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Change in gait biomechanics after total ankle replacement and ankle arthrodesis: a systematic review and meta-analysis

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ABSTRACT

Background: The aim of this systematic review with meta-analysis was to determine the change in gait biomechanics after total ankle replacement and ankle arthrodesis for end-stage osteoarthritis.

Methods: Electronic databases were searched up until May 2019. Peer-reviewed journal studies including adult participants suffering from end-stage ankle osteoarthritis and reporting pre- and post-operative kinematics, kinetics and spatio-temporal effects of total ankle replacement and ankle arthrodesis during walking were included with a minimum of 12 months follow-up. Seventeen suitable studies were identified and assessed according to methodological and biomechanical qualities. Meta-analysis was performed by calculating the effect size using standard mean differences between pre- and post-operative gait status.

Findings: Seventeen studies with a total of 883 patients were included. Meta-analysis revealed moderate evidence of an improvement in lower limb kinematics, kinetics and spatio-temporal parameters after total ankle replacement. Moderate evidence indicated an increase in ankle moment, hip range of motion and walking speed after ankle arthrodesis.

Interpretation: The currently available evidence base of research papers evaluating changes in gait biomechanics after total ankle replacement and ankle arthrodesis is limited by a lack of prospective research, low sample sizes and heterogeneity in the patho-etiology of ankle osteoarthritis. Following total ankle replacement, improvements were demonstrated for spatio-temporal, kinematic and kinetic gait patterns compared to the pre-operative measures. Improvements in gait mechanics after ankle arthrodesis were limited to walking speed and ankle moment. Increased hip range of motion after ankle arthrodesis could represent a sign of compensation for the lack of ankle motion.

Keywords: Osteoarthritis; Ankle replacement; Arthroplasty; Arthrodesis; Gait Analysis; Biomechanics

1. INTRODUCTION

Osteoarthritis (OA) of the ankle is a common chronic disorder characterized by progressive joint degeneration, significant pain and disability, with approximately 1% of the world's adult population living with symptomatic ankle OA.^{1,13,20,33,42} Currently, the “gold standard” surgical treatment is ankle arthrodesis (AA), which provides good pain relief and a relatively well-documented long-term survivalship of AA.^{14,15,22,47,48} However, AA leads to deficits in work and leisure activities and to adjacent joint degeneration,^{4,12,19,35,54} thought to be a consequence of altered mechanical loads as a result of the change in function of the ankle.^{4,5,12,19} These disadvantages have encouraged the use of motion-sparing procedures such as total ankle replacement (TAR), the potential benefits of which are conserving the existing pre-operative ankle range of motion (RoM), improving gait and protecting the adjacent joints^{8,10,26}, although the latter has not yet been proven.³⁴

Three-dimensional gait analysis (3DGA) is the state of the art of measuring lower limb joint kinematics and kinetics simultaneously during activities of the daily living. Three narrative reviews of the literature reported the impact of TAR and AA on the lower limb gait mechanics and outcomes.^{3,28,36} However, these papers did not assess the overall effect size of these procedures on the biomechanical parameters of interest between pre-and post-operative time points, which raises questions regarding the evidence supporting the biomechanical value of TAR and AA in patients suffering from end-stage ankle OA. The relative advantages of TAR versus AA continue to be one of the most debated topics in foot and ankle surgery. Do TAR patients maintain or improve their pre-operative dorsi-/plantarflexion ankle motion during gait? Do TAR and AA patients improve their foot mechanics relative to their pre-operative state? The debate also continues as to which ankle prosthesis design should be used to provide the best clinical outcome, the evidence from the TAR group overall being unclear. The objective of this review is to present a quantitative assessment of the scientific credibility

and clinical utility of the present knowledge regarding the assessment of the biomechanical effect of TAR and AA in patients suffering from end-stage ankle OA.

2. METHODS

The systematic review protocol was developed in accordance to the guidelines provided by the Preferred Reporting of Systematic Reviews and Meta-Analysis (PRISMA) Statement.²⁹

The protocol for the review was registered in the International Prospective register for Systematic Reviews (PROSPERO; registration no. CRD42018110053).

2.1. Search strategy

The Population, Intervention, Comparison and Outcome (PICO) framework was used to define the search strategy. The following databases were searched from inception: Cochrane Library, PubMed and Web of Science (via ISI Web of Knowledge) (until May 2019). The three main groups of keywords covering all MeSH terms and keywords related to “ankle osteoarthritis”, “biomechanical and locomotion metrics” and “ankle arthrodesis / ankle prosthesis” were used in this review (example for PubMed in Fig. 1). Databases were searched by two reviewers, with agreement required on the number of search hits achieved before screening was initiated. References and abstracts of studies were stored alphabetically using the reference management software Mendeley (Elsevier, Netherlands). Additional relevant papers were found by examining the reference lists of papers identified in the initial searches. Duplicate references sourced from different electronic searches were removed. The inclusion and exclusion process was performed by two reviewers (JLB & PAD) based on the title and abstract of the identified papers. A full-text evaluation was undertaken if the title and abstract did not provide adequate information. A consensus meeting was held to resolve any areas of disagreement between reviewers, and the opinion of a 3rd reviewer (AN) was

sought if a consensus was not reached. To affirm the inclusion of all eligible studies, one reviewer (PAD) subsequently manually screened the reference lists of all included articles.

2.2. Eligibility criteria

Studies published in English as full papers were eligible for inclusion in this review when they met the following criteria: 1) participants were adults aged ≥ 18 years undergoing primary TAR and AA; 2) ankle OA was the principal indicator for surgical intervention; 3) studies reported at least pre-operative and post-operative gait data; 4) a minimum of 12 months follow-up providing evidence of any pre- to post-operative changes in gait;^{2,51} 5) the use of non-invasive/in-vivo 3DGA using a motion capture system to collect at least joint kinematic data based on the trajectories of skin-mounted markers.); and 6) the participants were able to perform the given task unaided. Studies including participants with a history of other major medical conditions affecting gait or previous surgery (e.g. neuromuscular diseases, revision lower limb arthroplasty, etc.) were not eligible for inclusion. Letters, conference proceedings, case reports, cadaveric studies, bone pin (invasive) studies, abstracts and reviews were excluded from the review.

2.3. Methodological quality assessment

A modified version of the Downs and Black Quality Index was used to evaluate the methodological quality of the selected papers.¹⁶ The methodological quality of the papers was assessed using a subset of the data extracted to gauge both internal and external validity. Two reviewers (PAD, LC) independently evaluated the quality of each study, and any discrepancies were resolved during a consensus meeting. The opinion of a 3rd reviewer (AN) was sought if a consensus could not be reached. The modified version of the Downs and Black Quality Index¹⁶ is scored out of 26, with higher scores indicating higher-quality

studies. The studies were ranked using the following classifications: “high quality” (HQ) having scores greater than 21; “moderate quality” (MQ) having scores between 17 and 21; “fair quality” (FQ) having scores between 14 and 17 and “poor quality” (PQ) having scores lower than 14.³¹ A Kappa inter-rater agreement test (Kappa (K) statistic) was used to evaluate the agreement between the two reviewers (PAD and LC). The K value was interpreted as follows: scores < 0.20 rated as Poor, scores between 0.21-0.40 rated as Fair, scores between 0.41-0.60 rated as Moderate, scores between 0.61-0.80 rated as Good, and scores between 0.81-1.00 rated as Very good. Studies rated as “poor quality” were excluded from the systematic review.

2.4. Outcome measures and data extraction

A data-extraction file created in Cochrane Review Manager (RevMan, V.5, Cochrane Collaboration, Oxford, UK) was used to extract numerical data from all studies by two reviewers (PAD & AN). Once completed, one of the two reviewers compared the original data with the extracted data to verify that the data were extracted accurately from the studies included in the meta-analysis. The primary outcome measures for this review were spatiotemporal, kinematic and kinetic parameters reported during level walking. Means and standard deviations (SD) for all gait variables relating to the affected ankle were extracted for pre-operative and the final post-operative assessments in order to determine the long term effect of surgery on gait function, as functional recovery can take 6 to 12 months.⁵¹ To assist the interpretation of findings, one investigator (PAD) extracted data regarding study design, participant characteristics and publication details.

