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Literature Review

The association of ankle dorsiflexion and dynamic knee valgus: A systematic review and meta-analysis

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ABSTRACT

Objective: The objective of this systematic review was to evaluate the association between ankle dorsiflexion (ADF) and dynamic knee valgus (DKV).
Methods: Electronic searches were conducted in MEDLINE, EMBASE, CINAHL and SPORTDiscus. A modified Downs and Black checklist was used for quality assessment and meta-analysis was performed to compare standardised mean differences (SMD) of ADF.
Results: Seventeen studies met the inclusion criteria. Meta-analysis showed that reduced ADF is associated with participants presenting with DKV compared to controls (SMD -0.65, 95% CI -0.88 to -0.41). Subgroup analysis showed consistent results regarding different forms of ADF measurement; restriction in ADF measured in weight-bearing position (SMD -1.25, 95% CI -2.24 to -0.25), non-weight-bearing with knee flexed (SMD -0.56, 95% CI -0.97 to -0.16) or non-weight-bearing with knee extended (SMD -0.54, 95% CI -0.80 to -0.28) was significantly associated with DKV.
Conclusion: The meta-analysis results provide evidence that reduced ADF is correlated with DKV. The assessment of ADF in the clinical setting is important, as it may be related to harmful movement patterns of the lower limbs.

1. Introduction

Reduced ankle dorsiflexion (ADF) has been reported as a risk factor for some conditions, such as patellar tendinopathy (Backman & Danielson, 2011; Malliaras, Cook, & Kent, 2006), Achilles tendinopathy (Rabin, Kozol, & Finestone, 2014), chronic ankle instability (Hoch et al., 2012), metatarsal stress fractures (Chuckpaiwong, Cook, Pietrobon, & Nunley, 2007), plantar fasciitis (Kaufman, Brodine, Shaffer, Johnson, & Cullison, 1999) and anterior knee pain (Taunton & Wilkinson, 2001; Witvrouw, Lysens, Bellemans, Cambier, & Vanderstraeten, 2000).

A modified lower extremity movement pattern has been reported as a risk factor for patellofemoral pain syndrome (PFP) (Powers, 2003; Rabin, Kozol, Moran, et al., 2014) and noncontact anterior cruciate ligament injuries (Hewett & Myer, 2011; Hewett, Myer, & Ford, 2006; Hewett et al., 2005). This pattern is composed of a combination of excessive femoral adduction, internal rotation, tibial internal rotation and the medial displacement of the knee and has been defined as dynamic knee valgus (DKV) (Hewett et al., 2005). Limited DF ROM has been reported as a possible contributor to excessive knee valgus (Fong, Blackburn, Norcross, McGrath, & Padua, 2011; Macrum, Bell, Boling, Lewek, & Padua, 2012; Sigward, Ota, & Powers, 2008; Stiffler, Pennuto, Smith, Olson, & Bell, 2015) and has been linked to harmful landing mechanics (Mason-Mackay, Whatman, & Reid, 2015).

It is hypothesized that deficits in ADF may occur due to the decreased extensibility of the gastrocnemius/soleus complex and restricted posterior talar glide on the tibia (Dill, Begalle, Frank, Zinder, & Padua, 2014; Macrum et al., 2012; Malloy, Morgan, Meinerz, Geiser, & Kipp, 2015; Mauntel et al., 2013). As subjects perform activities that lower the body's increasing knee flexion, this requires the tibia to move forward over the foot, thus increasing dorsiflexion. With restricted ADF, subjects may try to compensate for this lack of range in the sagittal plane with movement in the frontal or transverse plane throughout the kinetic chain (Bell-Jenje et al., 2016; Dill et al., 2014; Macrum et al., 2012; Mauntel et al., 2013; Rabin & Kozol, 2010; Rabin, Kozol, Moran,

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et al., 2014; Sigward et al., 2008; Wyndow et al., 2016). This compensation may come from the pronation of the foot (Dill et al., 2014; Lack et al., 2014), the internal rotation of the tibia (Dill et al., 2014), internal hip rotation and adduction (Bell-Jenje et al., 2016; Wyndow et al., 2016) or pelvic drop (Rabin & Kozol, 2010; Rabin, Kozol, Moran, et al., 2014), thus creating the DKV (Dill et al., 2014; Macrum et al., 2012; Malloy et al., 2015; Mauntel et al., 2013; Rabin & Kozol, 2010; Rabin, Kozol, Moran, et al., 2014; Sigward et al., 2008; Wyndow et al., 2016).

While several studies have been conducted to evaluate the association of ADF in DKV, the contrasting findings across studies hinder the ability to make firm conclusions, and thus a quantitative synthesis of published data is necessary. Therefore, the purpose of this study was to review and meta-analyse the association of ADF in the dynamic valgus of the knee.

2. Methods

This review was conducted according to the Preferred Reporting Items for Systematic Reviews (PRISMA) guidelines (Liberati et al., 2009; Moher, Liberati, Tetzlaff, & Altman, 2009) and Meta-analysis of Observational Studies in Epidemiology (MOOSE) (Stroup et al., 2000). The study protocol was pre-registered (PROSPERO 2016: CRD42016032820) and based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis Protocols (PRISMA-P) statement (Moher et al., 2015).

