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Conservative interventions to improve foot progression angle and clinical measures in orthopedic and neurological patients – A systematic review and meta-analysis

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ABSTRACT

To establish the comparative effects of conservative interventions on modifying foot progression angle (FPA) in children and adults with orthopaedic and neurological disease was the main aim of the literature review. Pubmed, Embase, Cinahl, and Web of Science were systematically searched for studies evaluating the effects of conservative interventions on correcting the FPA. The study protocol was registered with PROSPERO (CRD42020143512). Two reviewers independently assessed studies for inclusion and quality. Studies that assessed conservative interventions that could have affected the FPA and objectively measured the FPA were included. Within group Mean Differences (MD) and Standardized Mean Differences (SMDs) of the interventions were calculated for the change in FPA and gait performance (walking speed, stride/step length) and clinical condition (pain). Intervention effects on FPA were synthesized via *meta*-analysis or qualitatively. 41 studies were identified. For patients with knee osteoarthritis gait training interventions (MD = 6.69° and MD = 16.06°) were significantly more effective than mechanical interventions (MD = 0.44°) in modifying the FPA towards in-toeing ($p < 0.00001$). Increasing or decreasing the FPA significantly improved pain in patients with medial knee OA. Results were inconclusive for the effectiveness of gait training and mechanical devices in patients with neurological diseases. Gait feedback training is more effective than external devices to produce lasting improvements in FPA, reduce pain, and maintain gait performance in patients with medial knee OA. However, in neurological patients, the effects of external devices on improvements in FPA depends on the interaction between patient-specific impairments and the technical properties of the external device.

1. Introduction

Foot progression angle (FPA) is defined as the angle formed between the line interconnecting the calcaneus and the second metatarsal and the line of gait progression (Beyaert et al., 2003). An abnormal FPA is a frequently observed gait disorder in children and adults with neurological and orthopaedic disease (Hastings et al., 2010; Rerucha et al., 2017; Rethlefsen and Kay, 2013). For example, about 50–64% of children with cerebral palsy who are referred for clinical gait analysis walk with an internal FPA (Rerucha et al., 2017; Rethlefsen et al., 2006). Excessive in- or outward foot rotation affects the appearance of gait, impairs mechanical gait efficiency (Chang et al., 2007; Cui et al., 2019) and increases the risks for knee osteoarthritis (knee OA) and foot injuries (Beyaert et al., 2003; Chang et al., 2007; Hastings et al., 2010; Merriwether et al., 2016). Therefore, correcting FPA is an important goal of gait rehabilitation in patients with neurological and orthopaedic conditions and is increasingly used to prevent foot ulcers in diabetic patients (Merriwether et al., 2016) and to reduce pain in knee OA (Hunt et al., 2018; Hunt and Takacs, 2014). Abnormal FPA can be corrected by surgical and conservative interventions. The effectiveness of surgical interventions has been established in pediatric and adult cerebral palsy (Kim et al., 2018; Putz et al., 2016; Sung et al., 2018). However, invasive surgeries are restricted to correct only the most severe musculoskeletal deformities. Conservative interventions are promising alternatives to surgery because of lower risks of complications and potentially higher effectiveness (Nourai et al., 2015).

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Several conservative interventions are available to correct abnormal FPA and facilitate the normalization of gait in children and adults with neurologic and orthopaedic conditions. These include mechanical interventions (insoles, ankle–foot orthoses, shoe adaptations, external rotation straps) (Ganjehie et al., 2017; Uden and Kumar, 2012) and gait retraining through verbal instructions and real-time visual feedback to correct FPA while walking (Hunt et al., 2018; Hunt and Takacs, 2014). The aetiology of abnormal FPA differs depending on the underlying disease and severity of musculoskeletal impairments (e.g., muscle weakness) and even within the same patient group, the effectiveness of conservative interventions (e.g., mechanical or gait training) can vary. For example, while some patients with muscle weakness cannot voluntarily change the position of their foot while walking and require external devices to normalize the FPA (Long and Toscano, 1995), others (e.g., patients with knee OA) might be able to alter their FPA after a single session of gait feedback training without the need for mechanical devices (Simic et al., 2013). Until now, there is a lack of consensus as to which conservative intervention is appropriate and effective to correct FPA in neurological and orthopaedic patient groups. Consequently, clinicians rely on biomechanical principles and prior experience to make clinical decisions on correcting FPA. In addition, while the purpose of modifying FPA is to improve gait performance and mobility, it remains unclear whether this purpose is met, as the effectiveness of modifying FPA to improve gait performance and mobility in patients with neurological and orthopaedic conditions has not yet been well characterized. It might even be possible that some interventions lead to excessive correction of FPA which could impair certain patients' gait. For example, a more out-toeing gait might reduce pain in patients with knee OA but excessive out-toeing reduces patients' ankle power, reducing gait speed and gait efficiency (Chang et al., 2007).

The primary aim of this review was to provide a systematic overview of the comparative effectiveness of conservative interventions on modifying FPA in children and adults with orthopaedic and neurological conditions. The secondary aim was to determine the relationship between changes in gait performance (indexed by walking speed, step length) induced by modifications in FPA and clinical condition (characterized by pain). We provide patient group-specific recommendations for interventions to modify FPA and improve gait performance and associated clinical variables.

2. Methods

The systematic literature search and *meta*-analysis were reported in accordance with the recommendations of the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement (Moher et al., 2009). The protocol was registered in the PROSPERO database in April 2020 (registration number: CRD42020143512). Due to the large number of included studies the current review addresses only the effectiveness of conservative interventions on FPA during gait. For this purpose, studies investigating the effect of surgical interventions were excluded from data synthesis and will be assessed in an another review. Some minor changes were made on the main outcome measures and the risk of bias domains.

2.1. Search and screening process

Studies published up to January 2020, were systematically searched in four databases (Pubmed, Embase, Cinahl, and Web of Science), using the following Boolean search syntax: ("foot progression" OR FPA OR "angle of gait" OR (toeing AND (in OR out)) OR (toe AND (in OR out)) OR intoed OR out toed OR "internal foot rotation*" OR "external foot rotation*" OR inturning OR "pigeon toe*") AND (gait OR walk* OR locomot*). The search strategies specified per database can be found in Appendix A. The selection process started by removing duplicates followed by title screening and eventually abstracts and full texts of the respective studies. Two reviewers (CG & RS) independently assessed the eligibility criteria. If at least one of the authors included a title, it was included in the abstract phase. Abstracts and full texts were excluded when agreement existed between the two assessors. Disagreements were solved in a discussion meeting. In case of unreported data, authors were contacted. Reference lists of all included articles were checked on additional relevant studies.

2.2. Inclusion/exclusion criteria

Titles and abstracts were included if the study (i) was about an intervention that could have affected the FPA. Thereby, titles and abstracts were excluded if the study (ii) included 5 participants or less; (iii) was not primary research; (iv) was an animal study; (v) had a language different than Dutch, English or German. For the full text phase, in addition to the above mentioned in- and exclusion criteria, the following inclusion criteria were used. Full texts were included if the study (i) objectively measured the FPA during gait; (ii) was a randomized controlled trial (RCT) or had a pre-post or cross-over study design; (iii) showed that the change in FPA, if there was any, was the consequence of the intervention. To facilitate data interpretability only studies investigating the effect of conservative interventions were included in the current literature review.

2.3. Outcomes

The primary outcome was the change in FPA during gait. Secondary outcomes were gait performance (indexed by walking speed, stride/step length) and clinical condition (indexed by pain)

2.4. Quality assessment and the risk of bias

Due to the difference in included study designs (RCT's and observational studies), a combination of criteria from the risk of bias (Higgins and Green, 2011), the PEDro scale and the Wales list was used, together with a set of additional criteria, to perform the quality assessment (Maher et al., 2003; Van Der Wilk et al., 2015). The quality of the included studies was assessed by one author (MH) and checked by a second author (RS). The quality assessment form that was used can be found in Appendix B. Disagreements were resolved in a discussion meeting. Each item of the scale was scored with 'not applicable'; 'low risk of bias'; 'high risk of bias'; or 'unclear risk of bias'. The scores were summed per criterion and not per study, as the latter assigns weights to the different items in the scale that are difficult to justify (Higgins and Green, 2011).

