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Association between the level of partial foot amputation and gait: a scoping review with implications for the minimum impairment criteria for wheelchair tennis

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ASSOCIATION BETWEEN LEVEL OF PARTIAL FOOT AMPUTATION AND GAIT: A SCOPING REVIEW WITH IMPLICATIONS FOR THE MINIMUM IMPAIRMENT CRITERIA FOR WHEELCHAIR TENNIS

ABSTRACT

Objective: This scoping review examines how different levels and types of partial foot amputation affect gait and explores how these findings may affect the minimal impairment criteria for wheelchair tennis.

Methods: Four databases (PubMed, Embase, CINAHL, and SPORTDiscus) were systematically searched in February 2021 for terms related to partial foot amputation and ambulation. The search was updated in February 2022. All study designs investigating gait-related outcomes in individuals with partial foot amputation were included and independently screened by two reviewers based on Arksey and O'Malley's methodological framework and reported according to the PRISMA-ScR.

Results: Twenty-nine publications with data from 252 participants with partial foot amputation in 25 studies were analysed. Toe amputations were associated with minor gait abnormalities, and great toe amputations caused loss of push-off in a forward and lateral direction. Metatarsophalangeal amputations were associated with loss of stability and decreased gait speed. Ray amputations were associated with decreased gait speed and reduced lower extremity range of motion (ROM). Transmetatarsal amputations and more proximal amputations were associated with abnormal gait, substantial loss of power generation across the ankle and impaired mobility.

Conclusions: Partial foot amputation was associated with various gait changes, depending on the type of amputation. Different levels and types of foot amputation are likely to affect tennis performance. We recommend including first ray, transmetatarsal, Chopart and Lisfranc amputations in the minimum impairment criteria, excluding toe amputations (digits two to five), and we are unsure whether to in-or exclude great toe, ray (two to five), and metatarsophalangeal amputations.

Keywords: amputee, disability, gait, Para sport, classification, partial foot amputation

Word count: 250 words

What is already known on this topic

- Partial foot amputation is associated with gait pattern impairments, including spatiotemporal, kinetic, and kinematic gait characteristics, ground reaction force, and centre of pressure excursion.
- Athletes with a partial foot amputation are eligible for Para archery, Para athletics, Para badminton, Para cycling, Para rowing, Para swimming, Para table tennis, Para taekwondo, sitting volleyball, and wheelchair tennis. Athletes with partial foot amputation are excluded from the remaining 18 Paralympic sports.

What this study adds

- This review provides a consolidated overview of the gait pattern impairments associated with different levels and types of partial foot amputation.

How this study might affect research, practice or policy

Results of the review indicate how different levels and types of foot amputation are likely to affect tennis performance and may be used as supporting evidence for determining minimum impairment criteria for wheelchair tennis.

ASSOCIATION BETWEEN THE LEVEL OF PARTIAL FOOT AMPUTATION AND GAIT: A SCOPING REVIEW WITH IMPLICATIONS FOR THE MINIMUM IMPAIRMENT CRITERIA FOR WHEELCHAIR TENNIS

INTRODUCTION

Lower extremity amputation can negatively impact the quality of life[1,2] and is associated with higher morbidity and mortality.[3,4] People with limb amputations benefit from participating in regular physical activity and sports and should be encouraged to live a physically active life.[5] However, barriers to participating in physical activity and sports include functional limitations and comorbidities.[1,6]

Para sports aim to promote sports for people with disabilities. Non-disabled sports are modified to create a more inclusive and level playing field for people with different disabilities. No specific classification acts as an exclusionary criterion at the recreational level for most adapted sports programs. However, to be eligible to compete in Para sports at International Competitions under the jurisdiction of an International Sports Federation, an athlete with an impairment needs to undergo an athlete evaluation to be classified. During this athlete evaluation, it will be determined whether the impairment (in this case, amputation) meets the minimum impairment criteria of that sport, which is the minimum level of impairment required to participate in the sport.[7] For example, among the 28 Paralympic sports, only 10 have an eligible classification for persons with partial foot amputation: Para archery, Para athletics, Para badminton, Para cycling, Para rowing, Para swimming, Para table tennis, Para taekwondo, sitting volleyball, and wheelchair tennis (Table 1).[8] The other 18 sports require either a more proximal level of lower limb amputation or a different impairment (e.g. Para judo requires a visual impairment) to be eligible to participate.

