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Osteotomies around the knee alter alignment of the ankle and hindfoot: a systematic review of biomechanical and clinical studies

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- *Purpose:* Emerging reports suggest an important involvement of the ankle/hindfoot alignment in the outcome of knee osteotomy; however, a comprehensive overview is currently not available. Therefore, we systematically reviewed all studies investigating biomechanical and clinical outcomes related to the ankle/hindfoot following knee osteotomies.
- *Methods:* A systematic literature search was conducted on PubMed, Web of Science, EMBASE and Cochrane Library according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and registered on international prospective register of systematic reviews (PROSPERO) (CRD42021277189). Combining knee osteotomy and ankle/hindfoot alignment, all biomechanical and clinical studies were included. Studies investigating knee osteotomy in conjunction with total knee arthroplasty and case reports were excluded. The QUality Appraisal for Cadaveric Studies (QUACS) scale and Methodological Index for Non-Randomized Studies (MINORS) scores were used for quality assessment.
- *Results:* Out of 3554 hits, 18 studies were confirmed eligible, including 770 subjects. The minority of studies ($n = 3$) assessed both high tibial- and distal femoral osteotomy. Following knee osteotomy, the mean tibiotalar contact pressure decreased ($n = 4$) except in the presence of a rigid subtalar joint ($n = 1$) or a talar tilt deformity ($n = 1$). Patient symptoms and/or radiographic alignment at the level of the ankle/hindfoot improved after knee osteotomy ($n = 13$). However, factors interfering with an optimal outcome were a small preoperative lateral distal tibia angle, a small hip–knee–ankle axis (HKA) angle, a large HKA correction (>14.5°) and a preexistent hindfoot deformity (>15.9°).
- *Conclusions:* Osteotomies to correct knee deformity alter biomechanical and clinical outcomes at the level of the ankle/hindfoot. In general, these changes were beneficial, but several parameters were identified in association with deterioration of ankle/hindfoot symptoms following knee osteotomy.

Keywords
- knee osteotomy
- hindfoot alignment
- deformity correction
- biomechanical characteristics
- clinical outcome
- radiographic analysis

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Introduction

Lower limb deformity can be effectively corrected by osteotomies around the knee (1, 2, 3, 4, 5, 6, 7, 8, 9). The post-operative outcome is associated with relief of knee pain and improvement of function in the short and long term (5, 6, 10, 11, 12, 13, 14). At present, osteotomy surgeries around the knee are preoperatively planned with a focus on the hip–knee–ankle (HKA) axis. As this HKA axis stops at the tibial plafond, the hindfoot is not taken into account (4, 5, 6, 15, 16, 17, 18, 19). However, the correction of knee alignment can induce changes in the alignment of the tibiotalar and the subtalar joints, which might improve or deteriorate ankle function (20, 21, 22). Despite this replicated observation, the mechanism by which this interaction occurs is complex and poorly understood. Moreover, while an abundant amount of literature is present on the post-operative changes in lower limb alignment following knee osteotomy, a paucity of studies specifically investigates how the ankle/hindfoot alignment interferes with post-operative outcomes. The importance of taking into account the ankle/hindfoot alignment is reflected by the association with the lower limb alignment; e.g. knee varus corresponds to an oblique mechanical axis relative to the ground and enforces foot pronation through a coupled motion with the subtalar joint (23, 24, 25). Moreover, hindfoot deformity has the ability to increase the mechanical axis deviation around the knee by up to 25% (25, 26).

Ankle/hindfoot alignment impacts load transmission at the level of the knee joint with a possible repercussion on the outcome following knee osteotomy. For this reason, the rationale behind the present study is to inform clinicians on the role of the ankle/hindfoot alignment in patients who are candidates for knee osteotomy by providing a comprehensive overview of the current evidence and distilling recommendations for patient selection and surgical planning of osteotomies around the knee.

Therefore, we aimed to systematically review all studies investigating biomechanical and/or clinical outcomes associated with ankle/hindfoot alignment in the setting of knee osteotomy. We hypothesize that a corrective knee osteotomy will induce alterations of the ankle and hindfoot alignment, pressure distribution in the ankle joint and patient-reported outcome measures post-operatively.

Material and methods

The original protocol for this review is registered on PROSPERO (international prospective register of systematic reviews) which can be accessed online (CRD42021277189). Electronic databases, DARE, CDSR and PROSPERO, could not identify previously performed reviews investigating ankle/hindfoot alignment in the setting of osteotomies around the knee. A systematic review of the literature was subsequently conducted in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Fig. 1). PubMed, Web of Science, EMBASE and Cochrane library were searched to identify studies addressing the relationship between knee osteotomy and ankle/hindfoot malalignment, clinically and/or radiographically. On all electronic databases, identical search strategies were performed by combining 'knee osteotomy' OR 'femoral osteotomy' OR 'tibial osteotomy' AND 'hindfoot alignment' OR 'ankle alignment' OR 'hindfoot deformity' OR 'ankle deformity'. Additional studies were identified by screening the bibliographies. Data searches were up to date until February 2022. The obtained search results were reviewed in two consecutive steps, first screening the abstract and second reading the full text. The inclusion and exclusion criteria were applied by two reviewers (AB: board-certified orthopaedic surgeon, and AVO: orthopaedic resident). Disagreements over a particular study were resolved via discussion with a third reviewer (JV: board-certified orthopaedic surgeon). In this study, a preoperative ankle or hindfoot deformity was defined as either a medial (varus) or lateral (valgus) deviation from the neutral vertical or horizontal axis, prior to performing knee osteotomy.

Studies published from inception until February 2022 were selected according to the following eligibility criteria. The inclusion criteria consisted of (i) study design: randomized (RCT), non-randomized (nRCT) controlled trials, observational studies (prospective or retrospective),

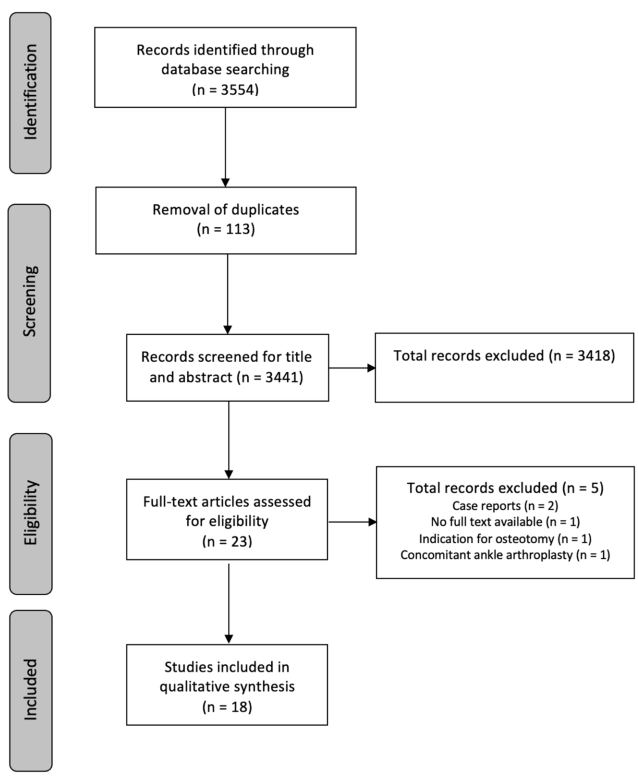

Figure 1
Flowchart outlining the selection of studies for inclusion in this systematic review in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA).

case–control studies and controlled laboratory studies; (ii) adult patients or cadaveric specimens who underwent knee osteotomy with concomitant clinical and/or radiographic and/or biomechanical ankle/hindfoot investigations; (iii) patient reported outcome measures and/or angular measurements and/or pressure measurements; (iv) follow-up time of at least 3 months in case of clinical studies; and (v) published in English. Studies were excluded if (i) the study design was a case report or an expert opinion and (ii) knee osteotomy was performed in conjunction with knee or ankle arthroplasty. Titles and abstracts were screened by the main author and selected for review. The obtained results were peer evaluated to ensure that no abstracts had been excluded unnecessarily. The full text of these articles was retrieved and assessed by the same review team.