2.1. Search strategy

Two researchers independently performed a search in four medical databases—MEDLINE, CINAHL, SPORTDiscus and EMBASE—from database inception until September 2016. The search strategy was composed of medical subject headings (MeSH) and free text search terms, synonyms and combinations to capture all of the related papers. Three concepts were combined for the search in databases using the Boolean operator 'AND': (1) 'knee', 'knee angle', 'knee valgus', 'dynamic knee valgus', 'knee kinematics', 'knee alignment', 'knee frontal plane', 'knee movement', 'dynamic valgus', 'hip', 'hip adduction'; (2) 'ankle', 'ankle joint', 'ankle movement', 'ankle dorsiflexion', 'ankle range of motion', 'ankle mobility', 'lunge test'; and (3) 'forward step down test', 'drop vertical jump test', 'single leg squat test', 'step down test', 'single limb squat test', 'drop jump screening', 'movement quality', 'range of movement". The terms within these concepts were combined with the Boolean operator 'OR'. The reference lists of the included manuscripts and personal files of the authors were checked to identify related studies.

2.2. Study selection

After the completion of the database searches, titles and abstracts identified using the search strategy were downloaded into EndNote X7.1 (Thomson Reuters, California, USA). Duplicates were deleted, and two independent reviewers screened all abstracts for inclusion. A third reviewer was available to contribute to any disagreement if necessary. Full texts were obtained when necessary. A flow chart of the search and study selection is provided in Fig. 1.

2.3. Inclusion and exclusion criteria

To be included, studies had to report the association between at least one outcome measure for ADF and one for the kinematics of the knee and/or hip in the frontal plane and/or hip in the transverse plane in any dynamic task. Healthy men and women of all ages or those with any condition in the knee—symptomatic or asymptomatic— were considered for the review. No restrictions over language and publication date were applied. Only studies published as full-text articles were included. Conference proceedings, poster presentations, reviews, case studies, editorials, letters and abstract-only texts were not considered for this review.

2.4. Data extraction

Two reviewers extracted the information from each of the selected studies. A synthesis of the data of the included studies is provided in Table 1. The information was organised around the authors, publication dates, sample sizes, mean ages, levels of activity, conditions, study designs, group allocations, outcome measurement methods, subject tasks and results.

2.5. Quality assessment

Due to the lack of established assessment tools for non-interventional studies, the assessment of the articles in this review was performed using a customised scale from the checklist of interventional studies that Downs and Black designed (Downs & Black, 1998). The modification involved the selection of items to better reflect the methodological considerations of observational studies, as they were expected to be the majority of the included studies, so that resulting in a scale of 10 items (Table 2). The items were related to: a description of the hypothesis/objective, the main outcomes in the Introduction or Methods sections, the participants' characteristics, the main findings, estimates of random variability, actual probability values, a representative sample of subjects, appropriate statistical tests, and valid and reliable outcome measures. Some authors have used this method (Cashman, 2012; Cronstrom, Creaby, Nae, & Ageberg, 2016; Giles, Webster, McClelland, & Cook, 2013; Ranger, Wong, Cook, & Gaida, 2015), but its efficacy is not established. Two authors discussed the methodological quality assessment of the studies, and a third author resolved any disagreements.

2.6. Meta-analysis

A meta-analysis was performed using RevMan (V.5.3, The Cochrane Collaboration, Copenhagen, Denmark). A random-effects model was used due to calculate the standardised mean difference (SMD) after the extraction of sample sizes, means and standard deviations from the articles. Continuous data were weighed using the inverse variance method. Means and standard deviations were used to compare groups. In studies with group allocations dichotomised by quality-of-knee/hip kinematics, the group with a lower quality of knee/hip kinematics outcomes was considered the DKV group, and the one with higher quality was considered the control group to simplify the data analysis, when the original authors had not already defined this division. In studies with group allocations dichotomised by the amount of ADF, the groups were divided into a lower or higher ADF group accordingly. Heterogeneity was assessed using the I^2 statistic, which describes true variation across studies as a percentage, where values around 25% indicate low heterogeneity, 50% medium and 75% high heterogeneity among studies (Higgins, Thompson, Deeks, & Altman, 2003).

In studies with group allocations by quality-of-knee/hip kinematics, the outcome for ADF was explored with meta-analyses, and data from seven studies were included, as they reported the mean and standard deviation for the measures of ADF (D. R. Bell, Padua, & Clark, 2008; David R. Bell et al., 2012; Mauntel et al., 2013; Park, Cynn, & Choung, 2013; Rabin & Kozol, 2010; Rabin, Kozol, Moran, et al., 2014; Stiffler et al., 2015). As the ADF measurement method