***** Insert Table 1 about here *****

This scoping review focuses on minimum impairment criteria in the Para sport of wheelchair tennis. Wheelchair tennis is a popular Para sport version of non-disabled tennis, and people with a partial foot amputation are eligible to compete. In 2021, the minimum impairment criteria for lower limb deficiency in wheelchair tennis were defined as “complete unilateral amputation of half the length of the foot (i.e., measured on the non-amputated foot from the tip of the great toe to the posterior aspect of the calcaneus) or equivalent minimum congenital limb deficiency”.[9] These minimum impairment criteria were adopted from Para athletics, and whether they were set at the correct level as an entry criterion for participating in wheelchair tennis has never been examined. Therefore, the International Tennis Federation (ITF) tasked an Expert Group to review the minimum impairment criteria for the Open Class of wheelchair tennis.

When developing evidence-based classification systems, the International Paralympic Committee (IPC) recommended that sports and researchers:[10]

1) specify the sport (class) and the eligible impairment types;
2) develop valid measures of impairment;
3) develop standardised and valid sport-specific measures of performance;
4) assess the strength of associations between the measures of impairment and performance; and
5) develop minimum impairment criteria and class profiles for the sport.

Following the IPC research steps, the ITF Expert Group aimed to assess the strength of the association between different levels of partial foot amputation and non-disabled tennis performance. Ideally, one would review all studies of tennis players with partial foot amputation playing standing tennis and determine the association between amputation type and mobility on the tennis court. However, such studies were not available, but studies of the association between the types of partial foot amputation and walking gait were. Gait is the outcome parameter most likely to affect mobility on the tennis court. It was hypothesised that the more proximal and more extensive the amputation, the more substantial the functional limitation and, hence, the motivation to undertake this review. Scoping reviews are ideal for determining the scope of the body of literature on a given topic, determining knowledge gaps, and providing an overview of the subject matter. Because of the scant literature on partial foot amputation and gait, a scoping review is more appropriate for this topic than a systematic review.[11] Therefore, this scoping review aimed to describe how different levels and types of partial foot amputation affect gait with a view to applying the findings to inform the development of minimal impairment criteria for wheelchair tennis.

METHODS

This scoping review was based on the 6-step methodological framework developed for scoping reviews.[12,13] The searching and selection processes followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis extension for scoping reviews (PRISMA-ScR) and aligned with the scoping review methodological framework.[13] The protocol of this scoping review was previously registered at the Open Science Framework Registry (https://osf.io/8gh9y) and published.[14]

Literature search and study selection

A comprehensive search strategy in PubMed, Embase, CINAHL and SPORTDiscus (via Ebsco) from inception to February 1st 2021, was developed by one reviewer (FO) in collaboration with a medical librarian (LS). Database searches were then carried out by two reviewers (BP, MJ). Search terms included controlled terms (MeSH in PubMed and Emtree in Embase, CINAHL Headings in CINAHL, and thesaurus terms in SportDiscus) and free-text terms. An updated search was carried out on February 19th 2022, which did not provide additional records. The following terms (including synonyms and closely related words) were used as index terms or free-text words: ‘amputation’ and ‘forefoot’ or ‘midfoot’ and ‘gait’. These terms were determined using the PICOS (Population, Interest/Exposure, Comparison, Outcome, and Study design) approach. The search was performed without date, geographical location, gender, sex, or language restrictions. The search strategies for all databases are available in Supplementary file S1.

Before screening the search results, duplicate articles were identified and removed using Endnote X19.2 (Clarivate, USA). The search yield was imported into Rayyan QCRI[15] and two independent reviewers (FO, SW) screened the titles and abstracts for potentially eligible studies. Where there was any disagreement over inclusion, a consensus was reached through discussion with a third reviewer (BP). Full-text versions were downloaded for all articles that appeared to meet the study inclusion criteria based on their titles and abstracts and reviewed to confirm eligibility. The reference lists of the selected studies were manually screened to identify additional relevant articles that may have been missed in the primary searches.

Inclusion and exclusion criteria

Included studies must have reported or analysed data from gait-related outcomes in individuals who underwent a partial foot amputation. The inclusion/exclusion criteria used to determine the eligibility of the included articles are available in Supplementary file S2. Reasons for exclusion are reported in the PRISMA flowchart in Figure 1.[16]

Data extraction and synthesis

Data synthesis was performed qualitatively and quantitatively for all analysed outcomes to build a solid theoretical framework of the types of amputation associated with substantial abnormalities in gait parameters. A meta-analysis was not planned due to incomplete reporting of outcomes (i.e., means, measures of spread, sample size) and clinical and methodological diversity in the evidence.[17] Therefore, we decided to use a structured reporting of effects[18] and calculated the mean difference (MD) with 95% confidence intervals (CI) between patients with an amputation and the corresponding control group. We quantitatively analysed the variables gait speed in meters per second (m/s), step length in centimetres (cm), cadence in steps per minute (steps/min), stance time in seconds (s), peak plantar pressure in kilopascal (kPa), and ankle power in watts per kilogram (W/kg) and per kilogram-meter (W/kg-m). The 95% CIs were calculated assuming a t-distribution. The results were reported from the distal to proximal level of amputation.