In the select studies, a division was made in two groups: (i) reports investigating the biomechanical interaction between knee osteotomy and ankle/hindfoot alignment and (ii) reports analysing the clinical interaction between knee osteotomy and ankle/hindfoot alignment. In each group, both the effect of the knee osteotomy on alignment at the level of the ankle/hindfoot and the impact of ankle/hindfoot alignment on the outcome at the level of the knee were observed. Studies were considered biomechanical if they comprised kinematic and kinetic investigations in the setting of knee osteotomy. Whereas studies were termed clinical if they focused on patient-reported outcome measures (PROMs) and/or radiographic data. The clinical impact of knee osteotomy on the ankle/hindfoot was assessed by evaluating changes in PROMs and/or classic radiographic measurements. The biomechanical impact was assessed by evaluating changes in pressure distributions and gait patterns. The type and source of funding were also derived from the selected studies. The heterogeneity in the study design and outcomes of the selected studies was investigated. Study details were summarized in a table for comparison.

The MINORS criteria (Methodological Index for Non-Randomized Studies) were used as a validated instrument to assess the methodological quality of non-randomized surgical studies, whether comparative or non-comparative. The checklist applied a series of questions (eight for non-controlled and twelve for controlled studies) to score relevant aspects of each study. The eight included categories to evaluate non-controlled studies are (i) a clearly stated aim, (ii) inclusion of consecutive patients, (iii) prospective data collection, (iv) endpoints appropriate to the aim of the study, (v) unbiased assessment of the study endpoint, (vi) follow-up period appropriate to the study aim, (vii) loss to follow-up less than 5% and (viii) a prospective calculation of the sample size. Each of these questions was answered with ‘not reported’ (0 points), ‘reported but inadequate’ (1 point) or ‘reported and adequate’ (2 points). For comparative clinical studies, four more questions were added, resulting in a global ideal score of 24. The MINORS checklist was assessed by the same review team. As there was no standardized evidence in the literature to classify MINORS scores, categories were determined in accordance with the study of Ekhtiari *et al.*: ‘very low’: 0 to 4 points; ‘low’: 5 to 8 points; ‘good’: 9 to 12 points; ‘excellent’: 13 to 16 points. In accordance with the study of Ekhtiari *et al.*, the first quartile was considered ‘very low’, the second quartile as ‘low’, the third as ‘good’ and the fourth quartile as ‘excellent’ for comparative studies. The quality of cadaveric studies was assessed using the highly reliable and valid QUality Appraisal for Cadaveric Studies (QUACS) scale. The checklist applied a series of 13 questions. The following subjects were scored: (i) a clearly stated aim, (ii) sufficient information about the sample, (iii) thorough description of methodology, (iv) state and type of embalmment of the specimens, (v) number of researchers, (vi) unambiguous description of the results, (vii) statistical methodology, (viii) consistency of the findings, (ix) photographs of the observations, (x0) discussion within the context of current evidence, (xi) clinical implications and (xii) limitations of the study. Each item was scored either by 0 (not reported or inadequate) or 1 (reported and adequate) point, resulting in a global ideal score of 13. The score was described as the ratio of the reached score to the maximum score in percentage. Parallel to the aforementioned interpretation of the MINORS score, the first quartile was considered as ‘very low’, the second as ‘low’, the third as ‘good’ and the fourth as ‘excellent’ (27).

Following the search and identification of eligible studies, the variation in measurement methods used to determine biomechanical and clinical outcome parameters in the different studies did not allow to perform a meta-analysis. Therefore, a narrative synthesis of the individual study results was performed in line with the guidance from the Centre for Reviews and Dissemination. No external funding was obtained for this study.

Results

A total of 3554 hits were identified based on the proposed search criteria. Subsequently, 113 duplicate studies were removed from the analysis. Following, 3441 records were screened for title and abstract. The inclusion and exclusion criteria were applied to the remaining 23 studies. Two case reports and a study published in 1993 of which no full text was available were excluded. One study combined knee osteotomy with ankle arthroplasty and a second performed distal femoral osteotomy for high femoral anteversion instead of knee joint malalignment. A final number of 18 studies were confirmed eligible for review. A detailed overview of the study selection process was presented by a flowchart (Fig. 1).

Study characteristics

Based on 13 retrospective cohort studies (20, 21, 22, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37), two case–control studies (38, 39) and three laboratory studies (40, 41, 42), a total of 770 subjects were assessed. Five of these reports were classified as biomechanical (35, 38, 40, 42) and thirteen as clinical studies (20-22, 28-34, 36, 37, 39). The study details are reported in Table 1. Data extracted from included studies are summarized in Table 2.

Biomechanical reports included three cadaveric studies (40, 41, 42), one gait analysis study (38) and one study assessing the distribution patterns of subchondral bone density (35). The mean sample size in the included biomechanical studies was 18 (range: 7–40). Regarding the investigational modalities, three studies applied intra-articular pressure sensors (40, 41, 42), two studies used full-leg X-radiographs (35, 38), one study added concomitant computed tomography (CT) imaging (35) and one study implemented a mobility capturing (MoCap) system (38). Clinical reports included twelve retrospective studies (20, 21, 22, 28, 29, 30, 31, 32, 33, 34, 36, 37) and one case-control study (39). The mean sample size of patients included in the clinical studies was 53.1 (range: 10–118). The mean follow-up period was 33.7 months (range: 3 months–8 years). Six of the clinical studies assessed the PROMs using subjective clinical scoring systems (20, 21, 22, 37, 38, 39). Radiographic analysis relied on full-leg radiographs. Detailed ankle or hindfoot radiographs were added in three out of the thirteen studies (31, 32, 36). Regarding the source of funding of both the biomechanical and clinical studies, three studies reported that their work was done without financial support (29, 36, 37). One study reported industry funding, which was received

Table 1 Study details.

Study	Funding source	Study design	LOE[*]	Cohort description	*n*	Sex M	Sex F	Mean age	Follow-up time
Ariywatkul *et al.* (28)	N/R	RCS	III	Varus knee alignment + medial opening wedge HTO	34	1	33	51	12 months
Choi *et al.* (22)	N/R	RCS	III	Varus knee alignment + medial opening wedge HTO	86	48	38	61.6	26.4 months
Choi *et al.* (29)	No	RCS	III	Varus knee alignment + medial opening wedge HTO	35	N/R	N/R	N/R	12 months
Kazemi *et al.* (30)	N/R	RCS	III	Varus knee alignment + HTO	39	16	23	37.5	6 months
Kazemi *et al.* (31)	Yes	RCS	III	Varus knee alignment + opening wedge HTO	33	9	24	31.9	> 10 months
Kim *et al.* (32)	N/R	RCS	III	Varus knee alignment + HTO	40	7	33	69.9	N/R
Konrads *et al.* (33)	Yes	RCS	III	Varus knee alignment	118	N/R	N/R	N/R	
				Valgus knee alignment	36	N/R	N/R	N/R	
				HTO or DFO	154	58	96	51	N/R
Krause *et al.* (40)	N/R	LS	N/A	Cadaveric knees + varus and valgus knee alignment + HTO or DFO	12	7	5	75.8	N/A
Kwon *et al.* (34)	Yes	RCS	III	Varus knee alignment + HTO	81	24	57	55.5	N/R
Kyung *et al.* (38)	Yes	CCS	III	Varus knee alignment + opening or closing wedge HTO	24	6	18	55.0	12.7 months
Lee *et al.* (39)	N/R	CCS	III	Varus knee alignment + HTO	50	12	38	53	>12 months
Matsubara *et al.* (35)	N/R	RCS	IV	Varus knee alignment					>12 months
				Medial opening wedge HTO	18	7	11	60.5	
				Lateral closing wedge HTO	12	3	9	59.1	
Miyazaki *et al.* (36)	No	RCS	III	Varus knee alignment + medial wedge opening HTO	43	12	31	64.8	3 months
Monteiro *et al.* (37)	No	RCS	III	Varus knee alignment	34	N/R	N/R	49	
				Valgus knee alignment	8	N/R	N/R		
				HTO and/or DFO	42	19	20		55 months
Shah *et al.* (21)	N/R	RCS	III	Varus knee alignment + medial opening wedge HTO	43	31	12	45.2	59 months
Suero *et al.* (42)	Yes	LS	N/A	Cadaveric knees; varus knee alignment + medial opening wedge HTO	7	N/R	N/R	N/R	N/A
Suero *et al.* (41)	Yes	LS	N/A	Cadaveric knees; varus knee alignment + medial opening wedge HTO	7	N/R	N/R	N/R	N/A
Takeuchi *et al.* (20)	N/R	RCS	IV	Varus knee alignment + lateral closing wedge HTO	10	1	9	66.7	8 years

[*]Data from: Obremskey WT, Pappas N, Attallah-Wasif E, Tornetta P, 3rd, Bhandari M. Level of evidence in orthopaedic journals. *The Journal of bone and joint surgery American volume*. 2005 **87** 2632–2638.
CCS, case–control study; DFO, distal femoral osteotomy; HTO, high tibial osteotomy; LOE, level of evidence; LS, laboratory study; N, number of patients; N/A, not applicable; N/R, not reported; OA, osteoarthritis; RCS, retrospective cohort study.