2.5. Data synthesis and analysis

Where adequate data were reported, means and standard deviations (SDs) of the following gait variables were used to calculate standardized mean differences (SMD and 95% confidence intervals) between pre- and post-operative assessments using Cochrane Review Manager (V.5) (RevMan, V.5, Cochrane Collaboration, Oxford, UK): ankle RoM, maximal ankle dorsiflexion and plantarflexion angle, maximal ankle moment, maximal ankle power, knee RoM, hip RoM, walking speed, cadence, stance duration and step length. When means and SDs were not reported by the authors estimations were made using the methodology described by Wan et al. and medians and interquartile ranges used.⁵² Meta-analyses were performed by calculating the effect size using the standardized mean differences, and a random-effects model. Interpretation of SMD magnitude was based on previous recommendations, where SMD values were considered large (> 1.2), medium (0,6-1,2) or small ($< 0,6$). No significant differences were considered to have been identified from the meta-analysis when the 95% confidence interval was exceeded 0 ($P < 0.05$). When appropriate data (e.g. means and SDs) were not provided in the publication, authors were contacted with a request to provide additional data. In the case of non-response, the variables were recorded as “not reported” and excluded for further analysis.²⁵ Forest plots were produced using Cochrane Review Manager (V.5) to facilitate the interpretation of SMD values and their respective 95% Confidence Interval (CI). Results of studies were pooled if adequate homogeneity was found to occur in terms of research design and outcome measures. The level of statistical heterogeneity for pooled data was tested by using a chi-squared test and I^2 statistics.²⁴ Heterogeneity was defined as high ($>75\%$), moderate (50-75%), and low (25-50%).²⁴ When adequate data were reported in the same international system of units, mean differences (MD and 95% confidence intervals) between pre- and post-operative time points were calculated.

2.6. Evidence-based recommendations

Based on the previous publication of van Tulder et al. (2003), levels of evidence were assigned for each variable of interest, based on the statistical outcomes and methodological quality of the included studies.⁴⁹ Levels of evidence are described in Table 2.

3. RESULTS

3.1. Review selection and identification

Details of the search results and the process of inclusion and exclusion are shown in Table 1. A total of 6475 citations were retrieved from the electronic database search. After applying the eligibility criteria and searching reference lists, 129 references were identified as being eligible for full-text review based on their title and abstract. Of these, 112 papers were subsequently excluded, the main reasons for exclusion being cadaveric studies, finite element studies and studies without preoperative gait data. Seventeen papers were included for final review.

3.2. Quality assessment

The Downs and Black scale checklist scores ranged from 9 to 23 of a possible 26 (Appendix file 1). Of the 17 studies included, 2 had a score lower than 14 (rated as “poor quality”).^{9,18} One study was rated as high-quality scoring between 26 and 22,³⁹ and two studies were rated as “moderate quality” scoring between 18 and 21.^{11,37} Twelve studies were rated as “fair quality” scoring between 14 and 17.^{5,7,8,21,23,26,32,38,40,41,44,45} The Kappa inter-rater agreement

value, including the assessment of the 17 studies, was 0.747 (95% CI 0.682 to 0.813), indicating a good agreement between the two reviewers (PAD and LC). Of the 17 papers, 14 were case series studies, 1 was a prospective cohort study and 2 were retrospective studies (Table 2).

3.3. Sample selection, composition and description

Study details including sample sizes, participant demographics and type of prosthesis used are shown in Table 2. The number of participants ranged from 9 to 229 in the 17 studies. Gender male:female ratio was not reported in 3 studies. The subtype of OA was reported in 8 of the 17 studies. The characterization of the investigated ankle OA describing the subtype of ankle OA and its associated osteo-articular deformity was poorly described in 14 studies. Post-traumatic ankle OA was the most common aetiology reported by subjects in all of the included studies. Only one study reported the radiographic severity of ankle OA prior to surgery.⁵⁰ The most common intervals between intervention and follow up were 12 and 24 months (range: 12 to 49 months).

3.4. Study procedures related to gait specific measurement protocol

Conventional marker setups and lower limb models available with the Motion Capture systems were most commonly used for gait data acquisition, and kinematic and kinetic computation (Table 2). The foot was modelled in most of the studies as a single rigid element, except for the study of Flavin (2013). Variables relating to the mechanical behaviour of the lower limb were limited to the sagittal plane in 12 of the included studies.

3.5. Outcome measures

A summary of findings for each gait variable in the meta-analysis is shown in Table 3 & 4 and Supplementary Materials with detailed information of the magnitude of effects and the strength of evidence provided below.

3.5.1. Ankle dorsi- / plantarflexion RoM

Based on the overall pooled SMD from 11 studies totalling 280 participants, moderate evidence indicated an increase in ankle RoM after the implantation of TAR (SMD: 0.68, 95%CI 0.51 to 0.85) with a MD of 3.20° (95%CI 2.44-3.96)(Fig.2). Mobile-bearing TAR showed similar improvements in ankle RoM than the fixed-bearing TAR (Table 4).^{7-9,11,18,23,26,39,46,51}

There was limited evidence of no change in ankle dorsi-/plantarflexion RoM after an AA in the 17 studies (Fig.3).^{5,18,23}

3.5.2. Maximum ankle dorsiflexion angle

8 studies reported moderate evidence of an increase in ankle dorsiflexion angle after the implantation of a TAR (SMD: 0.37, 95%CI 0.14 to 0.59) with a MD of 1.72° (95%CI 0.70-2.73).^{7,9,11,18,26,37,44,46} Fixed-bearing TAR showed similar improvements in ankle dorsiflexion angle to the mobile-bearing TAR (Table 4).^{11,37,44}

Limited evidence indicated no change in ankle dorsiflexion angle after an AA.^{5,18,44}

3.5.3. Maximum ankle plantarflexion angle

Moderate evidence indicated an increase in ankle plantarflexion angle after implantation of a TAR (SMD: 0.37, 95%CI 0.14 to 0.60) with a MD of 2.03° (95%CI 1.07-2.99).^{7,9,11,18,26,39,44,46} Six studies^{7,9,18,26,39,46} analysing mobile-bearing prostheses reported moderate evidence of an increase in ankle plantarflexion angle after implantation (SMD: 0.38, 95%CI 0.06 to 0.71) with a MD of 2.18° (95%CI 0.78-3.58). However, pooled data of studies analysing fixed-bearing prostheses showed moderate evidence of no increase or decrease in ankle plantarflexion RoM after surgery.^{11,37,44}

Limited evidence of no change in ankle plantarflexion angle after an AA.^{5,18,44}

3.5.4. Peak plantarflexion ankle moment

Based on the pooled SMD from 10 studies totalling 224 participants, there was moderate evidence of an increase in peak plantarflexion ankle moment (SMD: 0.39, 95%CI 0.15 to 0.64) after TAR (Table 3 & 4, Fig.2).^{8,9,11,18,23,26,39,44,46,51} No MD could be given for studies analysing mobile-bearing prostheses as two of the studies^{9,26} normalized the data by a length measurement as well as a weight measurement.

There was moderate evidence of an increase in ankle moment after an AA (SMD: 0.54, 95%CI 0.17 to 0.92) with a MD of 0.16 N.m/kg (95%CI 0.05 to 0.27)(Fig. 3).^{5,18,23,44}

3.5.5. Maximal ankle power

The overall pooled SMD from 8 studies totalling 271 participants showed moderate evidence that patients exhibited an improvement in ankle power generation after TAR compared to pre-operative levels (SMD: 0.71, 95%CI 0.53 to 0.88) with a MD of 0.28 W/kg (95%CI 0.18 to 0.38) (Table 3 & 4, Fig.2).^{7,8,11,18,39,44,46,51} Three studies indicated moderate evidence that ankle power did not change after an AA (Fig.3).^{5,18,44}

3.5.6. *Knee flexion/extension RoM*

There was moderate evidence that patients with a TAR exhibited an improvement in knee flexion/extension RoM after implantation (SMD: 0.37, 95%CI 0.04 to 0.70) of a MD 2.92° (95%CI 0.17 to 5.67).^{8,11,23,44,46} Two studies^{8,46} showed limited evidence of an improvement in knee flexion/extension RoM after implantation of a mobile-bearing ankle prosthesis (SMD: 0.61, 95%CI 0.29 to 0.91) with a MD of 4.87° (95%CI 1.29 to 8.26). Two studies using fixed-bearing ankle prostheses showed moderate evidence that there was no difference between pre- and post-operative knee flexion/extension RoM.^{39,44}

Three studies indicated moderate evidence that knee flexion/extension RoM did not change after an AA.^{5,23,44}

3.5.7. *Hip Flexion/Extension RoM*

The papers provided moderate evidence that patients with a TAR exhibited an improvement in hip flexion/extension RoM after implantation (SMD: 0.62, 95%CI 0.38 to 0.86) with a MD of 3.90° (95%CI 2.33 to 5.46).^{8,11,23,44,46} The meta-analysis indicated evidence of moderate heterogeneity between studies analysing fixed-bearing prostheses ($I^2 = 62\%$), which was not the case for mobile-bearing prostheses and yielded no significant difference between pre- and post-operative conditions (SMD: 0.55, 95%CI -0.17 to 1.28).^{39,44}

There was moderate evidence of an increase in hip flexion/extension RoM after an AA (SMD: 0.89, 95%CI 0.44 to 1.34) with a MD of 4.77° (95%CI 2.54 to 7.00).^{5,23,44}

3.5.8. *Walking speed*

Fourteen studies totalling 534 participants reported moderate evidence that patients with a TAR exhibited an increase in walking speed after surgery (Table 3 & 4, Fig. 4) (SMD: 1.02,

95%CI 0.85 to 1.19) with a MD of 0.23 m/s (95%CI 0.19 to 0.27).^{7-9,11,18,21,23,26,37,39,41,44,46,51}