2.5. Data extraction

One author (MH) extracted the key data from each article to allow comparison of the interventions. This key data included the study design, type of intervention, subject characteristics (population, age, sex, number of participants), FPA outcomes, gait performance (walking speed , stride/step length) and clinical condition (pain), time to follow-up (if applicable) and the instrument used for measurement of the FPA. The extracted data was checked by a second author (RS).

2.6. Data synthesis and statistical analysis

Within group Standardized Mean Differences (SMDs) of the interventions were calculated for the change in FPA, clinical variables (pain) and gait performance (walking speed, stride/step length). The SMDs were calculated for immediate and longer-term effects (if applicable). SMDs were calculated as $\left(SMD = \frac{meandifference}{SDpooled}\right)$ (Elbourne et al., 2002; Faraone, 2008; Higgins et al., 2019) and categorised as trivial ($SMD < 0.2$) small ($0.2 \leq SMD < 0.5$), moderate ($0.51 \leq SMD < 0.8$) or large ($SMD \geq 0.8$)(Cohen, n.d.). The SMDs were extracted to assess the relation between changes in FPA and changes in gait performance and clinical condition. The association between SMDs of outcome measures and intervention types were quantified by Pearson correlation coefficients. Only studies that provided enough information to calculate the SMDs were included in these analyses.

Data was pooled using Review Manager Software Package 5.3.5 (Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014) if studies had the same design and assessed the same interventions in similar patient groups. If one study assessed different experimental conditions, the conditions were treated as separate interventions. A distinction was made between the direction of FPA change and the amount of change that was aimed for. Thereby, gait training studies measuring the immediate intervention effects and gait training studies measuring the long-term intervention effects on FPA were separated. Long-term effects refer to the effects determined after a period of training (more than one session) in which feedback was reduced and not present at the post-assessment and/or follow-up. Immediate effects refer to the effects determined during one session in which the feedback was still present. This distinguishes learning from adaptation. For the quantitative analysis, random-effects models were used and heterogeneity was quantified with the I^2 statistic (Ahn and Kang, 2018; Higgins et al., 2019). Meta-analyses were conducted only in case of homogenous subgroups ($I^2 < 30\%$), with ≥ 3 studies within a subgroup (Faraone, 2008). The mean difference (MD) in FPA was calculated, together with the standard error that was based on the SD and sample size of the study (Elbourne et al., 2002; Higgins, 2008). If these data were not directly available they were calculated or imputed (Elbourne et al., 2002). An alpha of 0.05 was used to determine statistical significance.

3. Results

The search strategy yielded 1879 unique titles. Fig. 1 provides an overview of the article selection process. Studies containing surgical

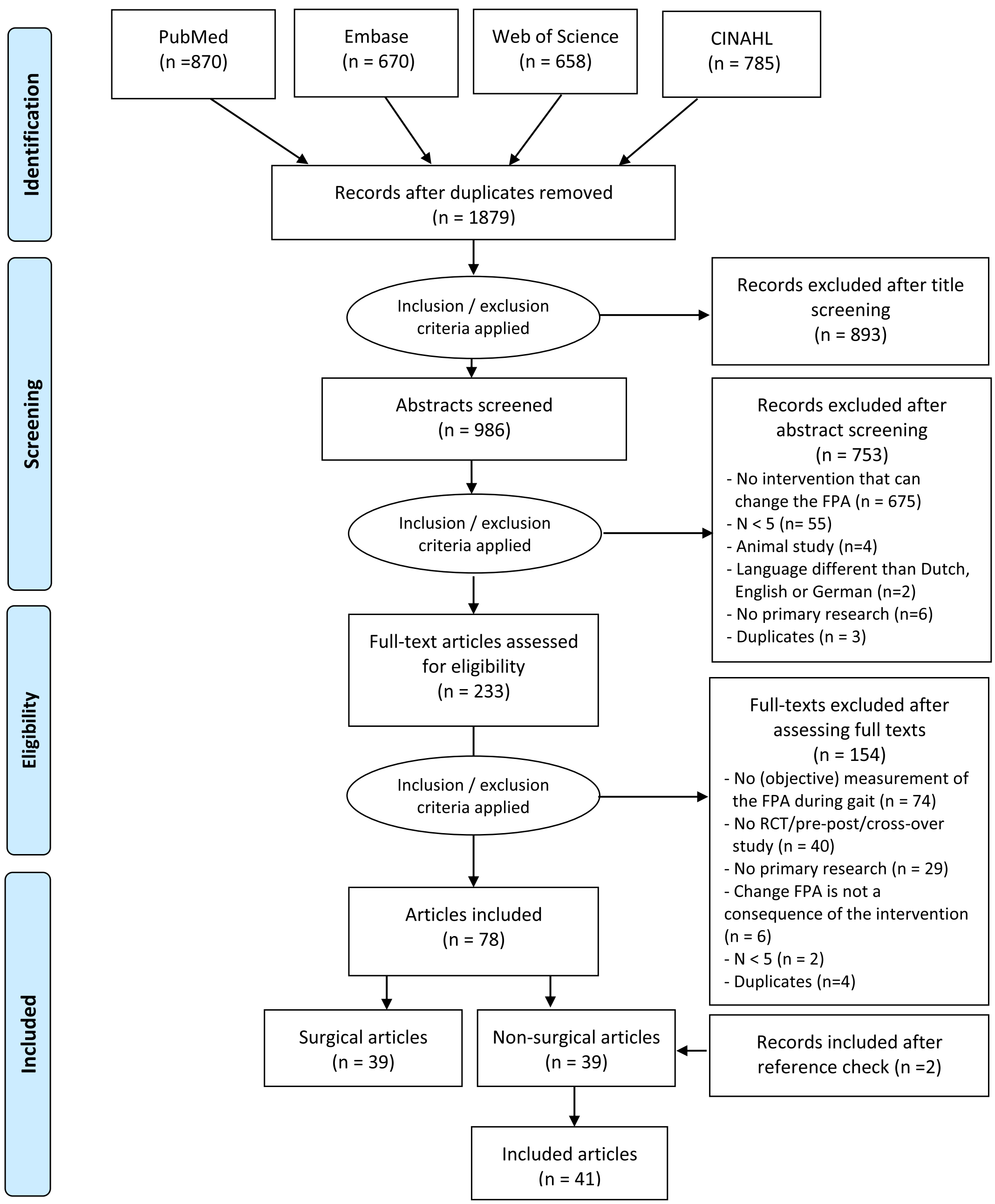

Fig. 1. PRISMA Flow Diagram showing the study selection.

interventions and studies containing conservative interventions were separated, resulting in 41 conservative intervention studies that were included in this review.

3.1. Characteristics of included studies

Appendix C summarized the studies characteristics. Studies were categorized based on type of subjects and interventions. The study populations included adults with medial knee OA (n = 18), adults with neurological disease (n = 4), children with cerebral palsy (CP) (n = 4), patients with lumbar degenerative kyphosis (n = 1) and healthy adults (n = 14). To collect FPA data, all studies used three-dimensional (3D) motion capture (n = 39) or GAITRite (n = 2), both reliable measurement systems (Menz et al., 2004; Tsushima et al., 2003; van Uden and Besser, 2004).

3.2. Methodological quality assessment and risk of bias

The risk of bias table can be found in appendix D. The domain with the highest risk of bias was 'participants were blinded to group or condition'. The domains that were adequately reported in the majority of studies were the participants characteristics, the general criteria like 'addressing of incomplete outcome data' and 'non-selective outcome reporting', and other bias sources like 'avoiding of co-interventions' and 'intervention vs. learning effect'. Four studies were RCTs and twenty-eight of the included studies were cross-over trials. There were three cohort studies included and six pre-post studies.