Table 2 Study details of clinical and radiographical outcomes, correlations and conclusions.

Study	Biomechanical outcome	Clinical outcome		Conclusion
		Subjective measures	Radiographical outcome	
Ariywatkul *et al.* (28)	N/R	N/R	The TT changed from 2.09° to 1.62° ($P > 0.05$). FTA correction of over 14.5° gives a 50% chance of altering ankle alignment in the coronal plane.	Altering the anatomical femorotibial axis with more than 14.5° results in increased risk for excessive talar tilt.
Choi *et al.* (22)	N/R	Significant improvement in mean WOMAC score ($P < 0.05$) and HSS score ($P < 0.05$) at the level of the knee following osteotomy; the VAS score improved in patients with ankle OA and a more parallel joint line post-operatively. It significantly decreased in group B patients.	TPI and TI decreased significantly ($P < 0.001$). No significant changes in TT were observed. Group A and B were defined for decreasing and increasing absolute values of TPI and TI, respectively. Mean preoperative LDTA was smaller in group B than in group A ($P < 0.001$).	In group A, the tibial plafond and talar dome became more parallel to the ground following MOWHTO. In group B (smaller preoperative HKA and LDTA), a shift from nearly neutral to a more valgus constitution of the tibial plafond and talar dome was observed. Coronal alignment changes affect ankle symptoms. The LDTA relates to pre- and post-operative TPI and TI.
Choi *et al.* (29)	N/R	N/R	No significant changes in TAS or TT ($P > 0.05$). Significant decrease of the TPI and TI following MOWHTO ($P < 0.05$); Significant increase in HAVA and HMA following osteotomy ($P < 0.05$).	MOWHTO positively interferes with preoperatively present hindfoot valgus deformity, decreasing the valgus deviation.
Kazemi *et al.* (30)	N/R	N/R	A significant change in TPI from 8.10° to −0.30° was observed ($P < 0.05$). No significant changes in LDTA and TT.	As the TPI decreases following HTO, shearing forces exerted on the tibiotalar joint are reduced.
Kazemi *et al.* (31)	N/R	N/R	The heel alignment angle changed from 5.9° to 3.4° valgus pre- to post-operatively ($P = 0.04$).	A significant positive relationship is observed between the amount of varus correction and changes in hindfoot alignment. The subtalar joint can compensate for knee deformities.
Kim *et al.* (32)	N/R	N/R	The ankle joint WBL ratio increased ($P < 0.001$), shifting the mechanical axis laterally. The AJLO-G decreased ($P < 0.001$).	HTO for genu varum correction results in a lateral shift of the ankle joint WBL and valgization of the ankle joint line orientation.
Konrads *et al.* (33)	N/R	N/R	The mean TPI changed from 4.2° to 1.0° ($P < 0.001$) and from from −2.8° to 0.2° ($P < 0.001$) following respectively valgization or varization. The mechanical LDTA changed from 87.2° to 85.8° ($P < 0.001$) and from 85.9 to 85.7 ($P > 0.05$).	Varization and valgization osteotomies around the knee alter the coronal orientation of the ankle, including both distal femoral and high tibial osteotomies.
Krause *et al.* (40)	The centre of force shifted 2.5 mm and 2.9 mm for 5° and 10° HTO respectively in a varus fixed position ($P < 0.001$). In a fixed valgus position, it shifted respectively 1.1 mm and 0.9 mm ($P < 0.001$).	N/R	N/R	For a fixed subtalar joint in varus or valgus, the centre of force shifts significantly following opening wedge HTO. There is no significant change in maximal pressure observed.
Kwon *et al.* (34)	N/R	N/R	The ankle joint axis point on the weight-bearing axis moves laterally by 0.9% of the length of the tibial plafond in the coronal plane for every degree decrease in HKA ($P < 0.001$).	Varus knee correction based on HTO can alter the subtalar and ankle joint.
Kyung *et al.* (38)	Comparing gait analysis, compensatory pronation was normalized following HTO.	N/R	The TAS angle remained 87.74° ($P > 0.05$). The TPI changed from 5.66° to 1.10° ($P < 0.001$).	Comparing gait analysis pre- and post-HTO, midfoot compensation was normalized following HTO. The hindfoot segment did not change significantly.
Lee *et al.* (39)	N/R	WOMAC scores not individually reported.	Following HTO, the TPI increased from −5.6° to 3.4° ($P < 0.001$). The AJLO-G decreased from 8.8° to 2.0° ($P < 0.001$).	Following HTO, the ankle joint comes more parallel to the ground. There was no statistically significant association between radiographic changes and clinical outcome.

(*continued*)

Table 2 Continued.

Study	Biomechanical outcome	Clinical outcome: Subjective measures	Clinical outcome: Radiographical outcome	Conclusion
Matsubara, *et al.* (35)	In the opening wedge group, the percentage of high-density area increased medially from 49.3% to 53.0% ($P < 0.05$) and decreased laterally from 21.4% to 17.2% ($P < 0.01$). In the closing wedge group, this percentage decreased medially from 55.7% to 35.7% ($P=0.001$) and increased laterally from 23.6% to 29.2% ($P < 0.01$).	N/R	Following opening wedge and closing wedge HTO, the TPI changed from 5.9° to −2.76° ($P < 0.001$) and from 7.41° to 0.97° ($P < 0.001$). There was no significant change in the LDTA.	Following opening wedge HTO without fibular osteotomy, the distribution pattern of subchondral bone density of the ankle shifted medially, whereas it shifted more laterally following closing wedge HTO with fibular osteotomy.
Miyazaki *et al.* (36)	N/R	N/R	The mean AJLO-G and JLCA decreased respectively from 6.2° to 1.3° and 3.6° to 2.7° ($P < 0.001$); following MOWHTO, the HAVA changed from 8.7° to 6.2° ($P=0.001$). The hindfoot alignment angle changed from 15.4° to 10.5° ($P < 0.001$). A preoperative hindfoot angle increasing 15.9° predicts under correction at the knee joint.	A greater hindfoot alignment angle increases the risk of undercorrection when performing a MOWHTO. For a hindfoot alignment angle ≥15.9°, MOWHTO should be reconsidered.
Monteiro *et al.* (37)	N/R	14% reported ankle pain following knee osteotomy. Ankle pain was not correlated with pre- and post-operative radiographic measurements ($P > 0.05$).	The TI changed from −6.65° to −0.78° and from 5.06° to 0.24°, respectively, in preoperative knee valgus or varus alignment. Similarly, the TPI changed from −6.43° to −0.3° and from 4.71° to 0.69°.	Following knee osteotomy, 14% of the patients developed low-grade ankle symptoms.
Shah *et al.* (21)	N/R	New-onset ankle or hindfoot pain was observed in 7 out of 35 cases following MOWHTO.	As the mean TPI changed from −0.8° to −9.2°, the joint became less parallel to the ground.	Approximately 20% of the cases had new-onset ankle pain following MOWHTO. The risk for developing symptoms increased for a change in TPI ≥ 10°.
Suero *et al.* (42)	Intraarticular ankle pressure minimally changed for a 5° change in the mechanical alignment ($P > 0.05$). For corrections of 10° and 15°, mean contact pressures decreases respectively by 14% ($P < 0.05$) and 17% ($P < 0.05$). The mean contact surface area decreased by 20% ($P=0.001$).	N/R	N/R	Changes in proximal tibia alignment alter the tibiotalar contact surface area and intraarticular ankle pressures. Progressive valgus realignment in HTO reduces the tibiotalar contact area linearly whereas the mean contact pressure decreases.
Suero *et al.* (41)	The mean intra-articular contact pressure and contact area in the ankle joint decreased respectively from 2623.3 N/mm^2 to 1873.8 N/mm^2 ($P < 0.001$) and from 3.5 mm^2 to 2.6 mm^2 ($P < 0.001$). Tibial external rotation further reduced mean contact pressure and contact area ($P < 0.001$).	N/R	N/R	Malrotation of the distal tibial fragment results in abnormal ankle pressures.
Takeuchi *et al.* (20)	N/R	The mean HSS score improved from 54 to 91 points ($P < 0.01$) at the level of the knee. The mean AOFAS scale improved from 56 to 88 points ($P < 0.01$).	The TI changed from 9.3° to −2.0° (medial inclination). The TT improved from 18° to 6.1°. The TAS changed from 88° to 84°.	Following MCWHTO, both clinical and radiographic improvements in TI and TT were observed. No statistically significant change was observed in TAS angle.