Four studies reported moderate evidence of an increase in walking speed after an AA (SMD: 0.76, 95%CI 0.37 to 1.15) with a MD of 0.17 m/s (95%CI 0.09 to 0.24) (Fig.4).^{5,18,23,44}

3.5.9. Cadence

Based on the overall pooled SMD of 8 studies totalling 247 participants, there was moderate evidence that patients with a TAR exhibited an increase in cadence after implantation (SMD: 0.66, 95%CI 0.45 to 0.87) with a MD of 8.14 steps/min (95%CI 6.03 to 10.25).^{7,8,11,18,23,44,46,51}

In contrast to the data for mobile-bearing prostheses, the meta-analysis yielded no significant difference in the cadence after implantation of a fixed-bearing ankle prosthesis.^{11,44}

There was moderate evidence that cadence did not change after an AA.^{5,18,23,44}

3.5.10. Stance duration (% of the gait cycle)

Based on a total of 7 studies totalling 199 participants, moderate evidence was found that patients exhibited a decrease in stance duration after the implantation of ankle prosthesis regardless of the type of prosthesis that was implanted (Table 3 & 4) (SMD: -0.35, 95%CI -0.55 to -0.15 and MD -0.01%, 95%CI -0.02 to 0.00).^{8,9,11,26,37,46,51}

One study reported very limited evidence that stance duration did not change after an AA.⁵

3.5.11. Step Length

Moderate evidence was demonstrated that patients with a TAR exhibited an increase in step length after implantation (SMD: 0.75, 95%CI 0.52 to 0.98).^{7,11,18,37,44,46,51} No MD could be established as one study³⁷ normalized step length by the height of the subjects. The meta-analysis indicated evidence of moderate heterogeneity between studies analysing fixed-

bearing prostheses ($I^2 = 62\%$), in contrast to that for mobile-bearing prostheses, and yielded a significant difference between pre- and post-operative conditions (SMD: 0.84, 95%CI 0.32 to 1.36).^{11,37,44} Four studies indicated moderate evidence of an increase in step length after implantation of a mobile-bearing ankle prosthesis (SMD: 0.66, 95%CI 0.42 to 0.90) with a MD of 0.06m (95%CI 0.02 to 0.09).^{7,18,46,51}

Limited evidence was demonstrated for no change in step length after an AA.^{5,44}

4. DISCUSSION

This systematic review aimed to synthesise previous research evaluating the biomechanical effect of TAR and AA in patients suffering from end-stage ankle OA. There is currently limited to moderate evidence that all spatio-temporal variables are improved following TAR irrespective of the type of prosthesis implanted. In contrast, very limited to moderate evidence was shown by the systematic review that there is no improvement in spatio-temporal variables after an AA except for walking speed.

The main potential benefit of TAR over AA reported in the literature is the conservation of the existing pre-operative ankle RoM.^{8,10,26} Data pooling of ankle kinematics showed a medium effect (3.20°) in increasing the dorsi-/plantarflexion RoM of the replaced ankle, using skin markers to assess motion. This methodology may well have resulted in an over-estimation of bone motion due to soft tissue artefact.^{30,53} The increase in RoM found could also be attributed to accessory offending motion hypermobility of the adjacent foot joints in studies where the foot was considered to be one rigid segment (Table 2). There was moderate evidence that experimental errors or natural gait variability could account for only a small increase in RoM for dorsiflexion (1.72°) and for plantarflexion (2.03°) during gait.⁴³ In the light of these results, it seems that TAR does increase the pre-operative ankle RoM. In contrast, a reduced ankle RoM should be an expected outcome for AA. Although the ankle

joint is fused, four studies reported the ankle dorsi- and/or plantarflexion RoM.^{6,18,23,44} The movements reported in these studies could be due to the rigid foot model used in the studies, the motion reported not being due to true ankle RoM, but the resulting compensation of the neighbouring joints. Future prospective studies evaluating TAR or AA should therefore use a 3D multi-segment foot model to avoid erroneous motion data relating of the surgical effects on foot mechanics.

A second potential benefit of TAR over AA reported in the literature is the protection of the adjacent and non-adjacent joints.^{8,10,26} Conventional gait models were used in most of the studies included in this review, allowing the evaluation of function of the neighbouring joints (i.e. hip, knee) pre and post surgery (Table 2). Twelve of the seventeen studies limited their analysis to the affected joint without considering the entirety of the lower kinetic chain. From a biomechanical point of view, such consideration is an important facet of any procedure since the segments of the lower limb are a linked system.^{17,27} Moderate evidence was found indicating that TAR patients increase their flexion-extension RoM at the knee and the hip post-operatively.^{8,11,23,44,46} In contrast, the evidence suggests that arthrodesis patients show no post-operatively change in knee RoM, but an increase (4.77°) in hip RoM. This would seem to reinforce the notion that patients suffering from the ankle OA compensate more at the hip than at the knee for reduced ankle RoM.⁴⁴ Future studies should combine 3D lower limb models with 3D multi-segment foot models to enhance our understanding of the functional compensatory adaptations occurring at the neighbouring joints after TAR and AA.

Both surgical patient groups in this review walked at a faster pace postoperatively (TAR : MD 0.23 m/s; AA : MD 0.17 m/s). However, this increased walking speed could be attributed to a different strategy for each surgical group.³⁶ It is suggested that TAR group improved their walking speed by increasing their cadence and reducing their step duration.⁶ Similar changes for both spatiotemporal variables were postoperatively obtained in this review. In

contrast, it is reported that arthrodesis patients increased their walking speed through an increase in step length accompanied by an increased hip RoM.⁶ Despite demonstrating the ability to walk faster and increased their hip RoM, the step length did not increase postoperatively for AA group in this review. Conflicting results between studies may explain why we were unable to detect an improvement in step length for AA group (Supplementary material 6).

Moderate evidence was found that all ankle kinetic variables are improved following TAR. Increase in peak plantar flexion moment and ankle power generation is a good indicator of an improvement in the ability to use the foot to propel forward and an increase in the strength of the calf muscles.²⁶ AA studies demonstrated moderate evidence of an increase in ankle dorsiflexion moment. However, there was also moderate evidence of a lack of effect on the generation of ankle power during gait.

During the past decade, development of TAR design has resulted in two major types: mobile-bearing implants, where the polyethylene meniscal bearing is free to slide on both tibial and talar articular surface components fixed to the bones, and fixed-bearing implants, where the meniscal bearing is fixed to the tibial component.²⁸ Unfortunately, there is a paucity of randomized trial studies which analyse differences in gait mechanics in patients with a fixed-versus mobile-bearing TAR. Only one study³⁹ considered this topic, and revealed no difference in outcomes between the two implant types. Pooled data from trials testing the two types of prosthesis individually showed limited differences in gait mechanics after TAR using the two implant designs (Table 3 & 4), the differences possible being the result of experimental error or natural gait variability.⁴³

There were of course limitations associated with the studies included in this review. The methodological quality assessment of the studies allowed the identification of several methodological limitations, such as the absence of outcome measurer blinding and reporting

of methodological validity. Moreover, the categorisation of ankle OA was limited and non-specific in most of the studies. The heterogeneity in the patho-etiology of ankle OA means that the functional consequences are difficult to define without considering the morphological and structural changes associated with the ankle OA, thereby making it difficult to generate meaningful pooled results for specific ankle OA sub-types. Only one study⁵¹ included in the review had an intervention group composed exclusively of post-traumatic ankle OA. In contrast to the global TAR results, patients suffering from post-traumatic ankle OA showed no evidence of an effect of TAR on peak plantarflexion moment, stance duration or step length. Future studies should clearly define the sub-type of end-stage ankle OA and their associated osteoarticular deformity. In the absence of this information, caution should be exercised when considering results generated by pooled data. A further limitation of the review was the lack of access to data generated or analysed in several of the papers. Where necessary authors were contacted with a request to provide additional data. Unfortunately, none of our requests were met, decreasing the number of studies and participants included in the meta-analysis.

5. CONCLUSION

Current research evaluating changes in gait biomechanics after TAR and AA is limited by a lack of prospective research, low sample sizes and heterogeneity in the patho-etiology of ankle OA. Meta-analysis revealed moderate evidence of a significant increase in lower limb kinematics, kinetics and spatio-temporal parameters after total ankle replacement. Improvement in gait variables after ankle arthrodesis was limited to ankle moment and walking speed. Increased hip RoM after AA could represent a sign of compensation for the lack of ankle motion. Future studies should combine 3D lower limb models with 3D multi-segment foot models to enhance our understanding of the functional compensatory

adaptations of the neighbouring joints after TAR and AA.

CONTRIBUTIONS

PAD and LC were responsible for the conception and design of the research, reviewing articles, analysing data, interpreting the results, writing and drafting the manuscript, and approving the final version of the manuscript. AN and JLB were responsible for conception and design of the review, reviewing articles, drafting, critically appraising and revising the manuscript for intellectual content. TL, BDB and IB were responsible for the conception and design of the review, drafting, critically appraising and revising the manuscript for intellectual content. All authors read and approved the final version of the manuscript.

