump height of each participant, potentially making results more consistent between participants as the challenge of the landing was tailored to height and physical ability, and also more sport-specific as it mimics the height a participant would land from when jumping during competition. Whitting et al.[46] was the only study to investigate unilateral landings. Attenuating forces through a single limb may have further contributed to in the kinematic results found this is study compared with those of Dill et al.[43] and Fong et al.[26] The landing-tasks in Stiffler et al.,[42] Dill et al.,[43] and Fong et al.[26] also involved horizontal jumps from a height rather than straight vertical drops that may have affected both kinematic and kinetic results.[58]

Individual landing strategies and interactions between mechanical variables also create difficulty in interpreting results. The ability to achieve a consistent endpoint with a variety of movement patterns is referred to as coordinative variability and the particular strategy used can vary widely both within and between individuals.[33,34] When the number of available mechanical degrees of freedom is constrained (e.g. reduction in DF ROM), the number of available movement patterns to complete a given task is reduced forcing individuals to select one of a number of alternative strategies.[33] Davids et al.[33] note that the analysis of pooled data means in the presence of coordinative variability can lead to non-significant results when mechanical changes are in fact occurring and may contribute to inconsistencies between studies as different groups of participants prefer different strategies. It is possible within each study that some participants did not compensate kinematically and experienced greater GRFs or LRs, while others increased their IC PF angle or altered knee or hip kinematics to attenuate forces. The number of possible compensations could result in too few participants utilising each one for a mean difference across participants to be found or in participants adjusting a combination of parameters to a small degree again resulting in no significant mean change in any single parameter. Unfortunately, the studies reviewed investigated only a few mechanical variables making it difficult to identify mechanical patterns and reasons for conflicting results. Further research is required in this area.

The difficulty with analysing mechanics in the presence of coordinative variability highlights the need for a measure which can identify when a mechanical pattern changes allowing for conventional statistical analysis of results. Although no studies were found which directly investigated the effect of DF ROM on lower-extremity stiffness, the studies described support the theory that lower-extremity stiffness may be altered in compensation for DF restriction. Furthermore, as stiffness captures a number of mechanical variables into a single measure it may have some utility in describing changes in movement patterns allowing for traditional statistical analysis of a highly individual and variable task.[59] Further research is needed to investigate the effect of DF ROM on landing stiffness and the potential for stiffness measures to identify changes in movement patterns. Furthermore, none of the landing-tasks investigated in the reviewed studies were sports-specific, limiting their applicability to injuries incurred during sporting tasks. Biomechanical studies that include goal-directed, sport-specific tasks are needed.

5. Conclusion

Restricted DF ROM may alter landing mechanics in a manner that predisposes athletes to injury. There is some support for increased frontal plane ankle motion, knee valgus, and frontal plane excursion, reduced knee and hip sagittal excursion, and increased peak vGRF, but results are inconsistent between studies. DF restriction does not appear to reduce peak DF angle on landing or TTP vGRF. Further studies are needed to investigate the effect of DF restriction on mechanical patterns rather than on individual mechanical variables, and to investigate sport-specific landing tasks.

Practical implications

- Reduced ankle flexibility may alter movement patterns during landing and increase landing forces.
- Altered movement patterns and greater forces may predispose athletes to injury.
- Screening athletes for ankle flexibility may assist in identifying those at an increased risk of injury.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jsams.2015.06.006

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