AJLO-G, ankle joint line orientation relative to the ground; AOFAS, American Orthopaedic Foot and Ankle Society; FTA, anatomical femorotibial angle; HAVA, hindfoot alignment view angle; HKA, hip–knee–ankle angle; HMA, hindfoot moment arm; HTO, high tibial osteotomy; JLCA, Joint line conversion angle; LCWHTO, lateral closing wedge high tibial osteotomy; LDTA, lateral distal tibial angle; MCWHTO, medial closing wedge high tibial osteotomy; MOWHTO, medial opening wedge high tibial osteotomy; N/R, not reported; OA, osteoarthritis; TAS, distal tibial articular surface; TI, talar inclination; TPI, tibial plafond inclination; TT, talar tilt; VAS, Visual Analogue Scale; WBL, weight-bearing line; WOMAC, Western Ontario and McMaster Universities Osteoarthritis Index; HSS, Hospital for Special Score.

outside the conducted studies (33). A total of five studies reported funding from a National Research Foundation and/or an independent research institute (31, 34, 38, 41, 42). Nine studies did not report disclosures or sources of funding (Table 1).

Biomechanical effect on the ankle/hindfoot

The biomechanical effect on the ankle and hindfoot of distal femoral osteotomy (DFO) or high tibial osteotomy (HTO) to correct knee varus deformity was studied in three *in vitro* cadaveric (40, 41, 42) and two *in vivo* reports (35, 38). Suero *et al.* in an *in vitro* study, observed that progressive correction of the mechanical knee alignment decreased mean tibiotalar contact pressure and contact surface area (39, 42). Similar findings were observed by Krause *et al.* for an adaptable, supple subtalar joint. However, in case of a rigid subtalar joint, the centre of force in the ankle joint shifted significantly more toward the lateral edge of the ankle joint (40). Matsubara *et al.* in an *in vivo* study, described increased medial tibial subchondral bone density following opening wedge osteotomy HTO when the fibula was left intact. The opposite phenomenon was observed for combined closing wedge and fibular osteotomy (35). Dynamic assessment based on gait analysis was performed by Kyung *et al.*, who observed normalization of midfoot pronation (38). The biomechanical effect of the ankle/hindfoot alignment on the knee osteotomy outcome was investigated by Suero *et al.*, who found increased knee contact pressures in the presence of a less parallel ankle joint line orientation (42).

Clinical effect on the ankle/hindfoot

The clinical effect of knee osteotomy on the ankle and hindfoot was described in 13 studies by investigating the PROMs and radiographic parameters (20, 21, 22, 28, 29, 30, 31, 32, 33, 34, 36, 37, 39). Regarding the PROMs, Takeuchi *et al.* observed a significant improvement of the mean American Orthopaedic Foot and Ankle Society (AOFAS) score following lateral closing wedge high tibial osteotomy (LCWHTO) ($P < 0.01$) (20). Similarly, Choi *et al.* described a significant improvement in the pain Visual Analog Scale (VAS) in the ankle osteoarthritis (OA) patient subgroup that obtained parallelization of the ankle joint line orientation following medial opening wedge high tibial osteotomy (MOWHTO). Of note, the VAS score did not significantly alter in patients without ankle OA who presented with a more parallel ankle joint line following surgery. In contrast, a significant increase in the VAS score was observed for the subgroup with a more valgus aligned ankle joint line post-operatively, both in patients with and without ankle OA (22). Moreover, Shah *et al.* demonstrated that approximately 20% developed new-onset, ankle pain following MOWHTO. This risk for symptom development markedly increased for a tibial plafond inclination (TPI) angle exceeding 10° (21). On the contrary, Monteiro *et al.* observed the onset or deterioration of ankle symptoms in 14% of the patients following knee osteotomy but did not observe a significant correlation with increasing ankle joint line obliquity (37). The clinical effect of ankle/hindfoot alignment on the knee joint following osteotomy was investigated in two studies (36, 39). Regarding the PROMs, a tendency of a residual higher Western Ontario and McMaster Universities Arthritis Index (WOMAC) score following HTO was observed in patients with a post-operative less neutral ankle joint line and hindfoot alignment but was not significant (39).

Regarding the radiographic alignment, 12 studies observed the horizontal ankle joint line alignment (20, 21, 22, 28, 29, 30, 32, 33, 34, 36, 37, 39). Eleven studies demonstrated preoperative valgus orientation of the ankle joint line which improved significantly as the ankle joint line attained a more parallel orientation relative to the ground (20, 22, 28, 29, 30, 32, 33, 34, 36, 37, 39). Of note, if the preoperative ankle joint line was nearly neutral, the tibial plafond and talar dome attained more valgus orientation (21, 22). Moreover, Ariywatkul *et al.* demonstrated that altering the anatomical femorotibial axis with more than 14.5° improves the risk for reduced parallelism of the ankle joint line (28). The vertical ankle joint alignment was assessed in nine studies based on the tibial anterior surface (TAS) angle, the lateral distal tibial angle (LDTA) and the weight-bearing line (WBL) ratio (20, 22, 29, 30, 32, 33, 34, 35, 38). The majority observed no significant changes in TAS and LDTA following knee joint osteotomy. However, it should be taken into account that a smaller preoperative LDTA resulted in an increased valgus angulation of the ankle joint post-operatively (22). Kim *et al.* quantified the WBL ratio of the ankle joint, which incremented as the mechanical axis shifted more laterally (32). In this respect, Kwon *et al.* determined that for a 1° correction of the HKA angle, the ankle joint axis point shifted laterally by 0.9% of the length of the tibial plafond (34). The hindfoot alignment was assessed in three studies based on the hindfoot alignment view angle (HAVA) and heel alignment angle. A significant improvement of the HAVA and heel alignment angle was observed post-operatively, which corresponded to a more neutral hindfoot alignment post-operatively (29, 36). Regarding the impact of radiographic ankle/hindfoot alignment on the knee joint following osteotomy, Miyazaki *et al.* stated that a preoperative HAVA exceeding 15.9° of valgus was a predictive factor for undercorrection of knee joint alignment (36).

Table 3 Assessment of the methodological quality of included clinical and biomechanical studies.