COMPETING INTEREST STATEMENT

The authors do not have any significant conflicts of interest relevant to this manuscript.

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LEGENDS

Figure 1: Flow diagram of search results

Figure 2: The change in gait parameters (Ankle Dorsi-/Plantar-flexion RoM, Peak Ankle Plantarflexion Moment, Peak Ankle Power Generation) following total ankle replacement (TAR global, Mobile-bearing prosthesis and Fixed-bearing prosthesis) compared to pre-operative status

Figure 3: The change in all gait parameters (Ankle Dorsi-/Plantar-flexion RoM, Peak Ankle

Plantarflexion Moment, Peak Ankle Power Generation) following ankle arthrodesis compared to pre-operative status.

Figure 4: The change in walking speed following total ankle replacement and ankle arthrodesis compared to pre-operative status

Table 1: Evidence based-recommendations

Table 2: Study and patient characteristics

Table 3: Summary findings for gait parameters. Change from pre-operative to post-operative status and quality of the evidence related to SMD : A) Total ankle replacement and B) Ankle arthrodesis

Table 4: Summary findings for gait parameters. Change from pre-operative to post-operative status and quality of the evidence related to SMD : A) Mobile-bearing ankle prosthesis and B) Fixed-bearing ankle prosthesis

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Table 1: Evidence-based recommendations (van Tulder et al., 2003)

- **Strong evidence** derived from three or more studies, including a minimum of two high quality (HQ) studies that are statistically homogenous; may be associated with a statistically significant or non-significant pooled results.
- **Moderate evidence** was based on statistically significant pooled results derived from multiple studies that are statistically heterogeneous, including at least one high quality study (HQ); or from multiple moderate quality (MQ) or fair quality (FQ) studies which are statistically homogenous.
- **Limited evidence** was based on results from one high quality study (HQ) or multiple moderate (MQ) or fair quality (FQ) studies that are statistically heterogeneous.
- **Very limited evidence** was based on results from one fair quality study (FQ).
- **No evidence** was based on pooled results insignificant and derived from multiple studies regardless of quality that are statistically heterogeneous.

Table 2 : Study and patient characteristics (NA : not applicable, NR : not reported, SD : standard deviation, FB : Fixed-bearing, MB : Mobile-bearing; Ankle prostheses : Salto Talaris® (Integra Life Sciences, USA), INBONE (Wright Medical Technology, USA); STAR™ (Stryker, Orthopaedics, USA) ; Agility (Depuy Synthes USA), Hinteagra (Integra, US); AES (Ankle Evolutive System, Transystem, France), BOX (Bologna-Oxford,,Finsbury, UK), Mobility (Depuy, UK).

Author (Year)	Study Design	Sample size (M/F ratio)			Mean age, SD (years)			Sub-type Ankle OA	Type of Prostheses	Biomechanical Model	Foot as 1 segment	Walking gait speed	Joints	Plane	Follow-up	Quality score
		TAR	AA	CTRL	TAR	AA	CTRL									
Segal CI Biomech 2018 ³⁷	Case series	20 (8/12)	13 (10/3)	NA	59.9 ± 8.7	53.4 ± 9.8	NA	NR	FB (Agility / Salto Talaris)	Plug-in Gait	Yes	Self-selected	Ankle, Knee, Hip	Sagittal	37	17
Brodsky FAI 2017 ³⁸	Case series	76 (28/48)	NA	NA	61.1 ± 10.3	NA	NA	PT 42 / 7 RA / 27 PM	MB (STAR)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	128	16
Tenenbaum FAS 2017 ³⁹	Case series	Old : 21 (8/13)	NA	NA	74.6 ± 3.4	NA	NA	NR	MB (STAR)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	27, 4	15
		Young : 21 (4/17)	NA	NA	55.4 ± 2.8	NA	NA	NR							26, 2	
Queen CORR 2017 ³⁴	Case series	FB : 15 (7/8)	NA	NA	61 ± 13	NA	NA	NR	FB (Salto Talaris)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	12	23
		MB : 18 (4/14)	NA	NA	65 ± 9	NA	NA	NR	MB (STAR)						12	
Brodsky BJJ 2016 ¹⁶	Case series	NA	20 (10/10)	NA	NA	58.9 ± 14.8	NA	PT 12 / PM 8	NR	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	24	15

Grier G&P 2016 ⁴⁰	Case series	Neutra 1: 32 (N R)	N A	N A	63.5 ± 9.6	N A	NA	NR	FB & MB (INBONE / Salto Talaris / STAR)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Frontal	24	15
		Varus : 38 (N R)	N A	N A	61.6 ± 7.7	N A	NA	NR	FB & MB (INBONE / Salto Talaris / STAR)						24	
		Valgus : 23 (N R)	N A	N A	64.6 ± 11.0	N A	NA	NR	FB & MB (INBONE / Salto Talaris / STAR)						24	
Caravaggi CI Biomech 2015 ¹	Retropective cohort study	10 (5/5)	N A	20 (11/9)	55 (range 36 to 70)	N A	28 (range 23 to 36)	NR	MB (BOX)	IOR LLM 2007	Yes	Self-Selected	Ankle, Knee, Hip	3D	60	12
Queen FAI 2014 ⁴¹	Case series	TAL: 22 (N R)	N A	N A	62.5 ± 11.1	N A	NA	PT 19 / PM 3	FB & MB (INBONE / Salto Talaris / STAR)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	12	14
		GS R: 37 (N R)	N A	N A	60.7 ± 9.5	N A	NA	PT 29 / PM 4 / Other 2	FB & MB (INBONE / Salto Talaris / STAR)						12	
		TAR: 170 (N R)	N A	N A	64.0 ± 9.4	N A	NA	PT 136 / PM 24 / Other 7	FB & MB (INBONE / Salto Talaris / STAR)						12	
Queen JBJS 2014 ⁴²	Case series	FB : 41 (N R)	N A	N A	63.8 ± 9.0	N A	NA	NR	FB (Salto Talaris)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	24	16
		MB 49 (N R)	N A	N A	62.4 ± 10.9	N A	NA	NR	MB (STAR)						24	
Queen CI Biomech 2014 ⁴³	Case series	78 (46/32)	N A	N A	63.6 ± 9.0	N A	NA	NR	FB & MB (Salto Talaris / STAR)	Modified Helen Hayes market set	Yes	Self-Selected	Ankle, Knee, Hip	Sagittal	24	17

Choi FAI 2013 ³⁵	Case series	21 (5/ 16)	N A	N A	69 ± 6.9	N A	NA	PT 12 / PM 8 / HEMA 1	FB (Salto Talaris)	Plug-in Gait	Yes	S e l f - S e l e c t e d	An k l e, K n e e, H i p	Sa g i t t a l	3 7, 2	18
Flavin FAI 2013 ²	Case series	14 (5/ 9)	1 4 (3 /1 1)	N A	56. 9 ± 8.6	60 .7 ± 16 .3	NA	17 PT, 4 PM, 4 CAI, 4 PT + CAI	MB (STAR)	Milwa ukee Foot Model	No	S e l f - s e l e c t e d	An k l e, H i n d f o t	Sa g i t t a l, F r o n t a l	1 2	12
Queen FAI 2012 ³⁶	Case series	51 (27 /24)	N A	N A	65. 0 ± 8.3	N A	NA	NR	FB (INBON E / Salto Talaris)	Modifi ed Helen Hayes market set	Yes	S e l f - s e l e c t e d	An k l e	Sa g i t t a l	2 4	20
Hahn FAI 2012 ⁴⁴	Case series	9 (4/ 5)	9 (6 /3)	N A	53. 9 ± 8.7	62 .7 ± 10 .7	NA	NR	NR	Plug-in Gait	Yes	S e l f - S e l e c t e d	An k l e, K n e e, H i p	Sa g i t t a l	1 2	16
Brodsk y JBJS 2011 ¹⁸	Case series	50 (10 /40)	N A	N A	60. 8 ± 11. 1	N A	NA	PT & PM 47 /RA 3	MB (STAR)	Modifi ed Helen Hayes market set	Yes	S e l f - S e l e c t e d	An k l e, K n e e, H i p	Sa g i t t a l	4 9	15
Ingross o G&P 2009 ¹⁷	Retro specti ve cohor t	10 (8/ 2)	N A	2 0 (1 1/ 9)	57. 4 ± NR	N A	27. 9 ± NR	PT 9 / PSOA 1	MB (BOX)	IOR LLM 2007	Yes	S e l f - S e l e c t e d	An k l e, K n e e, H i p	3D	1 2	16
Valder rabano CI Biomech 2007 ⁴⁷	Prosp ectiv e cohor t	15 (6/ 9)	N A	1 5 (6/ 9)	53. 3 ± NR	N A	52. 9 ± NR	PT 15	MB (Hintegra)	Helen Hayes marker set	Yes	S e l f - S e l e c t e d	An k l e, K n e e, H i p	3D	1 2	16