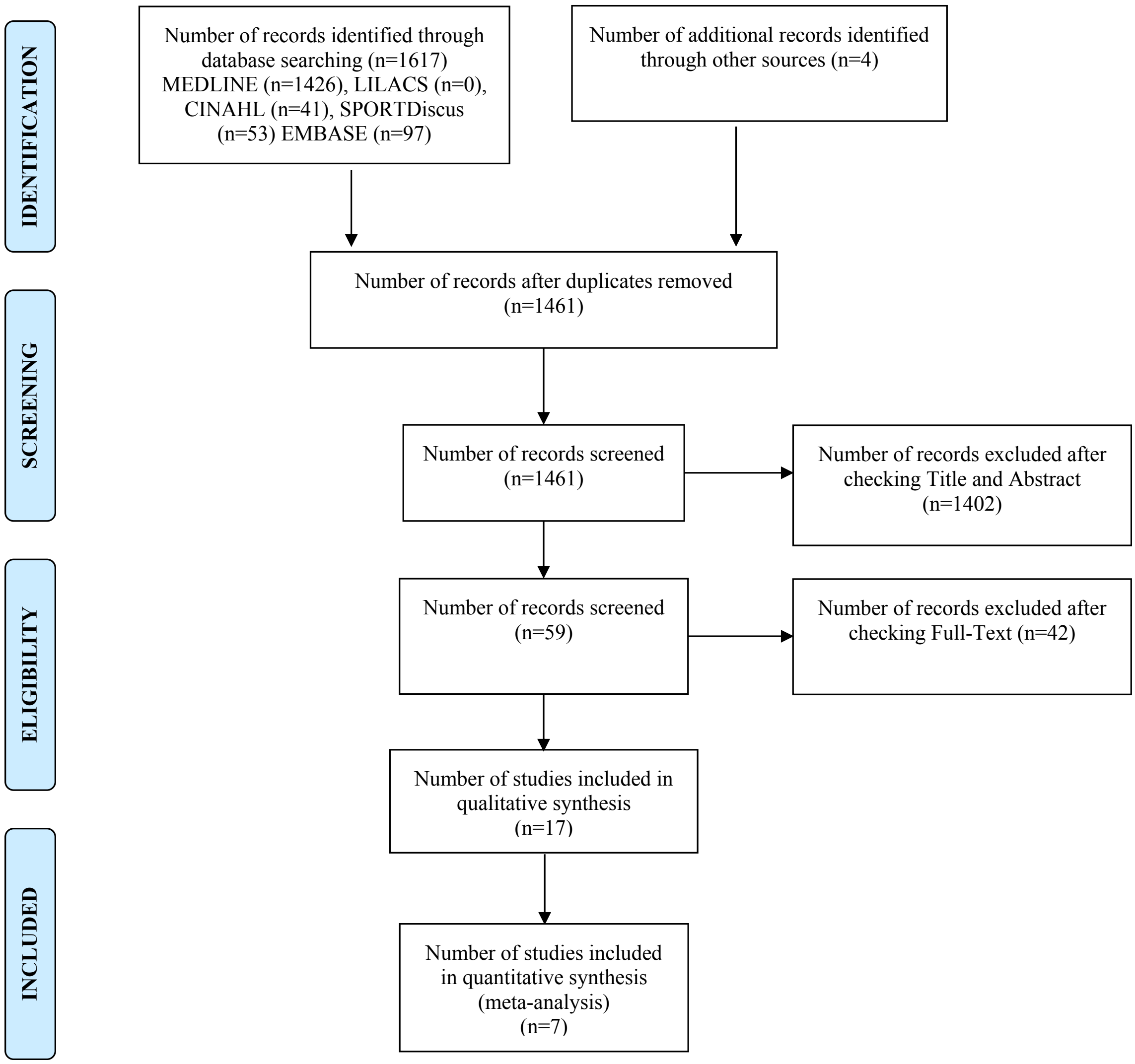

Fig. 1. PRISMA (*Preferred Reporting Items for Systematic Reviews and Meta-Analyses*) flow chart of electronic search.

varied among studies, subgroup analyses were performed with the studies that used the same form of measurement. Six studies verified ADF in an NWB position with the knee flexed, six studies in an NWB with the knee extended, and two studies in a WB lunge position (Fig. 2). Studies using within-subject designs or allocating groups by the amount of ADF were not considered for meta-analyses because this was not suitable or was deemed insufficient for meaningful comparison.

3. Results

3.1. Characteristics of included studies

The electronic searches resulted in the identification of 1617 articles, of which 13 were included in the final review (D. R. Bell et al., 2008; David R. Bell et al., 2012; Bell-Jenje et al., 2016; Dill et al., 2014; Fong et al., 2011; Macrum et al., 2012; Malloy et al., 2015; Mauntel et al., 2013; Ota, Ueda, Aimoto, Suzuki, & Sigward, 2014; Rabin & Kozol, 2010; Rabin, Kozol, Moran, et al., 2014; Rabin, Kozol, Spitzer, & Finestone, 2014; Sigward et al., 2008), and checking the references of the included articles led to the identification of another four papers (Park et al., 2013; Rabin, Portnoy, & Kozol, 2016b; Stiffler et al., 2015; Wyndow et al., 2016). Characteristics of included studies are summarised in Table 1.

3.2. Methodological quality assessment

The summary of the items retained from the original instrument and whether the studies met the criteria is presented in Table 2. The studies ranged from 7 out of 10 to 9 out of 10; therefore, the methodological quality of the studies included was good, which may indicate that strong conclusions can be draw with respect to methodology. Malloy et al. (2015), Mauntel et al. (2013) and Rabin, Kozol, and Moran, et al. (2014) achieved the highest scores. All of the studies met the criteria of reporting the objective, the main outcomes to be assessed, the participant characteristics, the main findings and the random variability of the data. The statistical tests used were considered appropriate, and the outcome measures used were valid and reliable for all studies. No study could meet item number 12 because the studies did not provide sufficient information if the sample was representative of the entire population.