The following data were extracted from the included articles: first author, year of publication, country involved, study design, aims of the study, study population (type of amputation, reason for amputation), mean age, control group, sample size, and sex. For study design, we followed the definitions of a case-control and cross-sectional study, as proposed by Dillon et al.[19] If the same patients were included in two or more publications, these publications were considered as one study for this review.

The following data related to the outcome measures were extracted from the articles: assessment methods, gait-related outcomes without a prosthesis (spatiotemporal parameters, centre of pressure (CoP), ground reaction force (GRF), kinetics, kinematics), comparison, key findings related to the outcomes of interest, study limitations, and conclusions.

In the case of a study providing only a median, interquartile range, and/or range, we transformed the values with an online tool that applied the quantile estimation method of McGrath et al.[20] Where data was presented in a figure only, GetData Graph Digitizer[21] was used to extract the values by measuring the length of the axes in pixels followed by the length of the relevant data of interest.[22] Results are presented in summary tables, and quantitative results are displayed with forest plots. The results are reported from distal to proximal level of amputation.

Methodological Quality Assessment

Two independent reviewers (FO, BP) assessed the methodological quality of all included studies using the Joanna Briggs Institute checklist for case reports (two studies) and analytical cross-sectional studies.[23,24] The checklist for case reports consisted of eight items, including questions on the demographic characteristics, the patient's history, clinical condition, diagnostic tests, intervention, post-intervention clinical condition, adverse events and take-away lessons (Supplementary file S3). The checklist for analytical cross-sectional studies also consisted of eight items, including questions on study inclusion criteria, participants and setting, exposure, the condition, confounding factors (two items), validity and reliability of the measurement technique, and statistical analysis (Supplementary file S4). Each question was rated as 'yes', 'no', 'unclear', or 'not applicable'. The reviewers discussed differences until they reached a consensus. The quality assessment outcome was not used to determine study inclusion or perform sub-group analysis based on methodological quality or risk of bias and was performed post-hoc.

Levels of evidence and grades of recommendation for the minimum impairment criteria were rated according to the Oxford Centre of Evidence-Based Medicine (OCEBM).[25]

RESULTS

Study selection

A total of 1083 articles were retrieved from the electronic databases. Four additional articles were identified from the reference lists of the included studies. After removing 423 duplicates and screening the titles and abstracts of the 664 remaining records, 35 studies were selected for full-text analysis. Six additional studies were excluded, and the reasons for exclusion are presented in a flowchart (Figure 1). Three research groups included the same patients in two,[26,27] two,[28,29] and three[30-32] different publications. Therefore, 29 publications of 25 studies met the inclusion criteria for this scoping review.

***** Insert Figure 1 about here *****

Characteristics of the included studies

The characteristics of the included studies are presented in Table 2. Most study designs were either cross-sectional (n=14) or case-control (n=6), with two case reports[33,34] and three pre-post studies.[35-37]

***** Insert Table 2 about here *****

Participants

The included studies comprised 448 participants, 257 of whom had a partial foot amputation, and 191 were controls or had a more proximal amputation. The mean number of participants with partial foot amputation per study was 10 (range from 1 to 30). Most studies included adults (n=23), and two included children.[36,38] The mean age of the adult participants with partial foot amputation ranged from 26 to 75.5 years, and 77.5% were male. Four studies did not report age,[34,37,39,40] and seven studies did not report sex.[19,30,32,36,39-43]

Methodological quality assessment

Quality assessment of the included studies is presented in Supplementary files S3 and S4. The assessment methods were not clearly described in one of the two case studies, but all other items in both studies scored a ‘yes’. Most of the 27 analytical cross-sectional studies assessed clearly described the criteria for inclusion (item 1; 22/27, 81%), the study subjects and setting (item 2; 25/27, 93%), and measured the outcomes in a valid and reliable way (item 7; 22/27, 81%). All analytical cross-sectional studies measured the exposure validly and reliably (item 3; 27/27, 100%) and used objective and standard criteria for measuring the condition (item 4; 27/27, 100%). Only 15 out of 27 (56%) studies adequately identified the confounding variables (item 5), and only 7/27 (26%) reported the strategies used to manage them (item 6). Most studies (15/21, 71%) used appropriate statistical analyses (item 8); in 6 cases, this item was not applicable.