Table 3 : Summary findings for gait parameters. Change from pre-operative to post-operative status and quality of the evidence related to Standard Mean Difference (SMD) : (NA: Not applicable, MD : mean difference, deg: degrees, HQ: High quality, MQ : Moderate Quality, FQ : Fair quality)

A. Total ankle replacement : pre-operative versus post-operative									
Variables	SMD/MD	Mean	Lower 95% CI	Higher 95% CI	I ²	Overall effect	Evidence	Quality studies	Effect
Ankle RoM (deg)	SMD	0.68	0.51	0.85	0	P<0.00001	Moderate	HQ (Queen et al., 2017); MQ (Choi et al., 2013), FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et al., 2011; Hahn et al., 2012; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Medium
	MD	3.20	2.44	3.96	0	P<0.00001			
Ankle DF RoM (deg)	SMD	0.37	0.14	0.59	27	P<0.001	Moderate	MQ (Queen et al., 2012; Choi et al., 2013), FQ (Ingrosso et al., 2009; Tenenbaum et al., 2017; Brodsky et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Small
	MD	1.72	0.70	2.73	32	P=0.0009			
Ankle PF RoM (deg)	SMD	0.37	0.14	0.60	25	P=0.001	Moderate	HQ (Queen et al., 2017), MQ (Choi et al., 2013), FQ (Ingrosso et al., 2009; Tenenbaum et al., 2017; Brodsky et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Small
	MD	2.03	1.07	2.99	11	P<0.0001			
Ankle Moment (N.m/kg)	SMD	0.39	0.15	0.64	36	P=0.002	Moderate	HQ (Queen et al., 2017), MQ (Choi et al., 2013), FQ (Valderrabano et al., 2007)	Small
	MD	NA	NA	NA	NA	NA			

								2007; Ingrosso et al., 2009; Brodsky et al., 2011; Tenenbaum et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	
<i>Ankle Power (W/kg)</i>	SMD	0.71	0.53	0.88	0	$P < 0.00001$	Moderate	HQ (Queen et al., 2017), MQ (Choi et al., 2013), FQ (Valderrabano et al., 2007; Brodsky et al., 2011; Tenenbaum et al., 2017; Brodsky et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013)	Medium
	MD	0.28	0.18	0.38	51	$P < 0.00001$			
<i>Knee RoM (deg)</i>	SMD	0.37	0.04	0.70	43	$P = 0.03$	Moderate	MQ (Choi et al., 2013), FQ (Brodsky et al., 2011; Hahn et al., 2012; Tenenbaum et al., 2017; Segal et al., 2018)	Small
	MD	2.92	0.17	5.67	55	$P = 0.04$			
<i>Hip RoM (deg)</i>	SMD	0.62	0.38	0.86	0	$P < 0.00001$	Moderate	MQ (Choi et al., 2013), FQ (Brodsky et al., 2011; Hahn et al., 2012; Tenenbaum et al., 2017; Segal et al., 2018)	Medium
	MD	3.90	2.33	5.46	9	$P < 0.00001$			
<i>Walking speed (m/s)</i>	SMD	1.02	0.85	1.19	35	$P < 0.00001$	Moderate	HQ (Queen et al., 2017), MQ (Queen et al., 2012; Choi et al., 2013), FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et al., 2011; Hahn et al., 2012; Queen et al., 2014; Grier et al., 2016; Tenenbaum et al., 2017;	Medium
	MD	0.23	0.19	0.27	55	$P < 0.00001$			

								Brodsky et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	
<i>Cadence (steps/min)</i>	SMD	0.66	0.45	0.87	15	$P < 0.00001$	Moderate	MQ (Choi et al., 2013), FQ (Valderrabano et al., 2007; Brodsky et al., 2011; Hahn et al., 2012; Tenenbaum et al., 2017; Brodsky et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013)	Medium
	MD	8.14	6.03	10.25	2	$P < 0.00001$			
<i>Stance Duration (%)</i>	SMD	-0.35	-0.55	-0.15	0	$P = 0.0005$	Moderate	MQ (Queen et al., 2012; Choi et al., 2013), FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et al., 2011; Tenenbaum et al., 2017), PQ (Caravaggi et al., 2015)	Small
	MD	-0.01	-0.62	0	3	$P = 0.001$			
<i>Step Length (m)</i>	SMD	0.75	0.98	26	26	$P < 0.00001$	Moderate	MQ (Queen et al., 2012; Choi et al., 2013), FQ (Valderrabano et al., 2007; Tenenbaum et al., 2017; Brodsky et al., 2017; Segal et al., 2018), PQ (Flavin et al., 2013)	Medium
	MD	NA	NA	NA	NA	NA			

B. Ankle arthrodesis: pre-operative versus post-operative									
Variables	SMD / MD	Mean	Lower 95% CI	Higher 95% CI	I ²	Overall effect	Evidence	Quality studies	Effect
Ankle RoM (deg)	SMD	-0.16	-0.99	0.68	71	$P = 0.71$	Limited	FQ (Hahn et al., 2012; Brodsky et al., 2016), PQ (Flavin et al., 2013)	No effect
	MD	-0.49	-3.48	2.51	75	$P = 0.75$			
Ankle DF RoM (deg)	SMD	0.64	-0.42	1.70	83	$P = 0.24$	Limited	FQ (Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	No effect
	MD	3.64	-2.23	9.51	87	$P = 0.22$			
Ankle PF RoM (deg)	SMD	-0.11	-1.20	0.97	85	$P = 0.84$	Moderate	FQ (Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	No effect
	MD	-0.54	-7.45	6.38	87	$P = 0.88$			
Ankle Moment (N.m/kg)	SMD	0.54	0.17	0.92	0	$P = 0.005$	Moderate	FQ (Hahn et al., 2012; Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	Small
	MD	0.16	0.05	0.27	0	$P = 0.004$			
Ankle Power (W/kg)	SMD	0.35	-0.06	0.76	0	$P = 0.09$	Moderate	FQ (Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	No effect
	MD	0.17	-0.03	0.36	0	$P = 0.09$			
Knee RoM (deg)	SMD	0.34	-0.09	0.77	0	$P = 0.12$	Moderate	FQ (Hahn et al., 2012; Brodsky	No effect
	MD	1.43	-0.53	3.38	0	$P = 0.15$			

								et al., 2016, Segal et al., 2018)	
<i>Hip RoM (deg)</i>	SMD	0.89	0.44	1.34	0	$P < 0.0001$	Moderate	FQ (Hahn et al., 2012; Brodsky et al., 2016, Segal et al., 2018)	Medium
	MD	4.77	2.54	7.00	0	$P = 0.0001$			
<i>Walking speed (m/s)</i>	SMD	0.76	0.37	1.15	0	$P < 0.0001$	Moderate	FQ (Hahn et al., 2012; Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	Medium
	MD	0.17	0.09	0.24	0	$P < 0.00001$			
<i>Cadence (steps/min)</i>	SMD	0.30	-0.07	0.68	0	$P = 0.11$	Moderate	FQ (Hahn et al., 2012; Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	No effect
	MD	3.05	-0.24	6.34	0	$P = 0.07$			
<i>Stance Duration (%)</i>	SMD	-0.20	-0.83	0.42	NA	NA	Very Limited	FQ (Brodsky et al., 2016)	No effect
	MD	0	-0.01	0.01	NA	NA			
<i>Step Length (m)</i>	SMD	0.13	-0.84	1.10	0.79	$P = 0.79$	Limited	FQ (Brodsky et al., 2016, Segal et al., 2018), PQ (Flavin et al., 2013)	No effect
	MD	0.03	-0.05	0.11	0.43	$P = 0.43$			

Table 4 : Summary findings for gait parameters. Change from pre-operative to post-operative status and quality of the evidence related to Standard Mean Difference (SMD) (NA: Not applicable, MD : mean difference, deg: degrees, HQ: High quality, MQ : Moderate Quality, FQ : Fair quality)