3.3. Effect of conservative interventions in patients with orthopaedic disease

Eighteen studies evaluated the effect of conservative interventions on FPA in patients with medial knee OA. The effect of gait feedback training was investigated in 13 studies by making use of real-time visual feedback (Booij et al., 2020; Charlton et al., 2018, 2019; Cheung et al., 2018; Hunt and Takacs, 2014; Richards et al., 2018a, 2018c, 2018b; Simic et al., 2013), haptic feedback (He et al., 2019; Shull et al., 2013) and mirror guided feedback training (Hunt et al., 2018, 2014). Six of these studies had a faded feedback program incorporating ≥ 6 weeks of training (Cheung et al., 2018; Hunt et al., 2018; Hunt and Takacs, 2014; Richards et al., 2018c, 2018b; Shull et al., 2013), of which three studies assessed the long-term effects of the program with a mean follow-up time of 2.7-months (Hunt et al., 2018; Richards et al., 2018b; Shull et al., 2013). During these follow-ups, feedback was removed for the participants. The long-term effects of proprioceptive and strength training were examined by one study (Cho et al., 2015). Mechanical interventions were assessed in four studies by using insoles (Khan et al., 2019; Lou et al., 2015; Yeh et al., 2014) and adapted shoes (Elbaz et al., 2010). Out of these, one study investigated the long-term effects (Elbaz et al., 2010) (Appendix C).

Fig. 2 shows meta-analyses for the subgroups 'real-time visual feedback training' and 'insoles'. The included studies had a cross-over design, aimed at increasing the FPA (towards in-toeing), and measured the immediate intervention effects on FPA. Real-time visual feedback training modified FPA towards in-toeing (MD = 6.69°, $p < 0.00001$; MD = 16.06°, $p < 0.00001$). There was no statistically significant evidence for insoles changing FPA (MD = 0.44°, $p = 0.92$). The test for subgroup differences showed that real-time visual feedback training was significantly more effective than wearing insoles in changing the FPA towards in-toeing ($p < 0.00001$).

Due to heterogeneity, interventions that aimed at changing the FPA towards out-toeing could not be included in the *meta*-analysis. These gait training interventions showed changes in FPA ranging from −0.8° to −21.8° (Charlton et al., 2019, 2018; Cheung et al., 2018; Hunt and Takacs, 2014; Simic et al., 2013).

Interventions assessing the long-term effects showed that proprioceptive training, real-time visual feedback training, and mirror guided feedback training significantly decreased FPA by 2°, 6.66°, and 8.0° respectively (Cho et al., 2015; Hunt et al., 2018; Hunt and Takacs, 2014). Thereby, real-time haptic and visual feedback training programs significantly increased in FPA by 7.0° and 2.1°, respectively (Richards et al., 2018b; Shull et al., 2013). Three of these studies showed retention of the treatments effects at follow-ups ≥ 1 month (Hunt et al., 2018; Richards et al., 2018b; Shull et al., 2013). The use of adapted shoes for 12 weeks significantly increased FPA by 1.1° (Elbaz et al., 2010).

Study or Subgroup	Mean Difference	SE	Natural walking Total	Intervention Total	Weight	Mean Difference IV, Random, 95% CI
2.1.1 Real-time visual feedback (relative small toe-in angle as goal)						
Booij et al. (2020)	7.37	1.53	30	27	33.1%	7.37 [4.37, 10.37]
Charlton et al. (2018)	5.1	1.8	16	16	23.9%	5.10 [1.57, 8.63]
Charlton et al. (2019)	7.5	2.2	15	13	16.0%	7.50 [3.19, 11.81]
Simic et al. (2013)	6.8	1.695	22	22	27.0%	6.80 [3.48, 10.12]
Subtotal (95% CI)			**83**	**78**	**100.0%**	**6.69 [4.97, 8.42]**
Heterogeneity: Tau² = 0.00; Chi² = 1.12, df = 3 (P = 0.77); I² = 0%						
Test for overall effect: Z = 7.60 (P < 0.00001)						
2.1.2 Real-time visual feedback (10 degrees toe-in as goal)						
Charlton et al. (2018)	17.8	2.175	16	16	28.1%	17.80 [13.54, 22.06]
Charlton et al. (2019)	17.3	2.2	15	13	27.5%	17.30 [12.99, 21.61]
Simic et al. (2013)	14.2	1.695	22	22	44.4%	14.20 [10.88, 17.52]
Subtotal (95% CI)			**53**	**51**	**100.0%**	**16.06 [13.73, 18.40]**
Heterogeneity: Tau² = 0.33; Chi² = 2.16, df = 2 (P = 0.34); I² = 7%						
Test for overall effect: Z = 13.48 (P < 0.00001)						
2.1.3 Insoles/Shoes						
Khan et al. (2019)	0.2	1.778	20	20	42.5%	0.20 [-3.28, 3.68]
Lou et al. (2015)	3	2.295	12	12	25.5%	3.00 [-1.50, 7.50]
Yeh et al. (2014)	-1.3	2.053	15	15	31.9%	-1.30 [-5.32, 2.72]
Subtotal (95% CI)			**47**	**47**	**100.0%**	**0.44 [-1.84, 2.71]**
Heterogeneity: Tau² = 0.00; Chi² = 1.98, df = 2 (P = 0.37); I² = 0%						
Test for overall effect: Z = 0.38 (P = 0.71)						

Test for subgroup differences: Chi² = 89.53, df = 2 (P < 0.00001), I² = 97.8%

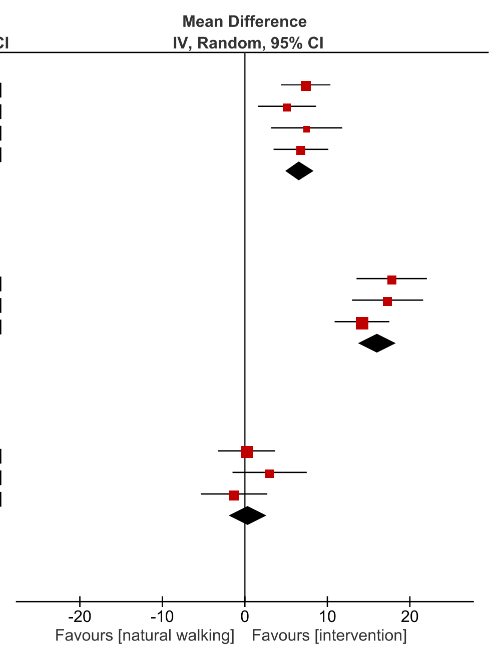

Fig. 2. Forest plot showing the immediate changes in FPA (degrees) as a result of real-time visual feedback training or insoles/shoes in patients with medial knee OA. Positive changes indicate a change in FPA towards in-toeing as a result of the intervention.

3.4. *Effect of conservative interventions in patients with neurological disease.*

Eight studies examined the effect of conservative interventions on FPA in patients with neurological disease. Due to differences in study design, study populations and interventions, no *meta*-analysis could be performed. Four studies evaluated the effect of orthoses in children with CP (Abd El Kafy and El-Shemy, 2013; Böhm et al., 2018; Danino et al., 2015; Kranzl et al., 2013). One of these studies reported a significant deterioration in FPA towards in-toeing when wearing ankle–foot orthoses (AFOs) as compared to barefoot by 4.3° (2.4°-6.17°) (Danino et al., 2015). Wearing TheraTogs resulted in significant improvements of the FPA in children with CP with a decrease of 4.4° in the direction of out-toeing (Abd El Kafy and El-Shemy, 2013). Studies examining the effect of floor reaction AFOs and dynamic AFOs did not find any significant effects on the FPA (Böhm et al., 2018; Kranzl et al., 2013).

The effect of conservative interventions in adults with a neurological disease was evaluated in four studies including post-stroke patients, patients with a post-cerebral hemispherectomy, multiple sclerosis and Parkinson disease (Fritz et al., 2011; Gutierrez et al., 2005; Kim et al., 2013; Luna et al., 2018). While plastic AFOs led to a significant deterioration in FPA by 8° towards in-toeing, heel open AFOs did not affect FPA in post-stroke patients Intensive mobility training increased the FPA towards in-toeing and was therefore effective in improving the FPA in patients with cerebral hemispherectomy (Fritz et al., 2011). In patients with multiple sclerosis, lower limb resistance training resulted in a decrease in FPA in the less affected leg, while no significant effect was found in the most-affected leg (Gutierrez et al., 2005). The effect of bodyweight-supported treadmill training on FPA was investigated in patients with Parkinson Disease. The authors reported a significant increase in the foot progression angle range of motion for the dominant but not the non-dominant limb (Luna et al., 2018).