Amputation levels and types

Amputation types included were the great toe (n=6), other toes (n=3), metatarsophalangeal (MTP) joint (n=2), ray (n=3), transmetatarsal (TMT) (n=14), Lisfranc (n=2), and Chopart (n=3) (Figure 2). Three studies[30-32,36,44] analysed a mixed group of partial foot amputees. Kanade et al.[44] included participants with great toe, other toes, ray, and TMT amputation but did not report them separately. Therefore, this publication is not discussed in the various subsections addressing the association between gait and different foot amputation types. Dillon & Barker[30-32] and Greene & Cary[36] reported gait-related outcomes specific to amputation types, and those data are discussed.

***** Insert Figure 2 about here *****

Reasons for amputation

Reasons for amputation included diabetes (n=10),[26-29,39,41,44-49] finger or thumb reconstruction (n=5),[33,37,38,40,50] trauma (n=4),[30-32,51-53] peripheral vascular disease (n=3),[39,42,43] tumour (n=1),[54] rheumatoid arthritis (n=1),[35] congenital and childhood-acquired amputation (n=1),[36] and frostbite (n=1).[34]

Gait-related outcomes

The complete list of outcomes, key findings of the included studies and descriptive synthesis of the results are presented in Table 3 and Supplementary file S5. The most often studied gait-related outcome measure was gait speed, examined in 15 studies included in this review.[26-29,32,34,36-38,42,44-46,48,50,52,53] Other outcome measures addressed in the studies included cadence (n=9),[32,37,38,42,45,46,50,52,53] step length (n=8),[28,34,37,40,45,50,52,53] single and/or double limb stance times (n=5),[32,34,37,45,53] stride length (n=6),[32,37,38,42,46,52] step width (n=2),[37,45] CoP (n=6),[30-33,38,43,50,51] peak plantar pressure (n=6),[26,28,44,47-49,51] ankle power (n=5),[28,31,46,52,53] walking distance (n=1),[35] and ambulatory function (n=1).[39]

***** Insert Table 3 about here *****

Gait speed

The mean difference in gait speed between individuals with an amputation, and the corresponding control groups, are presented as a forest plot in Supplementary file S6. Data of some studies are missing because they lacked a control group[29,36,38,50] or reported percentages only.[32,42] Two studies[34,52] compared individuals with amputations walking barefoot to walking with footwear, prosthesis, or both. Two studies[26,28,48] compared diabetic patients with non-diabetic controls. The remainder of the studies used appropriate control groups: diabetic patients for amputees with diabetes,[44,45] non-amputees with peripheral vascular diseases for amputees with peripheral vascular diseases,[42] and non-diabetic persons for non-diabetic amputees due to trauma.[32,53]

Cadence, ankle power, step length, stance time, and peak plantar pressure

Mean differences in cadence, ankle power, step length, stance time, and peak plantar pressures between the affected and non-affected foot or between the group of patients with an amputation and a control group are presented as forest plots in Supplementary files S7 to S12.

Great toe amputation

The association between great toe amputation and gait was addressed in five publications.[37,40,49-51] The sample size ranged from four to 12 patients per study. Duration of follow-up ranged from 6 months to 10 years. Outcome measures were spatiotemporal parameters, joint ROM, CoP excursion, and plantar pressures during gait.

Amputation of the great toe was related to morphological abnormalities of the foot, including varus drift (8°) of the second metatarsal, retraction of the sesamoids, a decrease in the height of the medial longitudinal arc, and descent of the first metatarsal head.[40] Great toe amputation was associated with instability on the medial side of the foot, with the line of progression of the CoP more laterally and a decrease in forward progression.[37,50,51] Gait speed was only minimally affected, but forward and lateral push-off was reduced.[37,40]

Toe amputation (digits two to five)

Toe amputation other than the great toe was addressed in three publications: one concerning the second toe,[38] one concerning one or more amputated toes,[46] and one concerning the second, third, and fourth toes.[33] Sample size ranged from one to 11. Amputation of the second toe may lead to claw foot, hallux valgus, and a narrower foot and postural instability during single-leg stance with eyes closed, with gait kinematics remaining within normal values in two studies.[33,38] Burnfield et al.[46] reported significantly reduced gait parameters (gait speed, cadence and stride length) in seven patients with toe amputations secondary to diabetes compared to healthy controls.

Ray amputation

The effect of ray amputation on gait was addressed in three publications.[36,45,54] Aprile et al.[45] compared six patients with ray amputation and type 2 diabetes to six patients with type 2 diabetes without amputation and six healthy subjects. The patients with diabetes and ray amputation walked slower and with more hip flexion. In addition, they had greater variability in lower extremity ROM and less ROM for the ankle, knee and hip compared to the patients with diabetes without amputation and the healthy controls. The authors concluded that the abnormal gait biomechanics might be caused by the severity of diabetes and the lack of a push-off phase from the great toe. Ramseier et al.[54] studied foot function in four patients after ray resection for a malignant tumour, with a follow-up between 21 months and 8 years. Foot function analysed with pedobarography was nearly normal, with a slightly laterally displaced CoP. Greene and Cary[36] included children with ray amputation in their study but did not report on this group separately, making it difficult to review their results.