3.3. Overall association between DF ROM and DKV

Seventeen articles that assessed the relationship between ADF and DKV were retrieved in this review. In each article, the results

Table 1
Characteristics of included studies.

Author, year	Subject characteristics – Sample by sex (age mean, activity level - condition)	Study design, group allocation	Ankle dorsiflexion ROM measurement method	Dynamic knee valgus measurement method	Subject tasks	Results
Bell et al., 2008	7M, 30F (20.7y, free of LL injury)	Case-control, control = 19, MKD = 18	NWB = knee flexed and extended – goniometer - degrees	MKD - medial movement of the midpoint of patella passing the great toe	Double leg squat	MKD group (15.3 ± 4.3) tended to have decreased ankle DF ROM (knee flexed) compared to controls (19.5 ± 8.4), p = 0.06. No significant differences for MKD group (8.5 ± 4.2) compared to controls (10.7 ± 6.7) in ankle DF ROM with knee straight, p = 0.23
Bell et al., 2012	9M, 22F (23.1y, free of LL injury)	Cross-sectional, control = 17, MKD = 14	NWB = knee straight and flexed – goniometer - degrees	MKD – medial movement of patella passing the great toe	Double leg squat	MKD group had less DF ROM (13.4 ± 7.8) compared to controls (17.9 ± 7.9) in knee straight position (p < 0.001). No significant difference between MKD (19.8 ± 8.4) and controls (19.8 ± 8.4) in knee flexed position.
Bell-Jenje et al., 2016	30F (20.4y, free of LL injuries)	Cross-sectional, ≤17° DF ROM = 10, >17° DF ROM = 20	3D kinematics – during LSD and EHSD- degrees	3D kinematics – hip adduction – hip internal rotation degrees	LSD and EHSD	Subjects in ≤17° DF ROM group had more hip adduction (18.3 ± 5.9) than subjects in >17° group (11.8 ± 4.1) in LSD. (p = 0.001, ES = 1.2). Subjects in ≤17° DF ROM had significantly more hip adduction (13.8 ± 5.1) than >17° group (10.2 ± 4.7). No statistical difference in hip internal rotation between groups in LSD or EHSD.
Dill et al., 2014	20M, 20F (20.3y, 19.8y, physically active)	Cross-sectional, normal DF ROM = 20, limited DF ROM = 20	NWB = knee straight – goniometer - degrees WB = lunge test – inclinometer	3D kinematics – knee valgus - degrees	Overhead squat, Single leg squat, Jumping landing	NWB=No significant differences. WB = greater knee varus in normal group (13.60 ± 10.28) than limited group (8.10 ± 6.32) in SLS (mean difference, 5.50°, F1,39 = 4.16; P = 0.048). No differences in JL and OHS.
Fong et al., 2011	17M, 18F (20.5y, physically active)	Cross-sectional, within-subject design	NWB = knee flexed and straight – goniometer - degrees	3D kinematics – knee valgus - degrees	Double leg drop landing	Knee valgus and both knee flexed (r = −0.330, P = 0.053) and extended (r = −0.290, P = 0.091) DF ROM had no significant correlation.
Macrum et al., 2012	14M, 15F (18-30y, physically active)	Cross-sectional, All subjects were allocated to wedge group and no wedge group	Pre-established ROM without and with wedge of 12°	3D kinematics – knee valgus – hip adduction and internal rotation - degrees and quantitative MKD – meters	Double leg squat without and with wedge of 12°	Knee valgus (NW = −3.4 ± 3.2, W = −4.1 ± 3.3, P = 0.02, *F*28 = 6.45, ES = 0.21) and MKD (NW 0.0007 ± 0.002 m, W 0.027 ± 0.014 m; *F*28 = 31.79, *P* < 0.01, effect size = 2.92) increased in wedge condition. No significant differences in hip variables between conditions
Malloy et al., 2015	23F (18-21y, healthy soccer players free of LL injuries)	Cross-sectional, within-subject design	NWB = knee straight – goniometer - degrees	3D kinematics – peak knee abduction angle - degrees	Double leg drop vertical jump – landing phase	Significant positive correlations were found between ankle dorsiflexion flexibility and peak knee abduction angle (*r* = 0.355, *p* = 0.048) during landing.
Mauntel et al., 2013	20M, 20 F (18-35y, physically active)	Cross-sectional, control group = 20, MKD group = 20	NWB = knee flexed and straight – goniometer - degrees	MKD - medial movement of the midpoint of patella passing the great toe	Single leg squat	MKD group displayed significantly less dorsiflexion ROM with the knee extended (5.5 ± 5.4 vs. 8.8 ± 4.7, ES = 0.65, Power = 0.515) and flexed (9.5 ± 6.2 vs. 14.2 ± 7.3, ES = 0.70, Power = 0.575) in comparison to the control group.
Ota et al., 2014	15M, 15F (21.7y, free of LL injuries)	Cross-sectional, All subjects were allocated to Free ROM, 10° DF, 0°, 10° PF groups	Pre-established ROM with ankle brace (Free ROM, 10° DF,0°, 10° PF)	3D kinematics – knee varus angle - degrees	Gait (Terminal stance phase)	Knee varus angle = Free, 1.0 (4.0); 10° DF, 1.5 (4.0); 0°, 2.0 (4.4); 10° PF, 2.9 (4.2). p < 0.01 at 0° and 10° PF.
Park et al., 2013	26F (22.7y, asymptomatic, free of LL injuries, no strength training or stretching 3 months prior to study)	Cross-sectional, FSD quality – Good = 11, Moderate = 14, Poor = 1	NWB = knee straight – goniometer- degrees	FSD quality	FSD	No significant difference was found for different qualities of movement in the FSD and the ankle dorsiflexion ROM. Good (6.6 ± 4.1), Moderate (5.3 ± 2.7), Poor (6.0) p = 0.374
Rabin & Kozol, 2010	29F (24.3y, free of LL pain or injury)	Cross-sectional, LSD quality – Good = 9, Moderate = 20	WB = lunge test with inclinometer NWB = knee flexed and straight – goniometer - degrees	LSD quality	LSD	WB = decreased ankle DF ROM in moderate (46.4 ± 4.8) compared to good LSD (55.8 ± 5.3) (p < 0.01). NWB = decreased ankle DF ROM in knee bent and straight in moderate LSD (20.9 ± 4.6, 10.8 ± 3.0) compared to good LSD (28.1 ± 5.2, 13.3 ± 4.3) (p < 0.05)
Rabin, Kozol, & Moran	39M, 40F (20.8y, 19.9y, soldiers with PFP)	Cross-sectional, LSD quality – Good = 30, Moderate = 49	WB = lunge test with inclinometer NWB = knee flexed –	LSD quality	LSD	NWB= Moderate group presented reduced DF ROM in both WB (49.2 ± 5.7) and NWB (22.4 ± 5.6) compared to Good