A. Total ankle replacement (Mobile-bearing) : pre-operative versus post-operative

Variables	SMD/MD	Mean	Lower 95% CI	Higher 95% CI	I^2	Overall effect	Evidence	Quality studies	Effect
Ankle RoM (deg)	SMD	0.64	0.46	0.83	0	$P < 0.00001$	Moderate	HQ (Queen et al., 2017), FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et al., 2011; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Medium
	MD	3.32	2.32	4.07	0	$P < 0.00001$			
Ankle DF RoM (deg)	SMD	0.23	0.01	0.46	0	$P = 0.04$	Moderate	FQ (Ingrosso et al., 2009; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Small
	MD	1.3	-0.02	2.61	22	$P = 0.05$			
Ankle PF RoM (deg)	SMD	0.38	0.06	0.71	46	$P = 0.02$	Moderate	HQ (Queen et al., 2017), FQ (Ingrosso et al., 2009; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Small
	MD	2.18	0.78	3.58	31	$P = 0.002$			
Ankle Moment (N.m/kg)	SMD	0.39	0.06	0.71	47	$P = 0.02$	Moderate	HQ (Queen et al., 2017), FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et al., 2011; Tenenbaum et al., 2017), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Small
	MD	NA	NA	NA	NA	NA			
Ankle Power (W/kg)	SMD	0.73	0.53	0.92	0	$P < 0.00001$	Moderate	HQ (Queen et al., 2017), FQ (Valderrabano et al., 2007; Brodsky et al., 2011; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013)	Medium
	MD	0.28	0.15	0.41	64	$P < 0.00001$			
Knee RoM (deg)	SMD	0.60	0.29	0.91	7	$P = 0.0001$	Limited	FQ (Brodsky et al., 2011; Tenenbaum et al., 2017)	Medium
	MD	4.78	1.29	8.26	48	$P = 0.007$			
Hip RoM (deg)	SMD	0.69	0.39	0.99	0	$P < 0.00001$	Limited	FQ (Brodsky et al., 2011; Tenenbaum et al., 2017)	Medium
	MD	4.58	2.70	6.45	0	$P < 0.00001$			
Walking speed (m/s)	SMD	0.91	0.71	1.11	5	$P < 0.00001$	Moderate	HQ (Queen et al., 2017), FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et al., 2011; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013; Caravaggi et al., 2015)	Medium
	MD	0.19	0.14	0.24	30	$P < 0.00001$			
Cadence (steps/min)	SMD	0.75	0.49	1.02	31	$P < 0.00001$	Moderate	FQ (Valderrabano et al., 2007; Brodsky et al., 2011; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013)	Medium
	MD	8.63	5.91	11.34	26	$P < 0.00001$			
Stance Duration (%)	SMD	-0.30	-0.55	-0.05	0	$P = 0.02$	Moderate	FQ (Valderrabano et al., 2007; Ingrosso et al., 2009; Brodsky et al., 2011; Tenenbaum et al., 2017), PQ (Caravaggi et al., 2015)	Small
	MD	-0.01	-0.02	0	10	$P = 0.03$			
Step Length (m)	SMD	0.66	0.42	0.90	0	$P < 0.00001$	Limited	FQ (Valderrabano et al., 2007; Tenenbaum et al., 2017; Brodsky et al., 2017), PQ (Flavin et al., 2013)	Medium
	MD	0.06	0.02	0.09	59	$P = 0.0007$			

B. Total ankle replacement (Fixed-bearing) : pre-operative versus post-operative

Variables	SMD/ MD	Mean	Lower 95% CI	Higher 95% CI	I ²	Overall effect	Evidence	Quality studies	Effect
Ankle RoM	SMD	0.95	0.46	1.44	0	$P=0.0001$	Moderate	HQ (Queen et al., 2017); MQ (Choi et al., 2013)	Medium
	MD	3.42	1.21	5.63	41	$P=0.002$			
Ankle DF RoM	SMD	0.55	0.07	1.03	56	$P=0.02$	Limited	MQ (Queen et al., 2012; Choi et al., 2013), FQ (Segal et al., 2018)	Small
	MD	2.21	0.66	3.76	41	$P=0.005$			
Ankle PF RoM	SMD	0.27	-0.11	0.64	0	$P=0.16$	Moderate	HQ (Queen et al., 2017); MQ (Choi et al., 2013); FQ (Segal et al., 2018)	No effect
	MD	1.29	-0.39	2.96	11	$P<0.0001$			
Ankle Moment (N.m/kg)	SMD	0.52	0.14	0.90	0	$P=0.007$	Moderate	HQ (Queen et al., 2017); MQ (Choi et al., 2013); FQ (Segal et al., 2018)	Small
	MD	0.16	0.02	0.30	15	$P=0.03$			
Ankle Power (W/kg)	SMD	0.64	0.22	1.06	16	$P=0.003$	Moderate	HQ (Queen et al., 2017); MQ (Choi et al., 2013); FQ (Segal et al., 2018)	Medium
	MD	0.28	0.13	0.43	0	$P=0.0002$			
Knee RoM	SMD	-0.07	-0.50	0.37	0	$P=0.77$	Moderate	MQ (Choi et al., 2013); FQ (Segal et al., 2018)	No effect
	MD	-0.43	-3.49	2.63	0	$P=0.78$			
Hip RoM	SMD	0.55	-0.17	1.28	62	$P=0.13$	Limited	MQ (Choi et al., 2013); FQ (Segal et al., 2018)	No effect
	MD	3.42	-1.57	8.41	74	$P=0.18$			
Walking speed (m/s)	SMD	0.86	0.49	1.24	37	$P<0.00001$	Moderate	HQ (Queen et al., 2017); MQ (Queen et al., 2012; Choi et al., 2013); FQ (Segal et al., 2018)	Medium
	MD	0.19	0.12	0.26	39	$P<0.00001$			
Cadence (steps/min)	SMD	0.45	0.01	0.89	0	$P=0.05$	Moderate	MQ (Choi et al., 2013); FQ (Segal et al., 2018)	No effect
	MD	6.01	0.26	11,77	0	$P=0.04$			
Stance Duration (%)	SMD	-0.45	-0.78	-0.12	0	$P=0.007$	Moderate	MQ (Queen et al., 2012; Choi et al., 2013),	Small
	MD	-0.01	-0.02	0	0	$P=0.009$			
Step Length (m)	SMD	0.84	0.32	1.36	62	$P=0.001$	Limited	MQ (Queen et al., 2012; Choi et al., 2013), FQ (Segal et al., 2018)	Medium
	MD	NA	NA	NA	NA	NA			

HIGHLIGHTS

- Moderate evidence to suggest that lower extremity biomechanics improved after total ankle replacement
- Moderate evidence to suggest that total ankle replacement improves pre-operative ankle range of motion by 3°
- No difference in outcomes between fixed- versus mobile-bearing prosthesis
- Ankle moment, hip range of motion and walking speed increased after ankle arthrodesis

Journal Pre-proof

	Concept #1	Concept #2	Concept #3
MeSH terms	"Ankle Osteoarthritis"	AND "Locomotion" OR "Biomechanical Phenomena" OR "Mechanics" OR "Mechanical Phenomena"	AND "Ankle Prosthesis" OR "Ankle Arthrodesis"
Title / Abstract	Ankle osteoarthritis OR arthritis	Motion OR movement OR locomot* OR kinematic* OR kinetic* OR dynamic* OR load* OR biomech* mechanic* OR moment* OR angle* OR rotation* OR force*	"Ankle prosthesis" OR "total ankle replacement" OR "total ankle arthroplasty" OR "ankle arthrodesis" OR "ankle fusion"