Metatarsophalangeal amputation

The gait of people with MTP amputation was analysed in two studies: one case report[34] and one study with different variables in the same patient group described in three different publications.[30-32]

Forczek et al.[34] reported on a 30-year-old alpinist, 1.5 years after bilateral MTP amputation due to frostbite injury. Analysis of spatiotemporal parameters showed that the patient had a slower gait speed, shorter steps, and decreased step frequency when walking barefoot than when wearing shoes. The authors concluded that this was related to reduced stability and lower confidence due to partial toe amputation when walking barefoot, as footwear provided more stable conditions.

Dillon et al.[30-32] studied seven amputees with mixed amputation levels (one MTP, one TMT, three Lisfranc, and two Chopart) and compared their gait to the mean gait parameters and 95% CI of seven[32] and eight[30] healthy controls.

People with bilateral MTP amputation had a peak ankle power similar to that reported at the lower end of the 95% CI of the control sample. This was in sharp contrast to the patients in whom the metatarsal heads were amputated, as the generation of work across the ankle of the amputated limb was virtually negligible.[30] The CoP progressed relatively normally along the length of the operated foot during the initial part of the stance phase.[31] However, after loading, the CoP did not move as far distally along the foot length as usually observed in people without amputation. The GRF peak was consistent, and the magnitude was comparable to the lower limits of the control population.[32]

Transmetatarsal amputation

In people with TMT amputation, the metatarsal heads are amputated, resulting in the absence of the forefoot and a shortened foot and reduced foot lever. TMT amputation was addressed in 13 studies.[26-32,35,36,39,41-43,46-48,53] The sample size ranged from 5 to 27 patients with TMT amputation, and the follow-up duration ranged from 6 months to 13.7 years. Outcome measures addressed in these studies were spatiotemporal parameters, GRF, CoP excursion, plantar pressures during gait, ROM, and power generation. It is unclear whether the five patients from the two studies by Pinzur et al.[42,43] were the same because their ages were reported in only one study.

In patients with TMT amputation, power generation across the ankle joint was virtually negligible (0.72 W/kg; compared to the normal cohort: 95% CI [2.56 to 5.06 W/kg]), regardless of the residual foot length.[30] According to the authors, this was due to the diminished ankle moment coupled with joint angular velocity reductions.

This diminished ankle moment was also found by Garbalosa et al.,[47] with the authors reporting that feet with TMT amputation have a significantly decreased heel and increased forefoot peak plantar pressure compared to the intact foot. A considerably decreased maximum dynamic dorsiflexion ROM (70% vs 90%) and a similar static ROM were measured in the ankles of the amputated feet compared to the ankles of the intact feet.

In TMT amputees, reductions in work across the affected ankles were compensated for by increased power generation at the hip joint.[30] They appeared to rely more heavily on advancing their leg using the hip flexor muscles rather than the plantar flexor muscles, which had a shortened lever arm.[27] Hip extension strength was highly correlated with gait speed, functional reach, and physical performance score.[29]

Dillon et al.[31] showed that the CoP did not continue to progress distally along the length of the residuum but remained well behind the distal end throughout most of the stance phase until double limb support. Wearing a prosthesis can improve the situation somewhat but does not resolve it. Tang et al.[53] found that ankle moments in the terminal stance of TMT amputation when walking barefoot was only 45% relative to the control group. This improved to 62% when wearing a prosthesis. Ankle power generation in the pre-swing phase was only 28% compared to the control group, improving to 31% after wearing the TMT amputation prosthesis.

People with a TMT amputation walk slower and generate lower plantar flexor ankle moments and power than age-matched controls.[26,27,48] In these studies, persons with diabetes and TMT amputation were compared to healthy controls. There have been no studies comparing healthy people with a TMT amputation to a healthy population without amputation or studies comparing people with diabetes with and without TMT amputation.

Lisfranc and Chopart amputation

Chopart amputation was addressed in three studies, one with four Chopart amputee patients[52] and two mixed with other amputation types,[30-32,36] resulting in a total of 11 patients with a Chopart amputation. Lisfranc amputation was reported in two studies, both mixed with other amputation levels, with a total of six patients with a Lisfranc amputation.