Table 1 (*continued*)

Author, year	Subject characteristics – Sample by sex (age mean, activity level - condition)	Study design, group allocation	Ankle dorsiflexion ROM measurement method	Dynamic knee valgus measurement method	Subject tasks	Results
et al, 2014			goniometer- degrees			group in WB (53.9 ± 5.7) (p < 0.01) and NWB (27.7 ± 4.0) (p = 0.01)
Rabin, Kozol, & Spitzer et al, 2014	55M (19.7, military recruits, free of LL injury)	Cross-sectional, LSD quality in DS and NDS – DS: Good = 33, Moderate = 20; NDS: Good = 26, Moderate = 28	Tested in DS and NDS. WB = lunge test with inclinometer NWB = knee flexed – goniometer – degrees.	LSD quality	LSD	WB = Ankle DF ROM greater in good quality LSD (52.7) than moderate LSD (48.3) in dominant side (p = 0.01, ES = 0.72, r = −0.44) and no difference was found in non-dominant side (p = 0.10, ES = 0.45, r = −0.31) NWB= Ankle DF ROM greater in good quality LSD (29.6) than moderate (25.7) in DS (p = 0.02, ES = 0.68, r = −0.43) and NDS good (29.9) and NDS moderate (26.1) alike (p = 0.03, ES = 0.63, r = −0.37)
Rabin et al., 2016b	10M, 20F (25.8y, free of LL pain or surgery 12 months prior to participation)	Cross-sectional, WB and NWB High DF ROM = 15, WB and NWB Low DF ROM = 15	WB = lunge test with inclinometer NWB = knee flexed – goniometer - degrees	3D kinematics – hip adduction and internal rotation - degrees	LSD	WB = significant difference in hip adduction between low DF ROM (17.3 ± 3.9) and high DF ROM (13.9 ± 3.7) (p = 0.02). No difference in hip internal rotation between low DF ROM (0.37 ± 8.9) and high DF ROM (−0.94 ± 6.6) (p = 0.75). NWB = significant difference in hip adduction between low DF ROM (18 ± 3.2) and high DF ROM (13.3 ± 4.0) (p < 0.01). No difference in hip internal rotation between low DF ROM (0.1 ± 7.4) and high DF ROM (−0.6 ± 8.3) (p = 0.98).
Sigward et al., 2008	39F (15.5y, soccer players free of LL injuries)	Cross-sectional, within-subject design	NWB = knee flexed – goniometer - degrees	3D kinematics – frontal plane knee excursion (difference between knee markers) - centimeters	Double leg drop landing	DF ROM (−3.5 ± 3.5) negatively correlated with knee excursion (r = −0.27, p = 0.05)
Stiffler et al., 2015	28M, 69F (20y, healthy recreationally active college-aged individuals)	Cross-sectional, control = 70, MKD = 27	NWB = passive and active knee straight and flexed – goniometer - degrees	MKD – excessive frontal plane knee motion medial to great toe	Overhead squat	Significant difference in DF ROM between control (10.82 ± 6.30) and MKD (8.20 ± 7.36) in passive knee straight position (p = 0.045). No difference between control (14.67 ± 7.82) and MKD (14.38 ± 8.94) in passive knee flexed (p = 0.328). Significant difference in DF ROM between control (4.10 ± 6.05) and MKD (0.52 ± 6.25) in active knee straight position (p = 0.017). No difference between control (8.95 ± 7.03) and MKD (7.03 ± 7.35) in active knee flexed (p = 0.070).
Wyndow et al., 2016	11M, 19F (22y, asymptomatic, free of LL injury or pain)	Cross- Sectional, within-subject design	WB = lunge test with tape measure using distance to wall technique	2D kinematics – knee valgus/varus angle - degrees	Single leg squat	Ankle DF ROM (10.7 ± 3.4) associated with greater valgus (4 ± 7) (β = 0.61, p = 0.008, OR = 1.8, 95% CI 1.1 to 2.3)