Study	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Total*
MINORS														
Ariywatkul *et al.* (28)	2	1	0	2	0	2	1	0	–	–	–	–	–	8
Choi *et al.* (22)	2	2	1	2	2	2	1	0	–	–	–	–	–	12
Choi *et al.* (29)	2	2	1	2	0	2	1	0	–	–	–	–	–	10
Kazemi *et al.* (30)	2	1	0	2	0	1	0	0	–	–	–	–	–	6
Kazemi *et al.* (31)	2	2	0	2	0	1	0	0	–	–	–	–	–	7
Kim *et al.* (30)	2	2	1	2	2	0	1	0	–	–	—	–	–	10
Konrads *et al.* (33)	2	2	0	2	0	0	1	0	–	–	–	–	–	7
Kwon *et al.* (34)	2	2	1	2	1	0	1	0	–	–	–	–	–	9
Kyung *et al.* (38)	2	2	1	2	0	2	0	0	2	1	1	2	–	15
Lee *et al.* (39)	2	2	0	2	0	2	2	0	2	2	2	2	–	18
Matsubara *et al.* (35)	2	2	1	2	2	2	1	0	–	–	–	–	–	12
Monteiro *et al.* (37)	2	2	0	2	1	2	2	0		—	–	–	–	11
Miyazaki *et al.* (36)	2	2	1	2	0	1	1	0	–	–	–	–	–	9
Shah *et al.* (21)	2	2	1	2	1	2	1	0	–	–	–	–	–	11
Takeuchi *et al.* (20)	2	1	0	2	0	2	0	0	–	–	–	–	–	7
QUACS														
Krause *et al.* (40)	1	1	1	0	0	0	1	1	0	1	1	1	1	9–69
Suero *et al.* (42)	1	0	1	0	0	0	1	0	0	0	1	1	1	6–46
Suero *et al.* (41)	1	1	1	0	0	0	1	1	0	1	1	1	1	9–69

MINORS (Methodological Index for Non-Randomized Studies) score. Items scored 0 (not reported), 1 (reported but inadequate) or 2 (reported and adequate); QUACS (QUality Appraisal for Cadaveric Studies). Items scored 0 (not reported or inadequate) and 1 (reported and adequate).
*Values are total (relative to maximum) % for QUACS.
N/A, not applicable.

Quality assessment

For the cadaveric studies, a mean of 61.3% on the QUACS scale was observed (range: 46–69). One study was considered a 'low' methodological quality and two studies a 'good' methodological quality. For the clinical, non-comparative studies, a mean of 9.2 (range: 6–12) was observed. Five studies contained a 'low' methodological quality and eight studies had a 'good' methodological quality. The mean score of the two case–control studies was 16.5 (range: 15–8). Both comparative studies were considered a 'good' methodological quality (Table 3).

Discussion

Myriad studies focused on the overall lower limb alignment after knee osteotomy, but a paucity of reports investigated the biomechanical and clinical outcomes related to the ankle/hindfoot alignment. Since most existing reports are scattered across the literature, we systematically reviewed all biomechanical and clinical studies investigating the relation between the ankle/hindfoot alignment and osteotomies around the knee. The principal findings of this study demonstrated that knee osteotomy to correct coronal plane deformity is able to reduce ankle joint line obliquity and improve patient-reported outcome scores at the ankle/hindfoot in the presence of a supple subtalar joint. Conversely, a less neutral ankle/hindfoot alignment improved the risk for undercorrection of the knee joint alignment and for increased patient-reported pain measures at the level of the knee. Off note, most reports focused on high tibial osteotomies correcting a knee varus deformity. Since distal femoral osteotomies were underreported in literature, the distillation of general findings was impeded. To the best of our knowledge, this study is the first to have systematically reviewed reports investigating the interplay between knee osteotomy and the ankle/hindfoot alignment in order to provide a comprehensive overview for orthopaedic researchers or clinicians.

Our study presents several limitations. First and common to other systematic reviews, some papers may not have been identified with the applied search criteria. This could be attributed to the initial search terms or exclusion of papers not written in English. However, additional screening of bibliographies was performed to improve the search process. Secondly, a relatively small number and a heterogeneous group of studies wereconfirmed eligible for this systematic review. Especially, the variability in reported biomechanical and clinical outcomes did not allow to calculate a meta-analysis or an overall intervention effect. Moreover, most reports focused on high tibial osteotomies to correct varus malalignment. The possible effects of a distal femoral osteotomy often remained uninvestigated. Future research should standardize reporting of both clinical PROMs and radiographic measurements to determine both knee and ankle/hindfoot alignment. Thirdly, quality assessment showed that four of the included studies had a relatively low methodological quality. For this reason, future studies should use prospective cohort studies with a substantial sample size. Methodological challenges of current PROMs could be addressed using newer generation patient-reported outcome measures and information systems. Similarly, shortcomings of plain radiographs such as rotational errors or superposition of osseous ankle and hindfoot structures can be overcome by the recent availability of weight-bearing cone beam CT imaging (43, 44, 45, 46, 47, 48). Finally, only one-third of the identified studies contained a follow-up time of 2 years or longer, and only three studies focused on distal femoral osteotomies. This may reduce the validity of this systematic review to draw long-term and general conclusions for knee osteotomy. Future long-term prospective studies using multivariate analysis should be performed to identify interference between knee osteotomy and ankle/hindfoot alignment and assess whether these differ between high tibial or distal femoral osteotomies.

Biomechanically, static *in vitro* studies demonstrated a reduction of the tibiotalar contact pressure at the level of the ankle joint after knee osteotomy (40, 42). However, this was negatively impacted in case of a higher degree of knee deformity correction or altered tibia rotation after osteotomy and when the subtalar joint was rigidity fixed (40, 41, 42). The latter could be attributed to the function of the subtalar joint, which acts as a torque transmitter to compensate for coronal plane deformity and to maintain the talus normally aligned relative to the tibia (40, 49, 50). Similar results were found in previous cadaveric reports, which demonstrated that post-traumatic coronal plane deformities of the proximal and middle third of the tibia of up to 15° had no statistically significant influence on the loaded area of the ankle until the subtalar joint was fixed (51, 52). *In vivo* research demonstrated comparable subchondral bone densities of the ankle joint toward control patients after osteotomy and less foot pronation during gait analysis (35, 38). This preoperative foot pronation was interpreted as a compensatory mechanism to acquire a plantigrade foot in a varus alignment of the knee (53). Post-operatively, data showed that this compensatory pronation could no longer be detected because there was no more need for the foot to accommodate for knee varus after corrective osteotomy.

Clinically, most of the studies demonstrated improvement of the ankle and hindfoot symptomology following knee osteotomy (20, 21, 22, 28, 29, 30, 32, 33, 34, 36, 37, 39). On the contrary, some studies demonstrated the onset or deterioration of hindfoot symptomology in association with several radiographic findings (21, 22). No studies could be identified investigating the repercussion of a residual hindfoot deformity on PROMs at the level of the knee. Radiographically, joint line obliquity at the level of the ankle was observed in the majority of patients preoperatively and reduced after