Greene and Cary[36] studied children with traumatic or congenital amputation and showed that patients with an MT, ray or TMT amputation had superior results over those with a Syme amputation. Patients with a Lisfranc or Chopart amputation had better overall function than those with a Syme amputation but needed to make greater adjustments to their gait. Patients with a Chopart amputation and equinus contracture had inferior results compared to patients with a Syme amputation.

Burger et al.[52] reported on four patients who underwent Chopart amputation due to trauma (mean age 42.3±17.2 years) and had a reduced gait speed (0.89±0.19 m/s) compared to the norm (≈1.40 m/s for age 60-65 years).[55] Gait speed improved when wearing a silicone prosthesis (1.18±0.2 m/s) and when wearing footwear with a standard (0.99±0.22 m/s) or silicone prosthesis (1.16±0.24 m/s), but it was never normalised.

Dillon and Barker[32] showed that in patients with Chopart amputation, power generation across the ankle was negligible, comparable to patients with TMT amputation. The hip joints were the primary source of power generation. The use of a clamshell prosthesis restored their effective foot length and normalised many aspects of their gait but did not restore ankle power generation.

DISCUSSION

This scoping review described how different levels of partial foot amputation affect gait. The main findings were that partial foot amputations were associated with various gait changes, depending on the type of amputation. Toe amputations were associated with minor gait abnormalities, and great toe amputations caused loss of push-off in a forward and lateral direction. Metatarsophalangeal amputations were associated with loss of stability and decreased gait speed. Ray amputations were associated with decreased gait speed and reduced lower extremity range of motion (ROM). Transmetatarsal amputations and more proximal amputations were associated with abnormal gait, substantial loss of power generation across the ankle and impaired mobility. These findings are discussed below from distal to proximal level of amputation.

Gait-related outcomes

As shown in the forest plots, great toe, TMT, Lisfranc and Chopart amputations were associated with significant loss of gait speed, but some studies lacked a proper control group. Cadence and stance times were measured in only a few small studies, and 95% CI could not be calculated, making it difficult to draw firm conclusions. The other studies showed no significant difference. The forest plot of peak plantar pressure and step length showed a wide 95% CI, which also precludes drawing valid conclusions. Step length was significantly reduced in patients with first ray amputation compared to a proper control group, but this study examined only six patients. The forest plots showed that ankle power was significantly reduced in TMT patients.

Great toe amputation

Toe amputation is the most common lower extremity amputation. In 2017, the incidence ranged from 78 per 100 000 males (43 per 100 000 females) in Australia to 31.3 per 100 000 males (20.1 per 100 000 females) in the Netherlands.[56] Based on this scoping review of the literature, amputation of the great toe did not lead to significant changes in gait, including gait speed, cadence, step length, step width, or the single and double limb stance times of each foot. However, great toe amputation can lead to medial instability of the foot, as shown by a decrease in the height of the medial longitudinal arch, a descent of the first metatarsal head, and sesamoid retraction, due to loss of the windlass mechanism of the plantar aponeurosis.[50] It is also associated with loss of weight-bearing of the great toe and lateralisation of the CoP under the second and third metatarsal and varus drift in the second metatarsal joint. Thus, great toe amputation was associated with loss of power on pushing off and lateral movements.[40]

Ray amputation

Ray amputation involves excision of the toe and part of the metatarsal. Aprile et al.[45] found abnormal gait biomechanics in patients with type 2 diabetes and ray amputation compared to patients with type 2 diabetes and no amputation or healthy subjects. Ray amputations were associated with a lower gait speed, a higher degree of hip flexion, greater variability in lower extremity ROM, and less ankle, knee, and hip ROM. The abnormal gait biomechanics may be caused by the severity of diabetes and the lack of a push-off phase from the great toe. In addition, neuropathy affects 50% of patients with diabetes and amputation, but only 1 in 6 patients with diabetes. Aprile et al.[45] concluded that these findings suggest that the abnormal gait performance may be due to the missing first ray and more severe neuropathic pain.

Harlow et al.[57] reported on a collegiate athlete with second ray amputation due to heterotopic ossification in the first web space. A year later, a right great toe cheilectomy was performed. Four years later, she was unable to return to competitive soccer, but could participate in exercise walking and low-impact athletic activities.

Few studies have reported on ray amputation and gait, making it difficult to draw firm conclusions. However, based on the current evidence, it is likely that ray amputation, particularly first ray amputation, has a significant effect on lower extremity function during gait.