Abbreviations: ROM – range of motion; F – female; M – male; LL – lower limb; LSD – lateral step down; EHSD – elevated heel step down; FSD – forward step down; WB – weight bearing; NWB – non-weight bearing; DF – dorsiflexion; PF – plantar flexion; PFP – patellofemoral pain; MKD – medial knee displacement; SLS – single leg squat; JL – jumping landing; DS – dominant side; NDS – non-dominant side; 2D – two-dimensional; 3D – three-dimensional.

were reported separately depending on the number of associations between the forms of measurement of ADF and knee/hip kinematics, and the number of tasks that the subject performed. In this case, we treated each association as an independent result. Then, of the 17 articles included, 44 associations between ADF and knee/hip kinematics were analysed. When observing these findings by task, five associations were assessed during double leg squats and three found a relation, while 15 were assessed during LSD and 11 found a relation, six were evaluated during overhead squats and two found a relation, five were evaluated during single leg squats and three found a correlation, six were assessed during drop landings and two found a relation, whereas FSD and gait were assessed once each and no association was found in any of them. In regard to findings by ADF measure, 13 associations were assessed with NWB with knee flexed and seven showed relationship with DKV, while 10 were assessed with NWB with knee extended and 7 presented relationship, and 10 were assessed with WB position and 5 showed correlation. Overall, these associations showed the relationship of ADF with DKV to be highly divergent so that impeding qualitative synthesis from drawing any conclusive assumptions.

3.4. Subgroup analysis and pooled results

Studies reporting ADF in the controls and DKV groups were subgrouped according to whether they measured ADF in an NWB position with the knee flexed (n = 6 studies), an NWB position with the knee extended (n = 6 studies) and a WB lunge position (n = 2 studies). In regards to the tasks performed, these studies assessed the participants during the double-leg squat (D. R. Bell et al., 2008; David R. Bell et al., 2012), single-leg squat (Mauntel et al., 2013), lateral step-down (Rabin & Kozol, 2010; Rabin, Kozol, Moran, et al., 2014), overhead squat (Stiffler et al., 2015) or forward step-down (Park et al., 2013). A forest plot was provided to illustrate the comparison between the SMDs of the studies and the pooled

Table 2
Description of methodological assessment of included studies according to modified Downs and Black checklist.

Author, year	Item number										Total
	1	2	3	6	7	10	11	12	18	20	
Bell et al., 2008	1	1	1	1	1	1	0	0	1	1	8
Bell et al., 2012	1	1	1	1	1	1	0	0	1	1	8
Bell-Jenje et al., 2016	1	1	1	1	1	1	0	0	1	1	8
Dill et al., 2014	1	1	1	1	1	1	0	0	1	1	8
Fong et al., 2011	1	1	1	1	1	1	0	0	1	1	8
Macrum et al., 2012	1	1	1	1	1	1	0	0	1	1	8
Malloy et al., 2015	1	1	1	1	1	1	1	0	1	1	9
Mauntel et al., 2013	1	1	1	1	1	1	1	0	1	1	9
Ota et al., 2014	1	1	1	1	1	0	0	0	1	1	7
Park et al., 2013	1	1	1	1	1	1	0	0	1	1	8
Rabin & Kozol, 2010	1	1	1	1	1	0	0	0	1	1	7
Rabin, Kozol, & Moran et al., 2014	1	1	1	1	1	1	1	0	1	1	9
Rabin, Kozol, & Spitzer et al., 2014	1	1	1	1	1	1	0	0	1	1	8
Rabin et al., 2016a, 2016b	1	1	1	1	1	1	0	0	1	1	8
Sigward et al., 2008	1	1	1	1	1	1	0	0	1	1	8
Stiffler et al., 2015	1	1	1	1	1	1	0	0	1	1	8
Wyndow et al., 2016	1	1	1	1	1	1	0	0	1	1	8

Items: 1 = hypothesis/aim/objective described; 2 = main outcomes in Introduction or Methods; 3 = characteristics of participants described; 6 = main findings described; 7 = estimates of random variability provided; 10 = actual probability values reported; 11 = subjects asked to participate were representative; 12 = subjects prepared to participate were representative; 18 = statistical tests for main outcomes were appropriate; 20 = main outcome measures were valid and reliable. Criteria: 1 = criterion met; 0 = criterion not met.