3.5. *Effect of conservative interventions in healthy adults*

Fifteen studies evaluated the effect of conservative interventions on FPA in healthy adults. The effect of gait feedback training on changing the FPA was investigated in nine studies by using real-time visual feedback training (Bennour et al., 2018; Eddo et al., 2019; Kettlety et al., 2020; Lindsey et al., 2020; van den Noort et al., 2015), real-time haptic feedback training (Chen et al., 2017; Shull et al., 2011; Uhlrich et al., 2018) and voluntary gait modifications (Van Den Noort et al., 2013). Mechanical interventions were assessed in six studies by making use of insoles (Huerta et al., 2009; Nakajima et al., 2009; Ulrich et al., 2020; Yeh et al., 2014), rounded soft shoes (Demura et al., 2012), and toe-separators (Xiang et al., 2020). All studies investigated the immediate effects of the interventions and focused on changing the FPA either towards an in- (Eddo et al., 2019; Kettlety et al., 2020; Lindsey et al., 2020; Shull et al., 2011; van den Noort et al., 2015) or out-toeing gait pattern (Chen et al., 2017; Huerta et al., 2009; Ulrich et al., 2020; Yeh et al., 2014), or both (Bennour et al., 2018; Nakajima et al., 2009; Uhlrich et al., 2018; Van Den Noort et al., 2013).

A *meta*-analysis was performed for the subgroups 'real-time visual feedback training' and 'insoles/shoes' (Fig. 3). The results showed that real-time visual feedback training had a significant effect on increasing FPA (MD = 8.46°, p < 0.00001). There was no strong evidence for the effectiveness of insoles/shoes on increasing FPA (p = 0.95). The test for subgroup differences showed that real-time visual feedback training was significantly more effective in changing the FPA towards in-toeing than insoles/shoes (p < 0.00001).

Due to heterogeneity, studies evaluating the effect of real-time haptic feedback training could not be included in the *meta*-analysis. Studies investigating the effect of real-time haptic feedback training showed a mean increase in FPA of 12.25° when aiming for in-toeing (Shull et al., 2011; Uhlrich et al., 2018) and a mean decrease of 9.8° when aiming for out-toeing (Uhlrich et al., 2018). Voluntary gait modifications in the direction of in- or out-toeing resulted in a significant increase of 18.71° and decrease of 15.88°, respectively (Van Den Noort et al., 2013).

3.6. *Effect of change in FPA on gait performance and pain*

Table 1 shows the SMDs of change in FPA, gait performance (stride/step walking speed, length) and clinical condition (pain). For patients with medial knee OA, nine studies were included in this table, of which seven studies measured pain and five studies measured clinical gait outcomes. For healthy adults, children with CP and adults with neurological disease, five, two and three studies were included respectively, all of them measuring the change in clinical gait outcomes.

Fig. 4 provides a visualization of the association between the absolute change in FPA and pain in patients with medial knee OA. Changes in FPA as a consequence of feedback training significantly correlated positively with changes in pain (r = 0.986; p = 0.014). Also, in studies measuring the effect of insoles, a correlation was found between the absolute change in FPA and the improvement in pain (r = 0.878; p = 0.318), but this correlation was not significant. Interestingly, a much smaller change in FPA led to a larger improvement in pain when using insoles compared to gait training. Gait training interventions mostly resulted in trivial changes in gait performance (Table 1). Insoles and

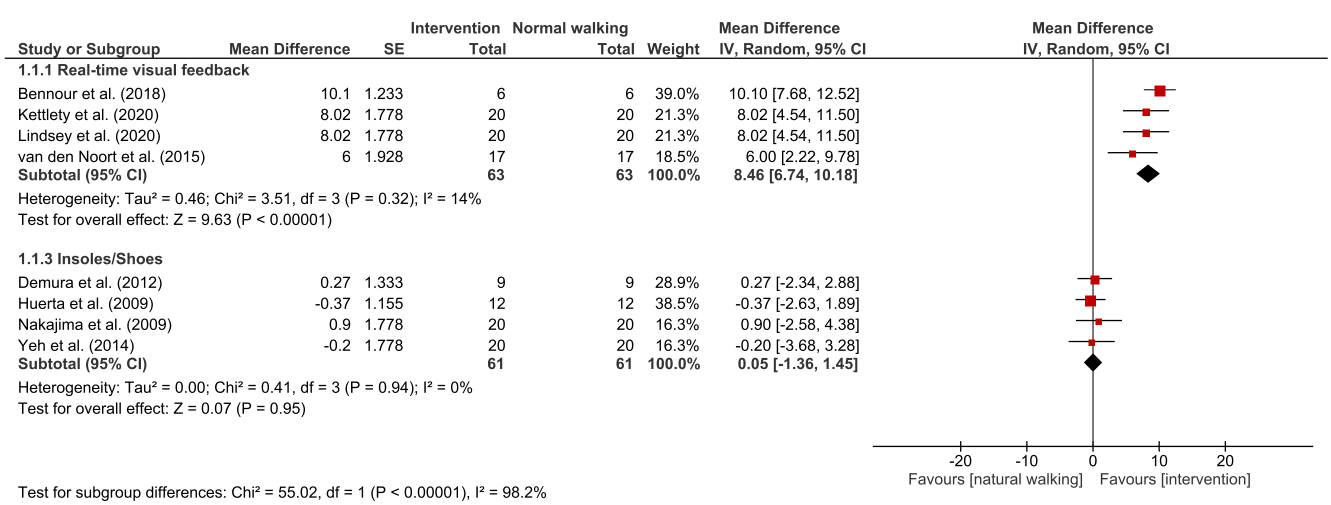

Fig. 3. Forest plot showing the immediate changes in FPA (degrees) as a result of real-time visual feedback training or insoles/shoes in healthy adults. Positive changes indicate a change in FPA towards in-toeing as a result of the intervention.

Table 1
Functional improvement table showing standardized mean differences for FPA, pain and gait performance as a result of different types of conservative interventions.