Metatarsophalangeal amputation

MTP amputation or disarticulation is an amputation of the toes that leaves the metatarsal heads in place. This amputation is not very common because surgeons generally prefer to perform a partial toe amputation or to include the metatarsal head in order to have enough skin tissue to cover the amputation stump. We found only two studies with this amputation, and each only included one patient. Unlike TMT amputation, after MTP amputation, power generation across the ankle stayed within the lower end of the 95% CI of the control sample.[30]

Transmetatarsal amputation

Amputation proximal to the metatarsophalangeal joints, including the metatarsal heads, is associated with a substantial reduction in power generation across the ankle, which is compensated by increased power generation across the hip joints and significantly reduced CoP excursions. A TMT amputation is associated with reduced ankle plantar flexor moments, with peak plantar flexor moments two-thirds of those measured in the control group.[28,32,53] The inability to generate enough power across the ankle was caused by a reduction in the capacity of the calf muscles to plantarflex the ankles and generate the necessary ankle torque to move the amputated foot. Limited distal progression of the CoP and a shorter foot lever of the amputated limb appear to contribute to the altered moments and power profiles in TMT amputation.[19,32]

The CoP remained proximal to the distal end of the amputated foot until after the contralateral heel contact with the ground. When there is double support, the CoP moves to the distal end of the amputated foot, and then the centre of mass shifts to the intact limb. In this situation, the lever arm of the GRF is longer, and the extent of the vertical GRF decreases so that the plantar flexion moment diminishes.[32]

Increased power generation across both hip joints provides the additional work necessary to move the body forward and compensate for reduced power generation across the affected ankle. The increase in work across the intact hip joint during early stance provides the forward impulse for the pelvis, and the increased power generation across the amputated side during early stance helps to move the body forward from the rear.[19]

Substantial reductions in gait speed and stride length were reported in several studies of patients with TMT amputations.[26-28,48] In all of these studies, the patients with TMT amputation had diabetes and were compared to healthy participants without diabetes or amputation. No studies compared the gait speed of patients with TMT amputation without diabetes to healthy controls without amputation, making it difficult to separate the effect of amputation from the effect of diabetes.

Lisfranc and Chopart amputation

Lisfranc and Chopart amputations are associated with a similar loss of power generation across the ankle due to the TMT amputation, with the accompanying abnormalities in gait parameters. Therefore, individuals with these proximal partial foot amputations may experience a substantial loss of function in their lower extremities, and their mobility will be significantly affected.

Potential implications for minimum impairment criteria in wheelchair tennis

This scoping review provides a consolidated overview of the gait pattern impairments associated with different levels of partial foot amputation. Descriptions of gait pattern impairments will guide the development of minimum impairment criteria for lower limb deficiency in the sport of wheelchair tennis. After great toe amputation, players may be disadvantaged when participating in standing tennis against non-disabled athletes, as the game requires frequent direction changes, sideways movements and forceful pushing off. On average, tennis players hit five strokes per rally[58,59] and change directions five times,[60] amounting to approximately 400 changes of direction in a best-of-3-set match.[61] More than 70% of movements in tennis are sideways; on average, a player covers 2 m per lateral movement.[62] In addition, the great toe is needed for the push-off during serving.[63] Ray amputations are associated with abnormal gait biomechanics and reduced gait speed. People with first ray amputations lack the push-off phase from the great toe. It is likely that ray amputation, particularly first ray amputation, will affect sprinting, jumping, turning, and mobility performance in tennis. TMT amputation is associated with substantial functional limitations of the lower extremities due to the loss of power generation across the ankle. Due to loss of power generation, the athlete may have reduced acceleration and deceleration, reducing their level of mobility in sport. Tennis requires frequent acceleration and deceleration over an extended period. Tennis matches (best-of-3-sets) last around one hour and a half.[64,65] Players cover 8 to 10 m per point and 550 to 700 m per set,[66,67] with a peak running speed of 20 km/h in elite male and 17 km/h in elite female players.[59,68-70] During a best-of-3-set tennis match, an elite tennis player accelerates more than 150 times with an acceleration speed of over 3 m/s^2.[71] It is unlikely that a player with a TMT amputation could produce the power necessary to match these physical demands. Mobility will likely be less affected in people with an MTP amputation than in people with a TMT amputation, but it is difficult to draw firm conclusions regarding the effect on mobility performance in sports based on the limited data. We expect that the effect of Lisfranc and Chopart amputations on tennis mobility is similar to that of a TMT amputation, but further studies in healthy individuals with these types of amputations are needed.