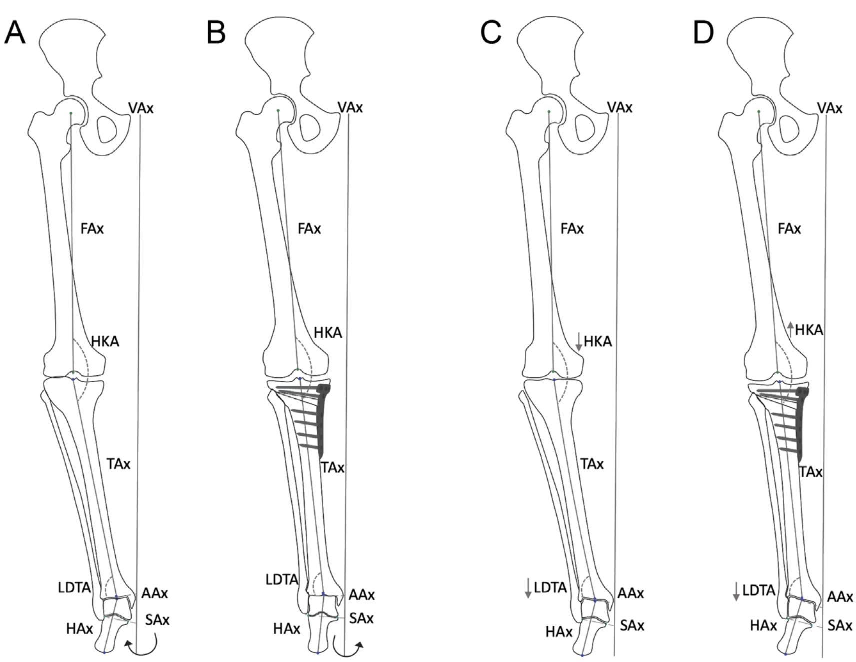

Figure 2
Hindfoot alignment in knee varus deformity pre- (A, C) and post-operative (B, D) following knee osteotomy. (A) The femoral axis (FAx) and tibia axis (TAx) constitute the hip–knee–ankle (HKA) angle and depict a varus angulation of the lower limb towards the vertical axis (VAx). The hindfoot contains a valgus compensation for the varus of the knee as demonstrated by the hindfoot axis (HAx) and subtalar axis (SAx). This mechanism presumably occurs due to the changes in the loading axis of the lower limb associated with varus of the knee, which triggers the subtalar joint to evert in the coronal plane to obtain a plantigrade foot. (B) HKA deformity is corrected following knee osteotomy and improvement of the valgus alignment of the hindfoot is noted as a result of the compensatory capacity of the subtalar joint. Note a preoperative varus orientation of ankle joint axis (AAx), which corrects parallel to the floor post-operatively. (C) the HKA angle demonstrates varus alignment of the lower limb with a smaller lateral distal tibia (LDTA) and HKA angulation preoperatively. (D) This resulted in a valgus orientation of the AAx, which was associated with newly onset or deterioration of symptoms at the level of the hindfoot. This phenomenon is aggravated when HKA corrections exceed 14.5° (28).

knee osteotomy (20, 21, 22, 28, 29, 30, 31, 32, 33, 34, 36, 37, 39). Additionally, some studies demonstrated changes in the weight-bearing axis, which shifted more centrally at the level of the ankle joint after knee osteotomy (36). These alternations might be beneficial for the ankle since joint line obliquity is associated with more shear stresses and deviation from the weight-bearing axis is related to uneven stress distribution on the articular cartilage surface (54, 55, 56, 57). Moreover, the majority of studies linked a more parallel joint line orientation of the ankle to improved subjective patient outcome scores following knee joint osteotomy. However, several studies identified other radiographic parameters in which these beneficial corrections may not apply: a small preoperative HKA and LDTA and a high HKA correction of more than 14.5° (22, 28). In the presence of these factors, ankle joint line obliquity increased after knee osteotomy instead of attaining a more neutral orientation.

Conversely, the hindfoot alignment impacted radiographic outcome at the level of the knee. A high preoperative hindfoot deformity was identified as a causative factor for undercorrection of the knee alignment after osteotomy despite an adequate preoperative planning of the correction and wedge size (28, 36).

The obtained findings parallel previous literature on the relation of the ankle and hindfoot alignment in the setting of total knee arthroplasty (58, 59, 60, 61, 62). Similarly, these studies demonstrated an improvement of both function and alignment in the majority of patients. However, stiffness or a remaining deformity of the ankle/hindfoot after knee arthroplasty was associated with a negative outcome. These findings were also attributed to deterioration of the subtalar joint function to compensate for an altered lower limb alignment (58, 59, 63).

Conclusion

In conclusion, this study demonstrates that correction of the lower limb alignment after knee osteotomy works in concert with the orientation of the ankle and hindfoot. Knee osteotomy is capable of improving biomechanical properties and clinical outcomes at the level of the ankle/hindfoot. However, this may not apply if there is a rigid subtalar joint, small preoperative LDTA and HKA or a large post-operative HKA correction (Fig. 2). Moreover, residual hindfoot deformity after knee osteotomy impacts pressure distribution and resulted in an undercorrection at the level of the knee alignment. Future research should include large prospective cohorts with longer follow-up, using standardized clinical as well as radiographical measurements pre- and post-operative in both distal femoral and high tibial osteotomies. This would help to understand and identify the optimal position of the ankle and hindfoot following knee osteotomy. In addition, randomized controlled trials could be performed in patients requiring knee osteotomy with concomitant hindfoot deformities or ankle pathologies to determine at which stage corrective treatment of the ankle/hindfoot would be indicated to improve the overall outcome of knee osteotomy and to draw long-term conclusions.

ICMJE Conflict of Interest Statement

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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Author contribution statement

A Van Oevelen: manuscript writing, study design and formal analysis; A Burssens: manuscript writing, study design, and formal analysis; N Krähenbühl: manuscript writing, conceptualization and generating figures; A Barg: manuscript writing and conceptualization; B Devos: manuscript writing, study design and conceptualization; E Audenaert: manuscript writing, study design, conceptualization and funding acquisition; B Hintermann: manuscript writing, conceptualization and interpretation of the findings; J Victor: manuscript writing, formal analysis, conceptualization, study design and funding acquisition.

References

1. **Brinkman JM, Lobenhoffer P, Agneskirchner JD, Staubli AE, Wymenga AB & Van Heerwaarden RJ**. Osteotomies around the knee: patient selection, stability of fixation and bone healing in high tibial osteotomies. *Journal of Bone and Joint Surgery. British Volume* 2008 **90** 1548–1557. (https://doi.org/10.1302/0301-620X.90B12.21198)

2. **Punwar S & Haddad FS**. High tibial osteotomy: back to the future. *British Journal of Hospital Medicine* 2007 **68** 36–41. (https://doi.org/10.12968/hmed.2007.68.1.22654)

3. **Wylie JD, Jones DL, Hartley MK, Kapron AL, Krych AJ, Aoki SK & Maak TG**. Distal femoral osteotomy for the valgus knee: medial closing wedge versus lateral opening wedge: a systematic review. *Arthroscopy* 2016 **32** 2141–2147. (https://doi.org/10.1016/j.arthro.2016.04.010)

4. **Snow M, Jermain P, Mandalia V, Murray J, Khakha R, McNicholas M, Dawson M** & UK Knee Osteotomy consensus Group. A 2021 consensus statement on osteotomies around the knee by the UK Knee Osteotomy consensus Group (KOG). *Knee* 2021 **33** 73–83. (https://doi.org/10.1016/j.knee.2021.08.034)

5. **Rosso F & Margheritini F**. Distal femoral osteotomy. *Current Reviews in Musculoskeletal Medicine* 2014 **7** 302–311. (https://doi.org/10.1007/s12178-014-9233-z)

6. **Bonasia DE, Governale G, Spolaore S, Rossi R & Amendola A**. High tibial osteotomy. *Current Reviews in Musculoskeletal Medicine* 2014 **7** 292–301. (https://doi.org/10.1007/s12178-014-9234-y)

7. **Ferrera A & Menetrey J**. Optimizing indications and technique in osteotomies around the knee. *EFORT Open Reviews* 2022 **7** 396–403. (https://doi.org/10.1530/EOR-22-0057)

8. McCormack DJ, Puttock D & Godsiff SP. Medial compartment osteoarthritis of the knee: a review of surgical options. *EFORT Open Reviews* 2021 **6** 113–117. (https://doi.org/10.1302/2058-5241.6.200102)

9. Jones GG, Jaere M, Clarke S & Cobb J. 3D printing and high tibial osteotomy. *EFORT Open Reviews* 2018 **3** 254–259. (https://doi.org/10.1302/2058-5241.3.170075)

10. Aoki Y, Yasuda K, Mikami S, Ohmoto H, Majima T & Minami A. Inverted V-shaped high tibial osteotomy compared with closing-wedge high tibial osteotomy for osteoarthritis of the knee: ten-year follow-up result. *Journal of Bone and Joint Surgery. British Volume* 2006 **88** 1336–1340. (https://doi.org/10.1302/0301-620X.88B10.17532)

11. Howells NR, Salmon L, Waller A, Scanelli J & Pinczewski LA. The outcome at ten years of lateral closing-wedge high tibial osteotomy: determinants of survival and functional outcome. *Bone and Joint Journal* 2014 **96–B** 1491–1497. (https://doi.org/10.1302/0301-620X.96B11.33617)

12. Niinimäki TT, Eskelinen A, Mann BS, Junnila M, Ohtonen P & Leppilahti J. Survivorship of high tibial osteotomy in the treatment of osteoarthritis of the knee: Finnish registry-based study of 3195 knees. *Journal of Bone and Joint Surgery. British Volume* 2012 **94** 1517–1521. (https://doi.org/10.1302/0301-620X.94B11.29601)

13. Saito T, Kumagai K, Akamatsu Y, Kobayashi H & Kusayama Y. Five-to ten-year outcome following medial opening-wedge high tibial osteotomy with rigid plate fixation in combination with an artificial bone substitute. *Bone and Joint Journal* 2014 **96–B** 339–344. (https://doi.org/10.1302/0301-620X.96B3.32525)

14. Coakley A, McNicholas M, Biant L & Tawy G. A systematic review of outcomes of high tibial osteotomy for the valgus knee. *Knee* 2023 **40** 97–110. (https://doi.org/10.1016/j.knee.2022.11.007)

15. Cooke TDV, Sled EA & Scudamore RA. Frontal plane knee alignment: a call for standardized measurement. *Journal of Rheumatology* 2007 **34** 1796–1801.