Study population	Study/ Article	Intervention	Condition / subgroup	Time to post-assessment	Within-group FPA SMD (pre- vs. post)*	Within-group pain SMD (pre- vs post)**	Within-group gait performance SMD (pre- vs post)***	Follow-up details
Knee OA	Charlton et al., 2019	Real-time visual feedback	Toe-in 10° 0° FPA Toe-out 10° Toe-out 20°	Immediate	2.49 (Large) 1.29 (Large) −0.45 (Small) −2.08 (Large)		0.04 (Trivial) 0.04 (Trivial) 0.03 (Trivial) 0.1 (Trivial)	No follow-up
	Richards et al., 2018b	Real-time visual feedback	Toe-in	6 weeks	0.76 (Medium)	0.46 (Small)		3 months: FPA SMD = 0.69; pain SMD = -0.6; 6 months FPA SMD = 0.69; pain SMD = -0.5
	Hunt & Takacs 2014	Real-time visual feedback	Toe-out	10 weeks	−1,02 (Large)	0.66 (Medium)	0 (Trivial)	No follow-up
	Hunt et al., 2018	Mirror-guided biofeedback	Increase toe-out 15°	4 months	−1.86 (Large)	1.09 (Large)	0.40 (Small)	5 months: FPA SMD = -1,43; pain SMD = 1.09 ; gait performance = 0.49
	Shull et al., 2013	Real-time haptic feedback	Toe-in	6 weeks	1.57 (Large)	1.03 (Large)		1 month: FPA SMD = 1.86; pain SMD = 1.37
	Lou et al., 2015	Shoes + insoles		Directly	0.5 (Small)		0.13 (Trivial)	No follow-up
	Elbaz et al., 2010	Shoes		12 weeks	0.28 (Small)	0.51 (Medium)	0.57 (Medium)	No follow-up
	Khan et al., 2019	LWI LWI + Toe-out		Directly	0.06 (Small) −4.11 (Large)	0.07 (Small) 0.97 (Large)		No follow-up
	Yeh et al., 2014	LWI		Directly	−0.32 (Small)	1.18 (Large)		No follow-up
Healthy adults	Bennour et al., 2018	Real-time visual feedback	Toe-in Toe-out	Directly	2.66 (Large) −2.62 (Large)		0 (Trivial) 0 (Trivial)	No follow-up
	Lindsey et al., 2020	Real-time visual feedback	Toe-in small Toe-in large	Directly	1.15 (Large) 1.64 (Large)		0.05 (Trivial) −0.03 (Trivial)	No follow-up
	Kettlety et al., 2020	Real-time visual feedback	Toe-in 3–5 SD	Directly	1.64 (Large)		−0.08 (Trivial)	No follow-up
	Uhlrich et al., 2018	LWI		Directly	0.5 (Small)		0.07 (Trivial)	No follow-up
	Demura et al., 2012	Shoes with rounded soft sole		Directly	0.10 (Small)		0.71 (Medium)	No follow-up
Children with CP	Böhm et al., 2018	Orthosis – FRAFO	Responders Non-Responders	Directly	0.51 (Medium) 0.34 (Small)		0.35 (Small) 0.44 (Small)	No follow-up
	Abd El Kafy, 2013	TheraTogs + strapping	Toe-out	3 months	−1.9 (Large)		1.79 (Large)	6 months: FPA SMD = -3.99; gait performance SMD 3.04
Adults with neurological disease	Gutierrez et al., 2005	Resistance training	Affected leg Less affected leg	8 weeks	−0.50 (Small) 0.85 (Medium)		0.44 (Small) 0.44 (Small)	
	Luna et al., 2018	Treadmill training	NDL TT DL TT NDL BWSTT DL BWSTT	8 weeks	−0.68 (Medium) 0.06 (Small) 0.66 (Medium) −0.76 (Medium)		0.19 (Trivial) 0.19 (Trivial) 0.53 (Medium) 0.53 (Medium)	
	Fritz et al., 2011	Intensive Mobility training			−0.39 (Small)		0.38 (Small)	

* Positive values indicate a change towards in-toeing
** A higher SMD indicates less pain during post-test/follow-up
*** For the gait performance, the stride/step length and walking speed were taken together. If both parameters were reported the mean SMD was calculated
Abbreviations: BWSTT = body weight supported TT, CP = cerebral palsy, FPA = foot progression angle, FRAFO = floor reaction ankle–foot orthosis, LWI = lateral wedged insole, NDL / DL = (non–)dominant limb, SMD = standardized mean difference, TT = treadmill training

orthoses, on the other hand, led in three studies to medium (Demura et al., 2012; Elbaz et al., 2010) or large (Abd El Kafy and El-Shemy, 2013) changes in gait performance. However, no association was found between these changes and the change in FPA.

4. Discussion

The primary aim of this systematic review and *meta*-analysis was to establish the comparative effectiveness of conservative interventions on modifying FPA in children and adults with orthopaedic and neurological conditions. The second aim was to determine the association between changes in FPA and gait performance (walking speed, step/stride length) and clinical condition (pain). We found that gait feedback training is significantly more effective than external devices to produce immediate improvements in FPA in patients with medial knee OA but not in neurological patients. Changes in FPA significantly correlated

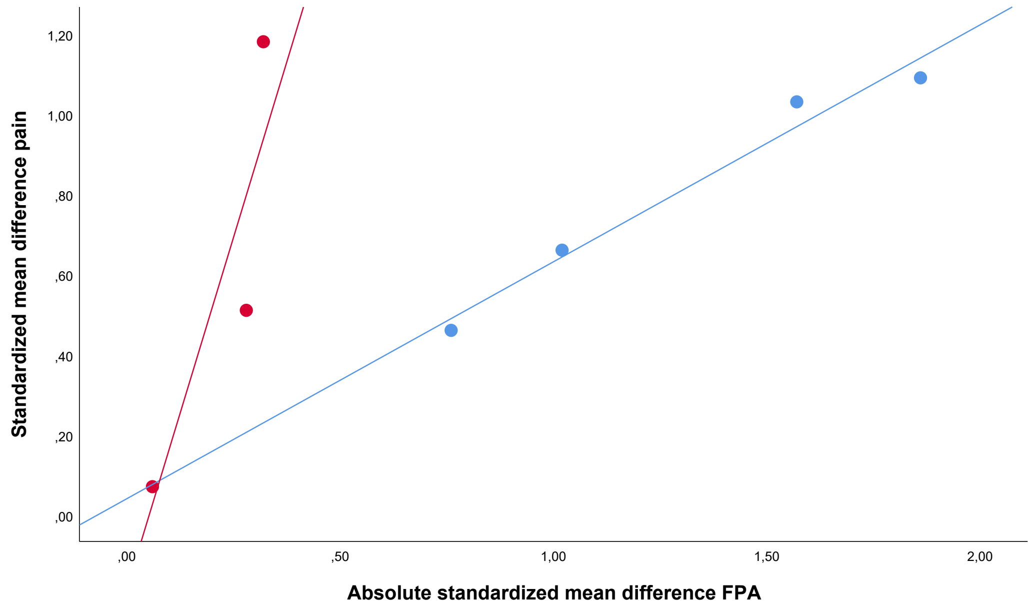

Fig. 4. The association between changes in FPA and pain as a result of feedback training (blue markers/line) and insoles/shoes (red markers/line) in patients with medial knee OA. Positive pain changes indicate an improvement in pain. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

positively with pain reduction in patients with knee OA. Various studies showed promising long-term effects of feedback training on FPA in patients with medial knee OA (Hunt et al., 2018; Richards et al., 2018b; Shull et al., 2013), but these effects were not significant and a statistical comparison with external devices could not be made.

4.1. Effects of conservative interventions on FPA in orthopaedic patients

Real-time visual feedback training was significantly more effective than insoles in modifying FPA towards in-toeing in patients with medial knee OA. Whether such immediate training effects could be retained remains unclear, but six studies showed promising results (Cheung et al., 2018; Hunt et al., 2018; Hunt and Takacs, 2014; Richards et al., 2018c, 2018b; Shull et al., 2013). These studies used fading visual and haptic feedback training programs during which the level of feedback was gradually reduced over weeks. The idea of fading feedback training programs is to increase retention of newly acquired motor skills by making subjects less dependent on feedback (Winstein, 1991). In two studies, training effects of haptic and mirror guided faded feedback training were retained even after a retention period of up to 5 months (Hunt et al., 2014; Shull et al., 2013). To further augment retention of the training effects, future studies should consider to use implicit instructions without providing patients with specific instructions on how to achieve the training goal (Masters, 1992; Richards et al., 2017). Current studies exclusively use explicit instructions which might interfere with retention of the acquired gait skills.

The goal of modifying FPA in patients with medial knee OA is to reduce pain and slow cartilage erosion by reducing peak joint contact forces at the medial compartment of the knee (Hunt et al., 2018; Shull et al., 2013). More internal FPA shift the vector of the ground reaction force closer to the knee joint center of rotation and reduce peak knee adduction moments when loading the limb with body weight (e.g., first peak knee adduction moment) (Shull et al., 2013). However, once the foot is fully on the ground and the ground reaction force progresses from the heel to the forefoot, external FPA reduce the second peak knee adduction moment which occurs just before the contralateral leg touches the ground (Chang et al., 2007). Interestingly, independent of the direction of FPA modification (in-or out toeing), gait feedback training reduced pain in patients with medial knee OA to a similar extent. These findings imply that patients with medial knee OA might benefit from any reductions in peak knee adduction moments, either induced by in- or out-toeing (Hunt et al., 2018; Hunt and Takacs, 2014; Richards et al., 2018b; Shull et al., 2013). In addition, previous studies showed that larger toe-in or toe-out angles do not necessarily result in larger reductions of peak knee adduction moments (Eddo et al., 2019; Lindsey et al., 2020; Simic et al., 2013). Since the direction of change in FPA does not affect clinical measures (e.g., pain), gait training regimes should allow patients with medial knee OA to choose their own strategy to adjust FPA and reduce pain during gait. An exploration of different gait training regimens by patients might facilitate retention of newly acquired gait skills after hospital discharge (Pacheco and Newell, 2015).