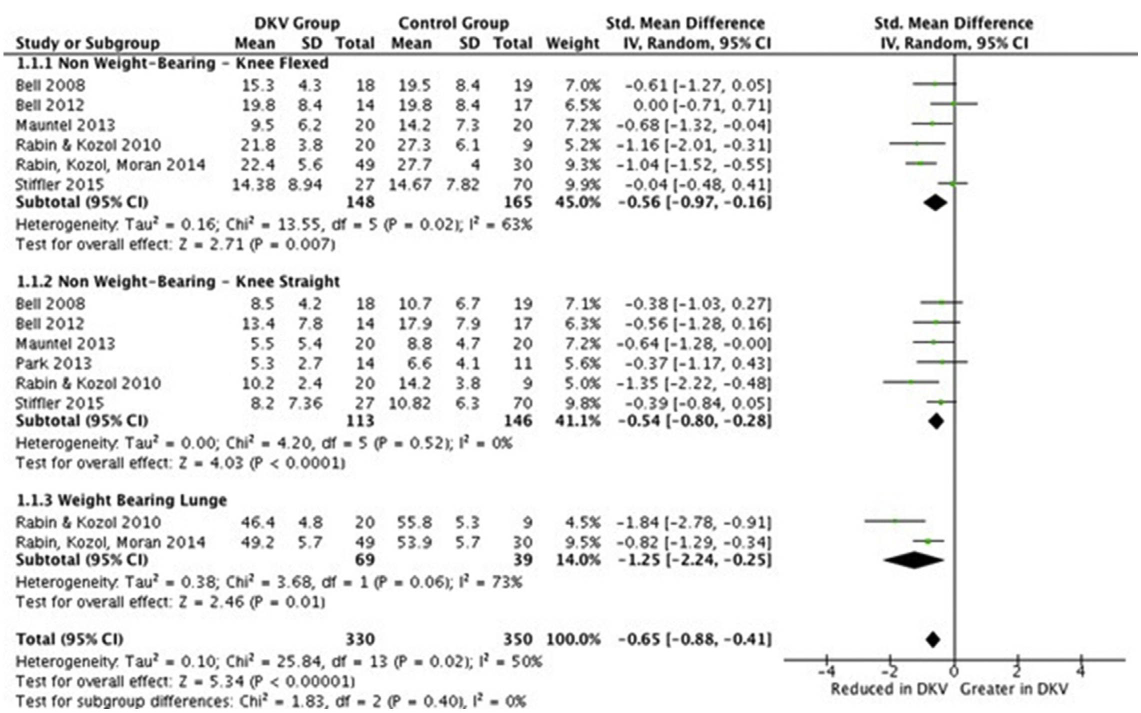

Fig. 2. Forest plot of DF ROM outcomes with subgroup analyses of different forms of measurement.

analysis between subgroups (Fig. 2). The different forms of measurement of ADF of the included studies contributed to the rationale for splitting the data into subgroups and including data from the same study in more than one subgroup. A pooled analysis of all subgroups showed statistically significant lower values of ADF in the DKV groups (n = 330) compared to the controls (n = 350) (SMD -0.65, 95% CI -0.88 to -0.41). Medium heterogeneity was found in the pooled analysis of all subgroups ($I^2 = 50\%$). Analysing the pooled results by subgroup, minimal heterogeneity was found in subgroup NWB – Knee Straight so the pooled analysis was deemed valid. The pooled analysis showed significantly lower values for ADF in the DKV groups compared to the controls (SMD -0.54, 95% CI -0.80 to -0.28, subgroup NWB – Knee Straight). The pooled analysis of subgroups NWB – Knee Flexed and WB Lunge also showed significantly lower values for ADF in the DKV groups compared to the control groups (SMD -0.56, 95% CI -0.97 to -0.16, subgroup NWB– Knee Flexed) (SMD -1.25, 95% CI -2.24 to -0.25, subgroup WB Lunge), but in contrast to subgroup NWB – Knee Straight they had medium to high levels of within-group heterogeneity ($I^2 = 73\%$), and the findings might be inconsistent.

4. Discussion

This review provides compelling evidence for an association between reduced ADF and DKV. The meta-analyses for ADF demonstrated that a reduced range of motion was present in the individuals presenting with DKV when compared to the controls. This result was consistent regardless of whether ADF was measured in an NWB position with the knee flexed, straight or in a WB position. It is already known that ADF measurement values differ from active to passive forms as well as in different knee positions (Krause, Cloud, Forster, Schrank, & Hollman, 2011), but how these variations can be associated with DKV is still unclear.

In the analysis of the studies assessing ADF with the knee flexed, the pooled results showed an association of reduced ADF and DKV. In contrast, the studies by Bell et al. (2008) and Stiffler et al. (2015) did not show a statistical difference for ADF between the DKV and control groups. However, it is reasonable to notice that the absolute mean values for the DKV group were lower than those for the control group, and this might be clinically important and requires further investigation. Although they presented statistically significant differences, the studies showing an association of reduced ADF and DKV must be carefully appraised. First, these studies investigated this association in different tasks—single-leg squats (Mauntel et al., 2013) and step-down maneuvers (Rabin & Kozol, 2010; Rabin, Kozol, Moran, et al., 2014). Although these tasks are considered reliable (Crossley, Zhang, Schache, Bryant, & Cowan, 2011; Piva et al., 2006) and valid (Lewis, Foch, Luko, Loverro, & Khuu, 2015) in assessing movement patterns at the trunk and lower limb, some differences may affect the participant's behavior during the task. According to the study by Lewis et al. (2015), single-leg squats require the pelvis to be in a more hiked and backward rotation position, as the goal of the task is to keep the non-stance heel off the ground. In contrast, step-downs present more of a pelvic drop and forward rotation at the non-stance leg, as the goal is to touch the ground with the non-stance leg. The movement pattern regarding hip and knee flexion, hip adduction, knee abduction and internal rotation appear to be similar in both tasks. ADF was not investigated, and it is still unclear how this variable presents in these tasks. Second, the study by Rabin and Kozol (2010) was done with women. It is known that women are more susceptible to presenting with DKV than their male counterparts (Ford, Myer, Toms, & Hewett, 2005). Last, the study by Rabin et al. (2014) was conducted with patients with PFP, as it is reported that individuals with this condition present with a faulty movement pattern and DKV. Research has also shown that reduced ADF is a risk factor for PFP (Witvrouw et al., 2000), so it is challenging to know for certain the relationships of cause and effect among these variables.