16. Deep K, Eachempati KK & Apsingi S. The dynamic nature of alignment and variations in normal knees. *Bone and Joint Journal* 2015 **97–B** 498–502. (https://doi.org/10.1302/0301-620X.97B4.33740)

17. Wright JG, Treble N & Feinstein AR. Measurement of lower limb alignment using long radiographs. *Journal of Bone and Joint Surgery. British Volume* 1991 **73** 721–723. (https://doi.org/10.1302/0301-620X.73B5.1894657)

18. Bartholomeeusen S, Van den Bempt M, van Beek N, Claes T & Claes S. Changes in knee joint line orientation after high tibial osteotomy are the result of adaptation of the lower limb to the new alignment. *Knee* 2020 **27** 777–786. (https://doi.org/10.1016/j.knee.2020.04.018)

19. Marques Luís N & Varatojo R. Radiological assessment of lower limb alignment. *EFORT Open Reviews* 2021 **6** 487–494. (https://doi.org/10.1302/2058-5241.6.210015)

20. Takeuchi R, Saito T & Koshino T. Clinical results of a valgus high tibial osteotomy for the treatment of osteoarthritis of the knee and the ipsilateral ankle. *Knee* 2008 **15** 196–200. (https://doi.org/10.1016/j.knee.2008.02.002)

21. Shah SMR, Roberts J & Picard F. Ankle and hindfoot symptoms after medial open wedge high tibial osteotomy. *Journal of Knee Surgery* 2019 **32** 269–273. (https://doi.org/10.1055/s-0038-1641143)

22. Choi GW, Yang JH, Park JH, Yun HH, Lee YI, Chae JE & Yoon JR. Changes in coronal alignment of the ankle joint after high tibial osteotomy. *Knee Surgery, Sports Traumatology, Arthroscopy* 2017 **25** 838–845. (https://doi.org/10.1007/s00167-015-3890-3)

23. Burssens ABM, Buedts K, Barg A, Vluggen E, Demey P, Saltzman CL & Victor JMK. Is lower-limb alignment associated with hindfoot deformity in the coronal plane? A weightbearing CT analysis. *Clinical Orthopaedics and Related Research* 2020 **478** 154–168. (https://doi.org/10.1097/CORR.0000000000001067)

24. Dagneaux L, Dufrenot M, Bernasconi A, Bedard NA, de Cesar Netto C & Lintz F. Three-dimensional biometrics to correlate hindfoot and knee coronal alignments using modern weightbearing imaging. *Foot and Ankle International* 2020 **41** 1411–1418. (https://doi.org/10.1177/1071100720938333)

25. Guichet JM, Javed A, Russell J & Saleh M. Effect of the foot on the mechanical alignment of the lower limbs. *Clinical Orthopaedics and Related Research* 2003 (415) 193–201. (https://doi.org/10.1097/01.blo.0000092973.12414.ec)

26. Duggal N, Paci GM, Narain A, Bournissaint LG & Nazarian A. A computer assessment of the effect of hindfoot alignment on mechanical axis deviation. *Computer Methods and Programs in Biomedicine* 2014 **113** 126–132. (https://doi.org/10.1016/j.cmpb.2013.09.010)

27. Wilke J, Krause F, Niederer D, Engeroff T, Nürnberger F, Vogt L & Banzer W. Appraising the methodological quality of cadaveric studies: validation of the QUACS scale. *Journal of Anatomy* 2015 **226** 440–446. (https://doi.org/10.1111/joa.12292)

28. Ariyawatkul T, Pornrattanamaneewong C, Narkbunnam R & Chareancholvanich K. Talar coronal malalignment as a consequence after high tibial osteotomy in osteoarthritic knee patients. *Journal of the Medical Association of Thailand* 2014 **97**(9) S34–S38.

29. Choi JY, Song SJ, Kim SJ, Kim SH, Park JS & Suh JS. Changes in hindfoot alignment after high or low tibial osteotomy. *Foot and Ankle International* 2018 **39** 1097–1105. (https://doi.org/10.1177/1071100718773767)

30. Kazemi SM, Qoreishi M, Behboudi E, Manafi A & Kazemi SK. Evaluation of Changes in the tibiotalar joint after High Tibial Osteotomy. *Archives of Bone and Joint Surgery* 2017 **5** 149–152. (https://doi.org/10.22038/abjs.2017.8430)

31. Kazemi SM, Aidenlou A, Qoreishy SM & Minaei R. High tibial osteotomy effects on subtalar joint in patients with genu varum. *Archives of Bone and Joint Surgery* 2022 **10** 166–170. (https://doi.org/10.22038/ABJS.2021.52069.2571)

32. Kim JG, Suh DH, Choi GW, Koo BM & Kim SG. Change in the weight-bearing line ratio of the ankle joint and ankle joint line orientation after knee arthroplasty and high tibial osteotomy in patients with genu varum deformity. *International Orthopaedics* 2021 **45** 117–124. (https://doi.org/10.1007/s00264-020-04799-0)

33. Konrads C, Eis A, Ahmad SS, Stöckle U & Döbele S. Osteotomies around the knee lead to corresponding frontal realignment of the ankle. *European Journal of Orthopaedic Surgery and Traumatology: Orthopedie Traumatologie* 2022 **32** 675–682. (https://doi.org/10.1007/s00590-021-03016-x)

34. Kwon SS, Yoo JD & Lee SY. Linear mixed modeling on the effects of varus knee surgery on the ankle joint weight-bearing axis. *Foot and Ankle Surgery* 2022 **28** 114–118. (https://doi.org/10.1016/j.fas.2021.02.008)

35. Matsubara S, Onodera T, Iwasaki K, Hishimura R, Matsuoka M, Kondo E & Iwasaki N. Discrepancy in the distribution patterns of subchondral bone density across the ankle joint after medial opening-wedge and lateral closing-wedge high tibial osteotomy. *American Journal of Sports Medicine* 2022 **50** 478–485. (https://doi.org/10.1177/03635465211062235)

36. Miyazaki K, Maeyama A, Yoshimura I, Kobayashi T, Ishimatsu T & Yamamoto T. Influence of hindfoot alignment on postoperative lower limb alignment in medial opening wedge high tibial osteotomy. *Archives of Orthopaedic and Traumatic Surgery* 2021 **143** 81–90. (https://doi.org/10.1007/s00402-021-04001-z)

37. Monteiro S, Barbosa L, Cardoso A, Machado L & Correia de Jesus M. Osteotomies around the knee are not correlated to substantial post-operative ankle pain. *Knee Surgery, Sports Traumatology, Arthroscopy* 2023 **31** 3637–3645. (https://doi.org/10.1007/s00167-021-06699-1)

38. Kyung MG, Cho YJ, Hwang S, Lee DO, Lee MC & Lee DY. Change in intersegmental foot and ankle motion after a high tibial osteotomy in genu varum patients. *Journal of Orthopaedic Research* 2021 **39** 86–93. (https://doi.org/10.1002/jor.24834)