Insoles and shoe adaptations did not significantly affect the FPA in orthopaedic patients with medial knee OA. Insoles and shoe adaptations mainly affect the position of the foot, ankle and knee joint in the frontal plane whereas changes in FPA require rotational adaptations in the transverse plane, possibly explaining the ineffectiveness of currently available mechanical interventions. Future studies should aim to establish mechanical devices allowing modifications of the foot and ankle joint in the transverse plane to modify the FPA. Especially those patients with severe symptoms of medial knee OA or an impaired ability to voluntarily change the FPA might benefit from mechanical interventions.

4.2. Effect of conservative interventions on FPA in neurological patients

TheraTogs are effective in normalizing FPA in children with CP but there are inconclusive and sometimes contradictory findings on the effectiveness of AFOs to normalize FPA in adults and children with neurological disease. For example, dynamic AFOs and floor reaction AFOs tend to normalize the FPA in children with CP (Böhm et al., 2018; Kranzl et al., 2013), whereas another study found AFOs lead to excessive increases in in-toeing gait (Danino et al., 2015). On the other hand, plastic AFOs lead to an excessive increase in out-toeing gait in post-stroke patients, while heel-open AFOs did not affect FPA and in diplegic but not hemiplegic children with CP FPA significantly increased when walking with AFOs (Danino et al., 2015; Kim et al., 2013). These controversial findings imply that the effectiveness of AFOs on FPA depends on interactions between patient-specific musculoskeletal impairments (e.g., ankle–foot deformities), the aetiology of abnormal FPA and the mechanical characteristics of AFOs. For example, children with CP suffer from foot deformities such as pes planovalgus (heel valgus, midfoot planus and forefoot abduction). A pes planovalgus might result in excessive abduction of the forefoot and metatarsophalangeal joints with respect to the ankle and external FPA. Dorsal ankle–foot orthoses might not normalize FPA in these patients since they do not correct the mal-positioning of the forefoot and metatarsophalangeal joints. Clinicians and scientists should account for these individual specific impairments and prescribe patient-tailored treatment recommendations when aiming to change the FPA with orthotic treatment in patients with neurological diseases.

4.3. Effects of modifying FPA on gait performance and pain

Changes in FPA as a consequence of gait feedback training significantly correlated positively with pain reductions (Fig. 4). Within gait training studies participants received uniform training regimens and either in or out-toeing was used to reduce peak knee adduction moments and pain in patients with medial knee OA. We propose that the effect of modifying FPA on pain reduction in patients with medial knee OA is specific to the exact location of the cartilage lesion at the medial compartment of the knee. Those patients with a more posterior lesion at the medial compartment of the knee might benefit more from in-toeing gait training regimes and reductions of the first peak knee adduction moment, while those patients with a more distal lesion might benefit more from out-toeing and a reduction of the second peak knee adduction moment. Future studies should investigate the interaction between the exact location of cartilage degeneration and effectiveness of in-or out-toeing gait training regimes and develop patient-specific treatment algorithms to maximize clinical treatment effects.

Overall changes in FPA did not deteriorate gait performance as measured by walking speed and step/stride length. This finding was unexpected, since excessive in-or out-toeing gait reduces the functional lever arm and moment producing capacity at the ankle joint (Cui et al., 2019). That neither a normalisation of the FPA, nor an increase or decrease in FPA affected gait performance implies that patients were able to compensate for the mechanical disadvantage of a shorter lever arm by, for example, increased ankle muscle activity.

4.4. Clinical implications

Clinicians should use gait feedback training rather than mechanical devices to reduce pain in patients with knee OA. Mechanical devices (e.g., insoles) might be used in addition to gait feedback training but the combined effect of gait feedback training and mechanical devices is unclear. To maximize training effects, clinicians should consider to individualize gait feedback training regimens based on the exact location of the cartilage lesion (posterior/anterior), and the patients training response to implicit and explicit feedback. The effectiveness of AFOs and shoe modifications on improvements in FPA in patients with neurological diseases remains unclear. Clinical decision-making processes for AFOs and orthotic treatment should be patient-specific and guided by pre-and post-corrective assessments of walking including objective measures of FPA (e.g., 3D gait assessments).

4.5. Recommendations for research

To maximize gait training effects, future studies should aim to establish whether explicit or implicit gait feedback training improve retention of newly acquired gait skills and whether patients with more proximal medial knee OA lesions benefit more from in- as compared to out-toeing gait training modifications. Lastly, future studies should aim to establish effective mechanical devices such as AFOs or shoe modifications to improve FPA in those patients unable to voluntarily change their gait through feedback training (e.g. neurological patients).

4.6. Study limitations

This is the first review with a *meta*-analysis to examine the patient group-specific effects of mechanical and gait training interventions in correcting FPA and improving associated clinical variables. Only four out of 41 studies were RCTs, meaning that high-level evidence about the effect of conservative interventions on changing FPA in orthopaedic and neurological patients is lacking. Furthermore, the most of the studies examined the immediate effects of conservative interventions preventing us from concluding which mode of gait feedback training is most effective to facilitate retention of changes in FPA. A final limitation is that we were unable to include all studies in the *meta*-analyses due to a lack of information or heterogeneous subgroups.

5. Conclusions

Gait feedback training is more effective than external devices to produce lasting improvements in FPA, reduce pain, and maintain gait performance in patients with medial knee OA. In neurological patients, the effects of external devices on improvements in FPA depends on the interaction between patient-specific impairments and the technical properties of the external device. Future studies should determine whether gait feedback training is effective to improve FPA in specific neurological patient groups and should examine the effects of conservative interventions on associated clinical variables.

Implication

Clinicians should use gait feedback training rather than mechanical devices to reduce pain in patients with knee OA. The effectiveness of AFOs and shoe modifications on improvements in FPA in patients with neurological diseases requires individualized and patient-specific approaches which preferably include objective assessments of FPA (e.g., 3D gait assessments).

Caution

Available data concerning gait performance and clinical condition were limited and high-level evidence about the effect of conservative interventions on changing FPA is lacking. Thereby, most of the included studies examined the immediate effect of conservative interventions, lacking knowledge about the long-term effects and retention of the training.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abd El Kafy, E., El-Shemy, S., 2013. Modulation of lower extremity rotational deformities using TheraTogs^{TM} and strapping system in children with spastic diplegia. Egyptian Journal of Neurology, Psychiatry and Neurosurgery 50, 397–402.

Ahn, E., Kang, H., 2018. Introduction to systematic review and meta-analysis. Korean Journal of Anesthesiology 71, 103–112.

Bennour, S., Ulrich, B., Legrand, T., Jolles, B.M., Favre, J., 2018. A gait retraining system using augmented-reality to modify footprint parameters: Effects on lower-limb sagittal-plane kinematics. Journal of Biomechanics 66, 26–35.

Beyaert, C., Haumont, T., Paysant, J., Lascombes, P., Andre, J.M., 2003. The effect of inturning of the foot on knee kinematics and kinetics in children with treated idiopathic clubfoot. Clinical Biomechanics 18, 670–676.

Böhm, H., Matthias, H., Braatz, F., Döderlein, L., 2018. Effect of floor reaction ankle–foot orthosis on crouch gait in patients with cerebral palsy: What can be expected? Prosthetics and Orthotics International 42, 245–253.

Booij, M.J., Richards, R., Harlaar, J., van den Noort, J.C., 2020. Effect of walking with a modified gait on activation patterns of the knee spanning muscles in people with medial knee osteoarthritis. Knee 27, 198–206.

Chang, A., Hurwitz, D., Dunlop, D., Song, J., Cahue, S., Hayes, K., Sharma, L., 2007. The relationship between toe-out angle during gait and progression of medial tibiofemoral osteoarthritis. Annals of the Rheumatic Diseases 66, 1271–1275.

Charlton, J.M., Hatfield, G.L., Guenette, J.A., Hunt, M.A., 2019. Ankle Joint and Rearfoot Biomechanics During Toe-In and Toe-Out Walking in People With Medial Compartment Knee Osteoarthritis. PM & R : the journal of injury, function, and rehabilitation 11, 503–511.