In the analysis of the studies assessing NWB ADF with the knee extended, the pooled results also demonstrated a significant association of limited ADF and DKV. The studies by Bell et al. (2008), Bell et al. (2012), Park et al. (2013) and Stiffler et al. (2015) presented no significant differences between ADF and DKV. This may be due to differences in tasks, as the study by Bell et al. (2008), Bell et al. (2012), and Stiffler et al. (2015) used double-leg squat tasks, whereas the studies with significant differences (Macrum et al., 2012; Rabin & Kozol, 2010) used single-leg tasks. The reason why the results of the study by Park et al. (2013) did not reach statistically significant differences may be due the fact that the subjects belonged to the department of physical therapy of the university where the study was conducted, as it may constitute a subject bias if we consider the fact that the subjects may have had knowledge about movement patterns.

Some studies have used sophisticated three-dimensional (3-D) and two-dimensional (2-D) motion analysis to evaluate knee/hip kinematics, whereas other studies have used more feasible and functional clinical tools using subjective visual observation. Another limitation of our review is that we considered visual observation, 2-D and 3-D kinematics as representing the same magnitude of DKV, as it is reported that 2-D knee frontal plane mechanics are only moderately associated with 3-D kinematics of the lower extremity in single-leg squats (Willson & Davis, 2008), even though the comparison between visual observation and 3-D kinematics has been shown to be better correlated (Rabin, Portnoy, & Kozol, 2016a).

Of the four studies that analyzed the outcomes during landing tasks, two studies (Dill et al., 2014; Fong et al., 2011) demonstrated an association of reduced ADF with DKV, and two showed no relation between these variables (Malloy et al., 2015; Sigward et al., 2008). A systematic review (Mason-Mackay et al., 2015) included these studies and discussed that different results may be attributed to differences in tasks, even though all of the tasks were reportedly landing tasks.

Some studies in this review conducted their assessments using single-leg squats and double-leg squats. The only study that could not find a correlation between reduced ADF and DKV was the one by Dill et al. (2014) assessing the double-leg squat in an overhead position. Although the two other studies using double-leg squats found significant results associating reduced ADF with DKV, some biomechanical differences between single-leg tasks and double-leg tasks could be the reason for the absence of a statistical difference in the study by Dill et al. (2014). During single-leg squats, the hip of the supporting limb has to move laterally to keep the center of mass above the base of support, thus maintaining the balance of the body and preventing the body from falling (Donohue et al., 2015; Powers, 2010). This lateral movement of the hip in single-leg tasks may explain increased hip adduction angles and therefore DKV in a comparison with double-leg tasks.

To date, only one study (D. R. Bell, Oates, Clark, & Padua, 2013) has been done in to check the influence of an intervention for improving ADF with the objective of reducing DKV. The intervention group was assigned to exercises aimed at increasing the strength and flexibility of the muscles proximal and distal to the knee joint, whereas the control group had no type of intervention. The authors found significant improvements in the intervention group for DKV and ADF but not for the isometric strength of hip extensors and abductors as well as knee flexors. Although these results are consistent with the findings of our systematic review and meta-analyses, further research with longitudinal cohorts is necessary to verify if restricted ADF is a predictor of DKV, as it has been shown to be a major contributor to knee injuries (Hewett et al., 2005).

Although it is not possible to ascertain if reduced ADF is a cause or an adaptation to DKV and causal inference cannot be implied from this association as the analyses performed were based in cross-sectional studies, it is strongly recommended that clinicians develop preventive strategies for both increasing ADF and reducing DKV as part of their injury prevention programmes, as these variables may potentially consist in risk factors for lower limb injuries if not addressed properly. Interventions such as manual tibiotalar joint mobilisation and manipulation (Loudon, Reiman, & Sylvain, 2014) and static-stretching of gastrocnemius/soleus complex (Terada, Pietrosimone, & Gribble, 2013) are already reported as effective for improving ADF as well as neuromuscular control training composed of plyometric and agility exercises with the inclusion of feedback on movement quality are among the options for effectively reducing DKV and must be inserted in preventive programmes (Ter Stege, Dallinga, Benjaminse, & Lemmink, 2014).

In our review, we aimed to identify the association of ADF and DKV; nonetheless, other factors must be considered, as research has shown their roles in contributing to frontal plane mechanics of the knee. Some of the factors to be appraised are other neuromuscular variables, as reduced knee and hip flexion angle (Dill et al., 2014), poor trunk alignment (Hewett & Myer, 2011), increased hamstring/quadriceps ratio (Myer et al., 2009), reduced gluteus maximus activation (Cronstrom et al., 2016), external hip rotators and abductors strength (Cashman, 2012; Khayambashi, Ghoddosi, Straub, & Powers, 2016; Powers, 2010) have been shown to be related to DKV. Clinicians should consider working on these variables alongside ADF and DKV to improve movement quality and potentially reduce the risk of lower limb injuries.

5. Conclusion

This review highlights that limited ADF appears to be linked with DKV. The assessment of ADF should be included in clinical practice as it may be related to individuals at risk of harmful lower limb movement patterns during dynamic tasks.

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