39. Lee KM, Chang CB, Park MS, Kang SB, Kim TK & Chung CY. Changes of knee joint and ankle joint orientations after high tibial osteotomy. *Osteoarthritis and Cartilage* 2015 **23** 232–238. (https://doi.org/10.1016/j.joca.2014.11.001)

40. Krause F, Barandun A, Klammer G, Zderic I, Gueorguiev B & Schmid T. Ankle joint pressure changes in high tibial and distal femoral osteotomies: a cadaver study. *Bone and Joint Journal* 2017 **99–B** 59–65. (https://doi.org/10.1302/0301-620X.99B1.38054)

41. Suero EM, Hawi N, Westphal R, Sabbagh Y, Citak M, Wahl FM, Krettek C & Liodakis E. The effect of distal tibial rotation during high tibial osteotomy on the contact pressures in the knee and ankle joints. *Knee Surgery, Sports Traumatology, Arthroscopy* 2017 **25** 299–305. (https://doi.org/10.1007/s00167-015-3553-4)

42. Suero EM, Sabbagh Y, Westphal R, Hawi N, Citak M, Wahl FM, Krettek C & Liodakis E. Effect of medial opening wedge high tibial osteotomy on intraarticular knee and ankle contact pressures. *Journal of Orthopaedic Research* 2015 **33** 598–604. (https://doi.org/10.1002/jor.22793)

43. Barg A, Bailey T, Richter M, de Cesar Netto C, Lintz F, Burssens A, Phisitkul P, Hanrahan CJ & Saltzman CL. Weightbearing computed tomography of the foot and ankle: emerging technology topical review. *Foot and Ankle International* 2018 **39** 376–386. (https://doi.org/10.1177/1071100717740330)

44. Bernasconi A, Cooper L, Lyle S, Patel S, Cullen N, Singh D & Welck M. Intraobserver and interobserver reliability of cone beam weightbearing semi-automatic three-dimensional measurements in symptomatic pes cavovarus. *Foot and Ankle Surgery* 2020 **26** 564–572. (https://doi.org/10.1016/j.fas.2019.07.005)

45. de Cesar Netto C, Godoy-Santos AL, Saito GH, Lintz F, Siegler S, O'Malley MJ, Deland JT & Ellis SJ. Subluxation of the middle facet of the subtalar joint as a marker of peritalar subluxation in adult acquired flatfoot deformity: a case-control study. *Journal of Bone and Joint Surgery. American Volume* 2019 **101** 1838–1844. (https://doi.org/10.2106/JBJS.19.00073)

46. Lintz F, de Cesar Netto C, Barg A, Burssens A, Richter M & Weight Bearing CT International Study Group. Weight-bearing cone beam CT scans in the foot and ankle. *EFORT Open Reviews* 2018 **3** 278–286. (https://doi.org/10.1302/2058-5241.3.170066)

47. Richter M, Seidl B, Zech S & Hahn S. PedCAT for 3D-imaging in standing position allows for more accurate bone position (angle) measurement than radiographs or CT. *Foot and Ankle Surgery* 2014 **20** 201–207. (https://doi.org/10.1016/j.fas.2014.04.004)

48. Sasaki R, Niki Y, Kaneda K, Yamada Y, Nagura T, Nakamura M & Jinzaki M. A novel anteroposterior axis of the tibia for total knee arthroplasty: an upright weight-bearing computed tomography analysis. *Knee* 2022 **36** 80–86. (https://doi.org/10.1016/j.knee.2022.04.009)

49. Wang B, Saltzman CL, Chalayon O & Barg A. Does the subtalar joint compensate for ankle malalignment in end-stage ankle arthritis? *Clinical Orthopaedics and Related Research* 2015 **473** 318–325. (https://doi.org/10.1007/s11999-014-3960-8)

50. Hintermann B, Knupp M & Barg A. Peritalar instability. *Foot and Ankle International* 2012 **33** 450–454. (https://doi.org/10.3113/FAI.2012.0450)

51. Tarr RR, Resnick CT, Wagner KS & Sarmiento A. Changes in tibiotalar joint contact areas following experimentally induced tibial angular deformities. *Clinical Orthopaedics and Related Research* 1985 **199** 72–80. (https://doi.org/10.1097/00003086-198510000-00011)

52. Ting AJ, Tarr RR, Sarmiento A, Wagner K & Resnick C. The role of subtalar motion and ankle contact pressure changes from angular deformities of the tibia. *Foot and Ankle* 1987 **7** 290–299. (https://doi.org/10.1177/107110078700700505)

53. da Silva HGPV, Zorzi AR, da Silva HPV & de Miranda JB. Gait analysis in short-term follow-up of medial opening wedge high tibial osteotomy. *European Journal of Orthopaedic Surgery and Traumatology: Orthopedie Traumatologie* 2018 **28** 939–946. (https://doi.org/10.1007/s00590-017-2099-1)

54. Egloff C, Paul J, Pagenstert G, Vavken P, Hintermann B, Valderrabano V & Müller-Gerbl M. Changes of density distribution of the subchondral bone plate after supramalleolar osteotomy for valgus ankle osteoarthritis. *Journal of Orthopaedic Research* 2014 **32** 1356–1361. (https://doi.org/10.1002/jor.22683)

55. Hintermann B, Barg A & Knupp M. Corrective supramalleolar osteotomy for malunited pronation-external rotation fractures of the ankle. *Journal of Bone and Joint Surgery. British Volume* 2011 **93** 1367–1372. (https://doi.org/10.1302/0301-620X.93B10.26944)

56. Schmid T, Zurbriggen S, Zderic I, Gueorguiev B, Weber M & Krause FG. Ankle joint pressure changes in a pes cavovarus model: supramalleolar valgus osteotomy versus lateralizing calcaneal osteotomy. *Foot and Ankle International* 2013 **34** 1190–1197. (https://doi.org/10.1177/1071100713500473)

57. Stufkens SA, Van Bergen CJ, Blankevoort L, Van Dijk CN, Hintermann B & Knupp M. The role of the fibula in varus and valgus deformity of the tibia: a biomechanical study. *Journal of Bone and Joint Surgery. British Volume* 2011 **93** 1232–1239. (https://doi.org/10.1302/0301-620X.93B9.25759)

58. Burssens A, De Roos D, Barg A, Welck MJ, Krähenbühl N, Saltzman CL & Victor J. Alignment of the hindfoot in total knee arthroplasty: a systematic review of clinical and radiological outcomes. *Bone and Joint Journal* 2021 **103–B** 87–97. (https://doi.org/10.1302/0301-620X.103B1.BJJ-2020-0143.R1)

59. Hara Y, Ikoma K, Arai Y, Ohashi S, Maki M & Kubo T. Alteration of hindfoot alignment after total knee arthroplasty using a novel hindfoot alignment view. *Journal of Arthroplasty* 2015 **30** 126–129. (https://doi.org/10.1016/j.arth.2014.07.026)

60. Lee JH & Jeong BO. Radiologic changes of ankle joint after total knee arthroplasty. *Foot and Ankle International* 2012 **33** 1087–1092. (https://doi.org/10.3113/FAI.2012.1087)

61. Norton AA, Callaghan JJ, Amendola A, Phisitkul P, Wongsak S, Liu SS & Fruehling-Wall C. Correlation of knee and hindfoot deformities in advanced knee OA: compensatory hindfoot alignment and where it occurs. *Clinical Orthopaedics and Related Research* 2015 **473** 166–174. (https://doi.org/10.1007/s11999-014-3801-9)

62. Oussedik S, Abdel MP, Victor J, Pagnano MW & Haddad FS. Alignment in total knee arthroplasty? *Bone and Joint Journal* 2020 **102–B** 276–279. (https://doi.org/10.1302/0301-620X.102B3.BJJ-2019-1729)

63. Hayashi K, Tanaka Y, Kumai T, Sugimoto K & Takakura Y. Correlation of compensatory alignment of the subtalar joint to the progression of primary osteoarthritis of the ankle. *Foot and Ankle International* 2008 **29** 400–406. (https://doi.org/10.3113/FAI.2008.0400)