Charlton, J.M., Krowchuk, N.M., Hatfield, G.L., Guenette, J.A., Hunt, M.A., 2018. Contralateral limb foot rotation during unilateral toe-in or toe-out walking in people with knee osteoarthritis. Gait and Posture 62, 132–134.

Chen, D.K.Y., Haller, M., Besier, T.F., 2017. Wearable lower limb haptic feedback device for retraining Foot Progression Angle and Step Width. Gait & posture 55, 177–183.

Cheung, R.T.H., Ho, K.K.W., Au, I.P.H., An, W.W., Zhang, J.H.W., Chan, Z.Y.S., Deluzio, K., Rainbow, M.J., 2018. Immediate and short-term effects of gait retraining on the knee joint moments and symptoms in patients with early tibiofemoral joint osteoarthritis: a randomized controlled trial. Osteoarthritis and Cartilage 26, 1479–1486.

Cho, Y., Kim, M., Lee, W., 2015. Effect of proprioceptive training on foot posture, lower limb alignment, and knee adduction moment in patients with degenerative knee osteoarthritis: A randomized controlled trial. Journal of Physical Therapy Science 27, 371–374.

Cohen, J., n.d. Statistical Power Analysis for the Behavioral Sciences Second Edition.

Cui, W., Wang, Changjiang, Chen, W., Guo, Y., Jia, Y., Du, W., Wang, Chenyan, 2019. Effects of Toe-Out and Toe-In Gaits on Lower-Extremity Kinematics, Dynamics, and Electromyography. APPLIED SCIENCES-BASEL 9.

Danino, B., Erel, S., Kfir, M., Khamis, S., Batt, R., Hemo, Y., Wientroub, S., Hayek, S., 2015. Influence of orthosis on the foot progression angle in children with spastic cerebral palsy. Gait and Posture 42, 518–522.

Demura, T., Demura, S., Yamaji, S., Yamada, T., Kitabayashi, T., 2012. Gait characteristics when walking with rounded soft sole shoes. Foot 22, 18–23.

Eddo, O.O., Lindsey, B.W., Caswell, S.V., Prebble, M., Cortes, N., 2019. Unintended Changes in Contralateral Limb as a Result of Acute Gait Modification. Journal of Applied Biomechanics 36, 13–19.

Elbaz, A., Mor, A., Segal, G., Debbi, E., Haim, A., Halperin, N., Debi, R., 2010. APOS therapy improves clinical measurements and gait in patients with knee osteoarthritis. Clinical Biomechanics 25, 920–925.

Elbourne, D.R., Altman, D.G., Higgins, J.P.T., Curtin, F., Worthington, H.V., Vail, A., 2002. Meta-analyses involving cross-over trials: Methodological issues. International Journal of Epidemiology 31, 140–149.

Faraone, S.V., 2008. Interpreting estimates of treatment effects: Implications for managed care. P and T 33.

Fritz, S.L., Rivers, E.D., Merlo, A.M., Reed, A.D., Mathern, G.W., De Bode, S., 2011. Intensive mobility training postcerebral hemispherectomy: Early surgery shows best functional improvements. European Journal of Physical and Rehabilitation Medicine 47, 569–577.

Ganjehie, S., Saeedi, H., Farahmand, B., Curran, S., 2017. The efficiency of gait plate insole for children with in-toeing gait due to femoral antetorsion. Prosthetics and Orthotics International 41, 51–57.

Gutierrez, G.M., Chow, J.W., Tillman, M.D., McCoy, S.C., Castellano, V., White, L.J., 2005. Resistance training improves gait kinematics in persons with multiple sclerosis. Archives of Physical Medicine and Rehabilitation 86, 1824–1829.

Hastings, M.K., Gelber, J.R., Isaac, E.J., Bohnert, K.L., Strube, M.J., Sinacore, D.R., 2010. Foot progression angle and medial loading in individuals with diabetes mellitus, peripheral neuropathy, and a foot ulcer. Gait & Posture 32, 237–241.

He, Z., Liu, T., Yi, J., 2019. A Wearable Sensing and Training System: Towards Gait Rehabilitation for Elderly Patients With Knee Osteoarthritis. IEEE SENSORS JOURNAL 19, 5936–5945.

Higgins, J., 2008. Chapter 9 : Analysing data and undertaking, in: Cochrane Handbook for Systematic Reviews of Interventions. pp. 1–43.

Higgins, J.P., Green, S., 2011. Chapter 8: Assessing Risk of Bias in Included Studies [WWW Document]. Cochrane Book Series, Cochrane Handbook for Systematic Reviews of Interventions.

Higgins, J.P.T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M.J., Welch, V.A., 2019. Cochrane Handbook for Systematic Reviews of Interventions. Wiley, Wiley Cochrane Series.

Huerta, J.P., Moreno, J.M.R., Kirby, K.A., Carmona, F.J.G., García, A.M.O., 2009. Effect of 7-degree rearfoot varus and valgus wedging on rearfoot kinematics and kinetics during the stance phase of walking. Journal of the American Podiatric Medical Association 99, 415–421.

Hunt, M.A., Charlton, J.M., Krowchuk, N.M., Tse, C.T.F., Hatfield, G.L., 2018. Clinical and biomechanical changes following a 4-month toe-out gait modification program for people with medial knee osteoarthritis: a randomized controlled trial. Osteoarthritis and Cartilage 26, 903–911.

Hunt, M.A., Takacs, J., 2014. Effects of a 10-week toe-out gait modification intervention in people with medial knee osteoarthritis: A pilot, feasibility study. Osteoarthritis and Cartilage 22, 904–911.

Hunt, M.A., Takacs, J., Hart, K., Massong, E., Fuchko, K., Biegler, J., 2014. Comparison of mirror, raw video, and real-time visual biofeedback for training toe-out gait in individuals with knee osteoarthritis. Archives of Physical Medicine and Rehabilitation 95, 1912–1917.

Kettlety, S., Lindsey, B., Eddo, O., Prebble, M., Caswell, S., Cortes, N., 2020. Changes in hip mechanics during gait modification to reduce knee abduction moment. Journal of biomechanics 99, 109509.

Khan, S.S.J., Khan, S.S.J., Usman, J., Mokhtar, A.H., Abu Osman, N.A., 2019. Combined effects of knee brace, laterally wedged insoles, and toe-out gait on knee adduction moment and fall risk in moderate medial knee osteoarthritis patients. Prosthetics and Orthotics International 43, 148–157.

Kim, H.J., Chun, M.H., Kim, H.M., Kim, B.R., 2013. Effects on foot external rotation of the modified ankle-foot orthosis on post-stroke hemiparetic gait. Annals of rehabilitation medicine 37, 516–522.

Kim, H.Y., Cha, Y.H., Byun, J.Y., Chun, Y.S., Choy, W.S., 2018. Changes in gait parameters after femoral derotational osteotomy in cerebral palsy patients with medial femoral torsion. Journal of pediatric orthopedics. Part B 27, 194–199.

Kranzl, A., Grasl, C., Csepan, R., Grill, F., 2013. Outcome of 23h bracing for tip-toe-walking children with cerebral palsy. Gait and Posture 38, S3.

Lindsey, B., Eddo, O., Caswell, S.V., Prebble, M., Cortes, N., 2020. Reductions in peak knee abduction moment in three previously studied gait modification strategies. Knee 27, 102–110.

Long, T.M., Toscano, K., 1995. Handbook of pediatric physical therapy, second edition.

Lou, S.-Z., Su, F.-C., Chen, Y.-C., 2015. Effects of Arch Support Insoles on Gait Patterns of Patients with Knee Osteoarthritis. JOURNAL OF MEDICAL AND BIOLOGICAL ENGINEERING 35, 202–208.

Luna, N.M.S., Lucareli, P.R.G., Sales, V.C., Speciali, D., Alonso, A.C., Peterson, M.D., Rodrigues, R.B.M., Fonoffc, E.T., Barbosac, E.R., Teixeira, M.J., Greve, J.M.D.A., 2018. Treadmill training in Parkinson's patients after deep brain stimulation: Effects on gait kinematic. NeuroRehabilitation 42, 149–158.