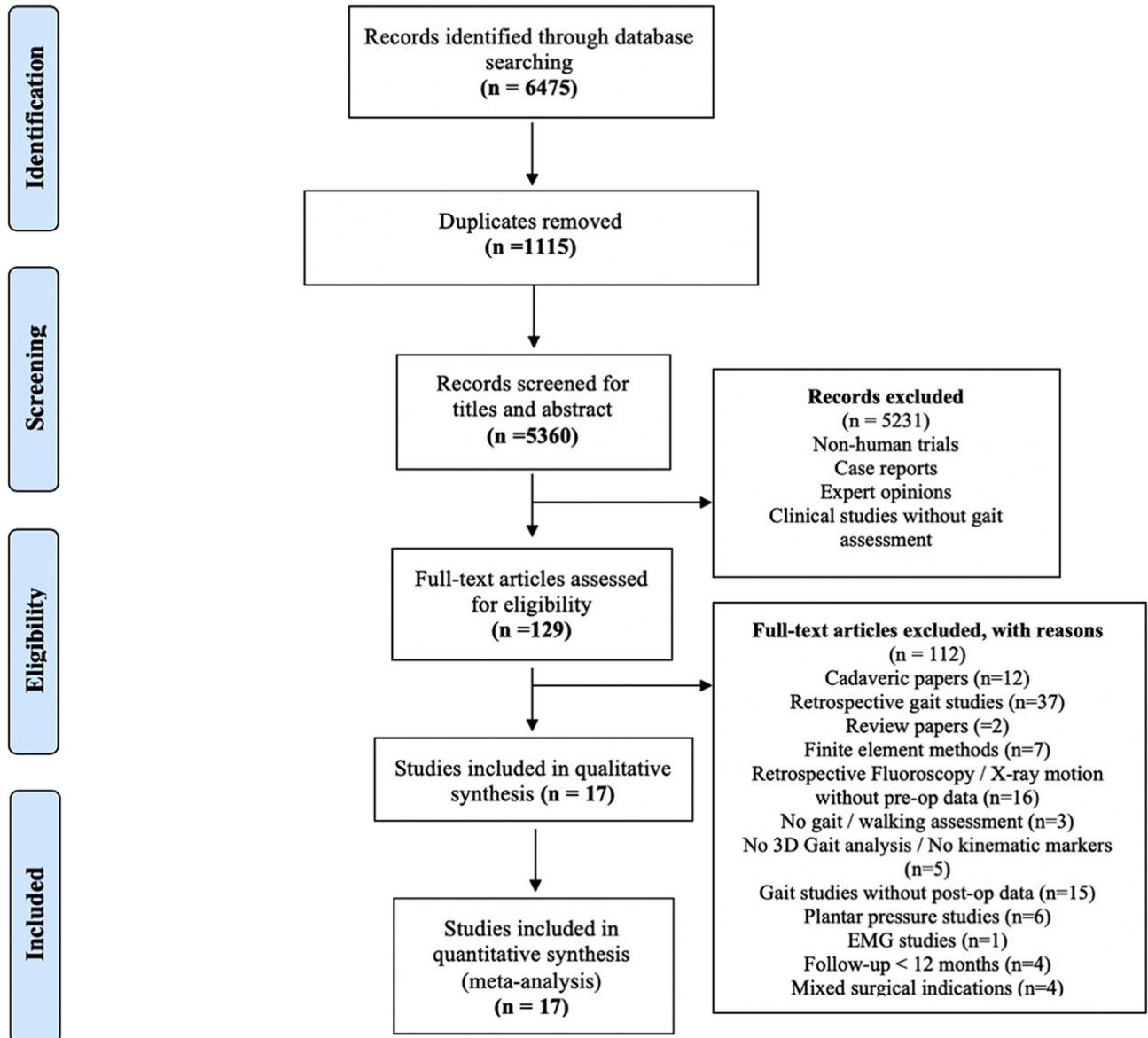
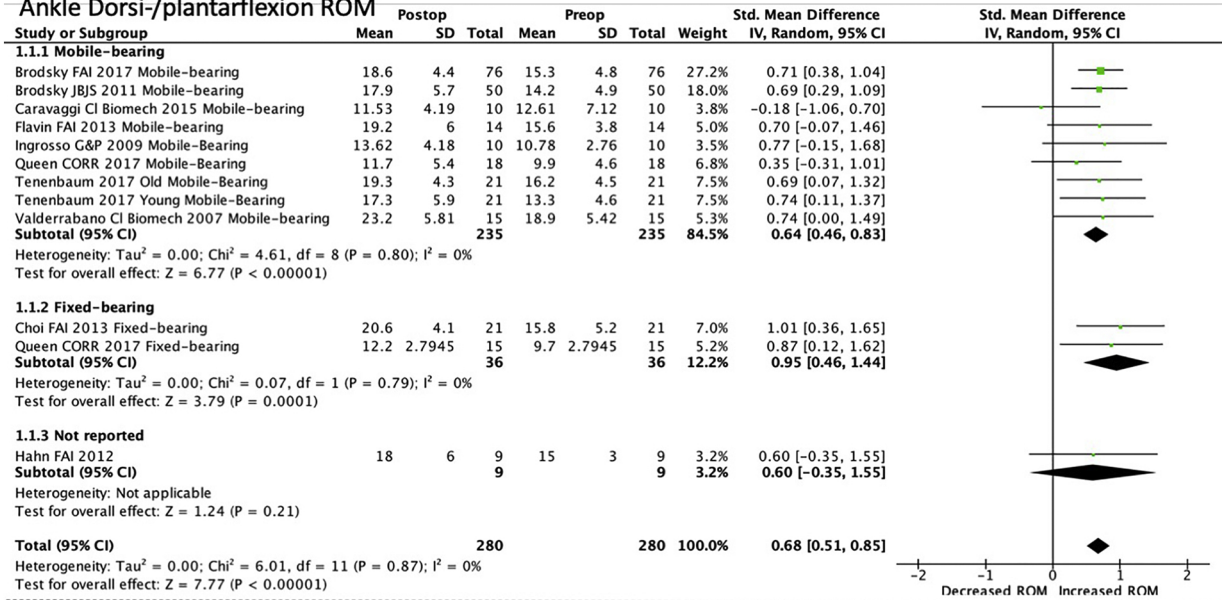
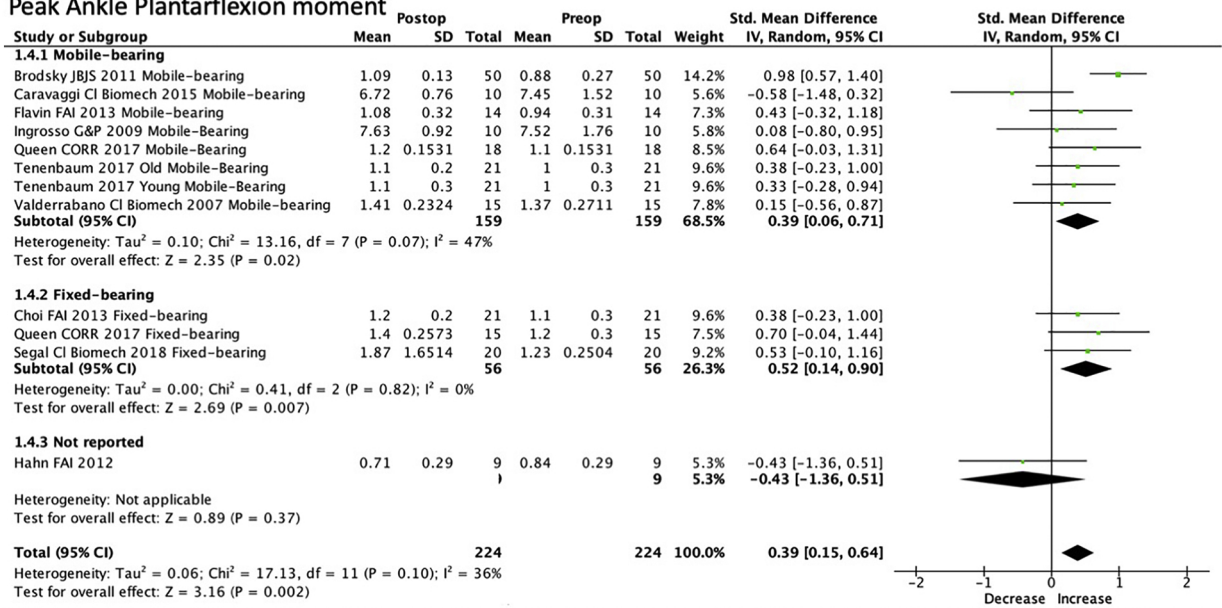


Figure 1

Ankle Dorsi-/plantarflexion ROM



Peak Ankle Plantarflexion moment



Peak Ankle Power Generation

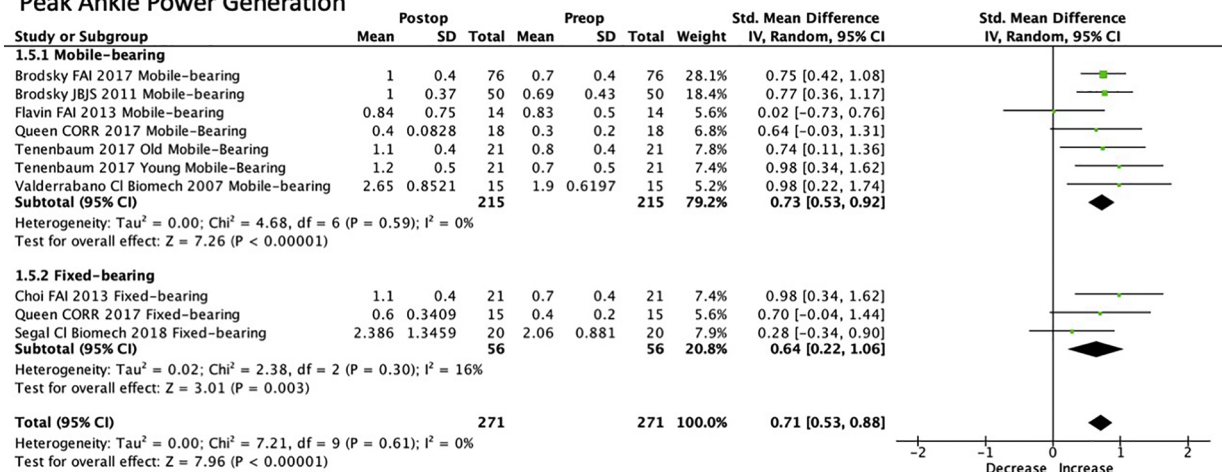
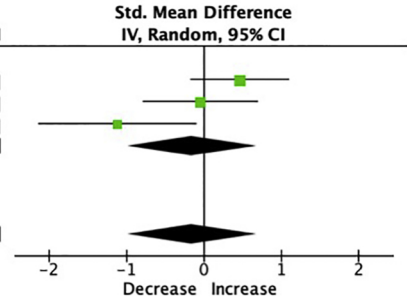