Maher, C.G., Sherrington, C., Herbert, R.D., Moseley, A.M., Elkins, M., 2003. Reliability of the PEDro Scale for Rating Quality of Randomized Controlled Trials. Physical Therapy 83, 713–721.

Masters, R.S.W., 1992. Knowledge, knerves and know-how: The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. British Journal of Psychology 83, 343–358.

Menz, H.B., Latt, M.D., Tiedemann, A., Mun San Kwan, M., Lord, S.R., 2004. Reliability of the GAITRite® walkway system for the quantification of temporo-spatial parameters of gait in young and older people. Gait and Posture 20, 20–25.

Merriwether, E.N., Hastings, M.K., Bohnert, K.L., Hollman, J.H., Strube, M.J., Sinacore, D.R., 2016. Impact of foot progression angle modification on plantar loading in individuals with diabetes mellitus and peripheral neuropathy. Edorium journal of disability and rehabilitation 2, 15–23.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., Altman, D., Antes, G., Atkins, D., Barbour, V., Barrowman, N., Berlin, J.A., Clark, J., Clarke, M., Cook, D., D'Amico, R., Deeks, J.J., Devereaux, P.J., Dickersin, K., Egger, M., Ernst, E., Gøtzsche, P.C., Grimshaw, J., Guyatt, G., Higgins, J., Ioannidis, J.P.A., Kleijnen, J., Lang, T., Magrini, N., McNamee, D., Moja, L., Mulrow, C., Napoli, M., Oxman, A., Pham, B., Rennie, D., Sampson, M., Schulz, K.F., Shekelle, P.G., Tovey, D., Tugwell, P., 2009. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. PLoS Medicine 6.

Nakajima, K., Kakihana, W., Nakagawa, T., Mitomi, H., Hikita, A., Suzuki, R., Akai, M., Iwaya, T., Nakamura, K., Fukui, N., 2009. Addition of an arch support improves the biomechanical effect of a laterally wedged insole. Gait and Posture 29, 208–213.

Nourai, M.H., Fadaei, B., Rizi, A.M., 2015. In-toeing and out-toeing gait conservative treatment; hip anteversion and retroversion: 10-year follow-up. Journal of Research in Medical Sciences 20, 1084–1087.

Pacheco, M.M., Newell, K.M., 2015. Transfer as a function of exploration and stabilization in original practice. Human Movement Science 44, 258–269.

Putz, C., Wolf, S.I., Geisbüsch, A., Niklasch, M., Döderlein, L., Dreher, T., 2016. Femoral derotation osteotomy in adults with cerebral palsy. Gait & posture 49, 290–296.

Rerucha, C.M., Dickison, C., Baird, D.C., 2017. Lower Extremity Abnormalities in Children. American family physician 96, 226–233.

Rethlefsen, S.A., Healy, B.S., Wren, T.A.L., Skaggs, D.L., Kay, R.M., 2006. Causes of intoeing gait in children with cerebral palsy. JOURNAL OF BONE AND JOINT SURGERY-AMERICAN 88A, 2175–2180.

Rethlefsen, S.A., Kay, R.M., 2013. Transverse plane gait problems in children with cerebral palsy. Journal of pediatric orthopedics 33, 422–430.

Richards, R.E., van den Noort, J.C., Dekker, J., Harlaar, J., 2017. Gait Retraining With Real-Time Biofeedback to Reduce Knee Adduction Moment: Systematic Review of Effects and Methods Used. Archives of Physical Medicine and Rehabilitation 98, 137–150.

Richards, R.E., van den Noort, J.C., van der Esch, M., Booij, M.J., Harlaar, J., 2018a. Effect of real-time biofeedback on peak knee adduction moment in patients with medial knee osteoarthritis: Is direct feedback effective? Clinical Biomechanics 57, 150–158.

Richards, R.E., van den Noort, J.C., van der Esch, M., Booij, M.J., Harlaar, J., 2018b. Gait retraining using real-time feedback in patients with medial knee osteoarthritis: Feasibility and effects of a six-week gait training program. The Knee 25, 814–824.

Richards, R.E., van der Esch, M., van den Noort, J.C., Harlaar, J., 2018c. The learning process of gait retraining using real-time feedback in patients with medial knee osteoarthritis. Gait & Posture 62, 1–6.

Shull, P.B., Lurie, K.L., Cutkosky, M.R., Besier, T.F., 2011. Training multi-parameter gaits to reduce the knee adduction moment with data-driven models and haptic feedback. Journal of biomechanics 44, 1605–1609.

Shull, P.B., Silder, A., Shultz, R., Dragoo, J.L., Besier, T.F., Delp, S.L., Cutkosky, M.R., 2013. Six-week gait retraining program reduces knee adduction moment, reduces pain, and improves function for individuals with medial compartment knee osteoarthritis. Journal of orthopaedic research : official publication of the Orthopaedic Research Society 31, 1020–1025.

Simic, M., Wrigley, T.V., Hinman, R.S., Hunt, M.A., Bennell, K.L., 2013. Altering foot progression angle in people with medial knee osteoarthritis: The effects of varying toe-in and toe-out angles are mediated by pain and malalignment. Osteoarthritis and Cartilage.

Sung, K.H., Kwon, S.S., Chung, C.Y., Lee, K.M., Cho, G.H., Park, M.S., 2018. Long-term outcomes over 10 years after femoral derotation osteotomy in ambulatory children with cerebral palsy. Gait and Posture 64, 119–125.

Tsushima, H., Morris, M.E., McGinley, J., 2003. Test-Retest Reliability and Inter-Tester Reliability of Kinematic Data from a Three-Dimensional Gait Analysis System. Journal of the Japanese Physical Therapy Association 6, 9–17.

Uden, H., Kumar, S., 2012. Non-surgical management of a pediatric "intoed" gait pattern - a systematic review of the current best evidence. Journal of multidisciplinary healthcare 5, 27–35.

Uhlrich, S.D., Silder, A., Beaupre, G.S., Shull, P.B., Delp, S.L., 2018. Subject-specific toe-in or toe-out gait modifications reduce the larger knee adduction moment peak more than a non-personalized approach. Journal of Biomechanics 66, 103–110.

Ulrich, B., Hoffmann, L., Jolles, B.M., Favre, J., 2020. Changes in ambulatory knee adduction moment with lateral wedge insoles differ with respect to the natural foot progression angle. Journal of Biomechanics 103, 109655.

Van Den Noort, J.C., Schaffers, I., Snijders, J., Harlaar, J., 2013. The effectiveness of voluntary modifications of gait pattern to reduce the knee adduction moment. Human Movement Science 32, 412–424.

van den Noort, J.C., Steenbrink, F., Roeles, S., Harlaar, J., 2015. Real-time visual feedback for gait retraining: toward application in knee osteoarthritis. Medical and Biological Engineering and Computing 53, 275–286.

Van Der Wilk, D., Dijkstra, P.U., Postema, K., Verkerke, G.J., Hijmans, J.M., 2015. Effects of ankle foot orthoses on body functions and activities in people with floppy paretic ankle muscles: A systematic review. Clinical Biomechanics 30, 1009–1025.

van Uden, C.J.T., Besser, M.P., 2004. Test-retest reliability of temporal and spatial gait characteristics measured with an instrumented walkway system (GAITRite). BMC musculoskeletal disorders 5, 13.

Winstein, C.J., 1991. Knowledge of results and motor learning - Implications for physical therapy. Physical Therapy 71, 140–149.

Xiang, L., Mei, Q., Fernandez, J., Gu, Y., 2020. A biomechanical assessment of the acute hallux abduction manipulation intervention. Gait and Posture 76, 210–217.

Yeh, H.-C., Chen, L.-F., Hsu, W.-C., Lu, T.-W., Hsieh, L.-F., Chen, H.-L., 2014. Immediate efficacy of laterally wedged insoles with arch support on walking in persons with bilateral medial knee osteoarthritis. Archives of physical medicine and rehabilitation 95, 2420–2427.