Figure 2

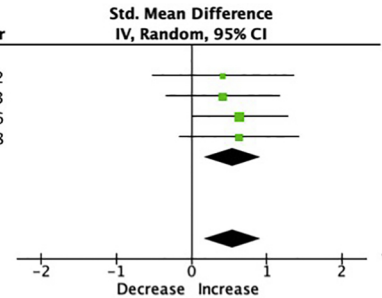
Ankle Dorsi-/plantarflexion ROM

Study or Subgroup	Postop			Preop			Weight	Std. Mean Difference		
	Mean	SD	Total	Mean	SD	Total		IV, Random, 95% CI	Std. Mean Difference	
2.1.3 Fusion										
Brodsky BJJ 2016 Fusion	14.87	3.7432	20	13.1	3.7432	20	37.5%	0.46	[-0.17, 1.09]	
Flavin FAI 2013 Fusion	15	2.2	14	15.2	5.6	14	34.6%	-0.05	[-0.79, 0.70]	
Hahn FAI 2012 Fusion	15	2	9	18	3	9	27.9%	-1.12	[-2.13, -0.11]	
Subtotal (95% CI)			43			43	100.0%	-0.16	[-0.99, 0.68]	
Heterogeneity: Tau ² = 0.38; Chi ² = 6.81, df = 2 (P = 0.03); I ² = 71%										
Test for overall effect: Z = 0.37 (P = 0.71)										
Total (95% CI)			43				43	100.0%	-0.16	[-0.99, 0.68]
Heterogeneity: Tau ² = 0.38; Chi ² = 6.81, df = 2 (P = 0.03); I ² = 71%										
Test for overall effect: Z = 0.37 (P = 0.71)										



Peak Ankle Plantarflexion moment

Study or Subgroup	Postop			Preop			Weight	Std. Mean Difference		Year	
	Mean	SD	Total	Mean	SD	Total		IV, Random, 95% CI	Std. Mean Difference		
2.4.3 Fusion											
Hahn FAI 2012 Fusion	0.8	0.19	9	0.71	0.22	9	16.3%	0.42	[-0.52, 1.35]	2012	
Flavin FAI 2013 Fusion	1.11	0.32	14	0.96	0.38	14	25.5%	0.41	[-0.34, 1.16]	2013	
Brodsky BJJ 2016 Fusion	1.11	0.3227	20	0.9	0.3227	20	35.3%	0.64	[0.00, 1.27]	2016	
Segal CI Biomech 2018 Fusion	1.323	0.3102	13	1.124	0.2996	13	22.9%	0.63	[-0.16, 1.42]	2018	
Subtotal (95% CI)			56			56	100.0%	0.54	[0.17, 0.92]		
Heterogeneity: Tau ² = 0.00; Chi ² = 0.32, df = 3 (P = 0.96); I ² = 0%											
Test for overall effect: Z = 2.81 (P = 0.005)											
Total (95% CI)			56				56	100.0%	0.54	[0.17, 0.92]	
Heterogeneity: Tau ² = 0.00; Chi ² = 0.32, df = 3 (P = 0.96); I ² = 0%											
Test for overall effect: Z = 2.81 (P = 0.005)											



Peak Ankle Power Generation

Study or Subgroup	Postop			Preop			Weight	Std. Mean Difference		
	Mean	SD	Total	Mean	SD	Total		IV, Random, 95% CI	Std. Mean Difference	
2.5.3 Fusion										
Brodsky BJJ 2016 Fusion	0.7	0.4195	20	0.5	0.4195	20	42.1%	0.47	[-0.16, 1.10]	
Flavin FAI 2013 Fusion	0.66	0.34	14	0.56	0.49	14	30.1%	0.23	[-0.51, 0.97]	
Segal CI Biomech 2018 Fusion	2.387	1.6701	13	1.952	1.0688	13	27.8%	0.30	[-0.47, 1.07]	
Subtotal (95% CI)			47			47	100.0%	0.35	[-0.06, 0.76]	
Heterogeneity: Tau ² = 0.00; Chi ² = 0.25, df = 2 (P = 0.88); I ² = 0%										
Test for overall effect: Z = 1.68 (P = 0.09)										
Total (95% CI)			47				47	100.0%	0.35	[-0.06, 0.76]
Heterogeneity: Tau ² = 0.00; Chi ² = 0.25, df = 2 (P = 0.88); I ² = 0%										
Test for overall effect: Z = 1.68 (P = 0.09)										

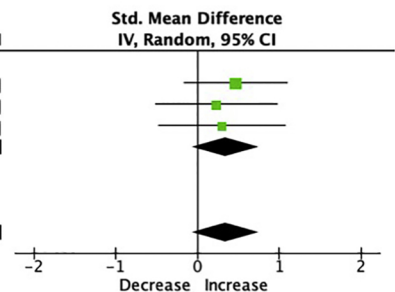
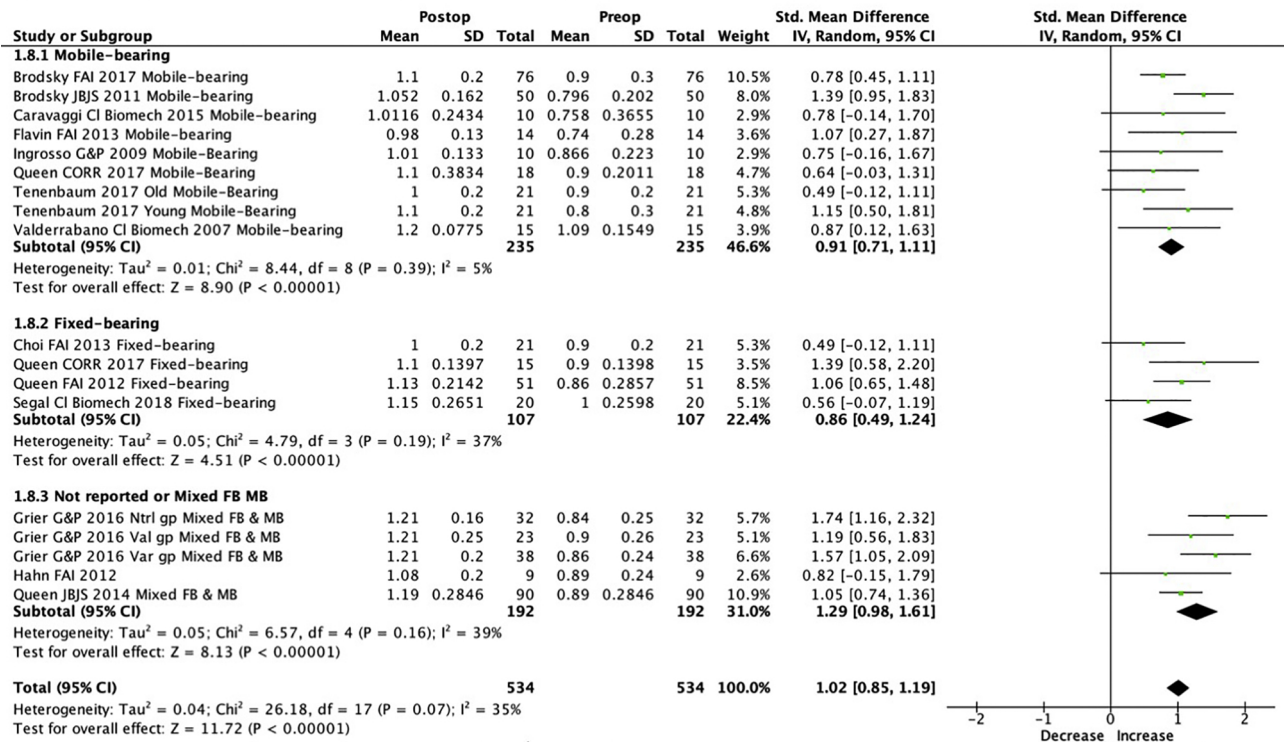


Figure 3

A. Walking speed : Total Ankle Replacement studies



B. Walking speed : Ankle Arthrodesis studies (Fusion)

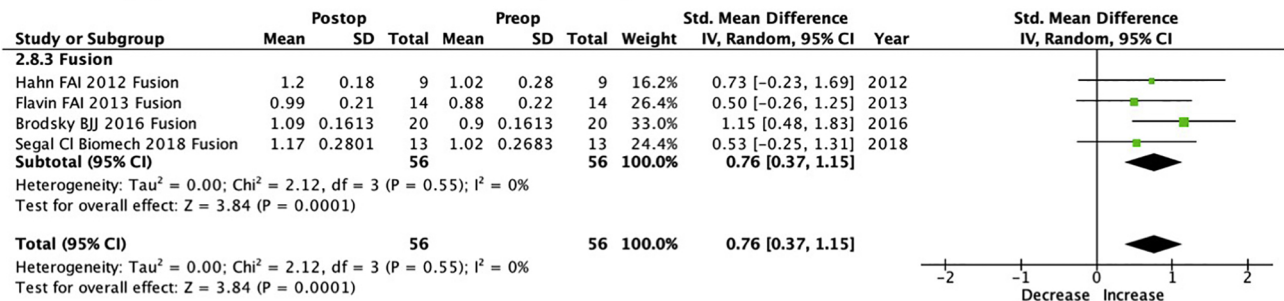


Figure 4