Recommendations

Minimum impairment criteria state the minimum level of impairment required to participate in the sport (i.e., wheelchair tennis). Factors that need to be considered in order to develop minimum impairment criteria are the extent to which the impairment (i.e., amputation) affects the ability of the player to execute the specific tasks and activities fundamental to non-disabled tennis, and the strength of the evidence.[72-74] Fundamental activities of non-disabled tennis include accelerations, decelerations, changes of direction, lateral movements, running and jumping. The minimum impairment criteria should be conservative enough to protect the integrity of the Para sport wheelchair tennis, but not so conservative that it excludes people with significant disadvantages in tennis. Based on the results of this scoping review, we recommend excluding toe amputations and including 1st ray, transmetatarsal, Chopart and Lisfranc amputations in the minimum impairment criteria for wheelchair tennis (Table 4). It is unclear whether great toe, ray and metatarsophalangeal amputations should be in- or excluded. This should be discussed further in an expert group and more research is recommended.

Strengths and limitations

The strengths of this scoping review are the systematic search and quantitative and qualitative data synthesis of all analysed outcomes, providing a comprehensive overview of the literature on partial foot amputation and gait. We identified 25 studies evaluating gait-related outcomes in patients who had undergone different types of partial foot amputation, allowing us to describe how different levels of partial foot amputation affect gait. However, 17 out of 25 studies were published more than 20 years ago, and the most recent study was published in 2018. This may have impacted the findings because surgical techniques may have improved over the years, surgical indications may have changed, and technology has advanced.

Our review was also limited by the small and heterogeneous populations in most studies. Amputee cohorts were diverse, including follow-up periods since amputation, amputation level, and involvement of the contralateral limb. Few studies drew comparisons between participants with amputation and a suitably matched control group. Eleven out of 25 studies included participants with amputation due to diabetes, and in nine out of 25 studies, the mean age of the participants was 58 years or older, making it difficult to extrapolate the findings to the athletic population.

CONCLUSIONS

Partial foot amputations were associated with various gait changes, depending on the type of amputation. Different levels and types of foot amputation are likely to affect tennis performance and should be considered when determining minimum impairment criteria for wheelchair tennis. We recommend studying gait and sporting performance in a large cohort of healthy, younger patients with similar partial foot amputation types and an adequately matched control group. However, since partial foot amputations in younger populations are relatively rare, and the most common causes are trauma, tumours and congenital anomalies, it may be difficult to get sufficiently large study groups with similar amputation types. Therefore, this would require multicenter studies.

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Contributors

FO, SW, CA and BP contributed to the conception and study design. LS contributed to the search strategy. FO, SW and BP conducted the data extraction, analysis and interpretation. TS performed the statistical analysis. FO, NH, CJR, SW and BP drafted the manuscript. All authors contributed to the manuscript with critical reviews and approved the final version of this paper.

Declaration of conflicting interests

CA is Editor-in-Chief for JOSPT and JST is Editor for BJSM. FO, SW, KF, NH, CJR, MGTJ, NK, SO, TS, LS, and NW declared no conflicts of interest. At the time of writing, BMP was a classification consultant for the ITF, tasked to review the ITF minimum impairment criteria, and Chair of the ITF Classification Working Group.

Trial registration

The protocol of this scoping review was previously registered at the Open Science Framework Registry ( ) and published.

ORCID IDs

Data sharing statement

Additional data from patients included in this study will not be available.

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Supplementary file S4. Joanna Briggs Institute (JBI) checklist score of the analytical cross-sectional studies included in this review (n=27).

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TABLES

Table 1. Minimum Impairment Criteria for the Eligible Impairment Limb Deficiency (lower limb only) for the 28 Paralympic Sports[8,9]

Sport	Minimum Impairment Criteria
Boccia:	Significant limb loss/deficiency of all four limbs; half of the lower limb amputated above the knee.
Football Five-a-Side:	Limb deficiency is not an Eligible Impairment.
Goal ball:	Limb deficiency is not an Eligible Impairment.
Para Alpine skiing:	Loss of one foot through the ankle.
Para Archery:	Loss of half one foot.
Para Athletics:	More than ½ loss of one foot or more than ¾ loss on both feet.
Para Badminton:	More than ½ loss of one foot or shortened leg of similar length.
Para Biathlon:	Loss of one leg above the ankle or shortened leg of similar length.
Para Canoe:	Loss of one leg below the knee or shortened leg of the same length.
Para Cross-Country Skiing:	Loss of one leg above the ankle or shortened leg of similar length.
Para Cycling:	More than ½ loss of one foot.
Para Equestrian:	Loss of one foot through the ankle or shortened leg of similar length.
Para Ice Hockey:	Loss of one leg through the ankle or shortened limb of similar length.
Para Judo:	Limb deficiency is not an Eligible Impairment.
Para Powerlifting:	Amputation through at least one ankle joint or a leg deficiency from birth at the same level.
Para Rowing:	Loss of half of one foot.
Para Shooting:	Complete loss of one foot or shortened leg of comparable length.
Para Snowboard:	Loss of one leg above the ankle or shortened leg of similar length.
Para Swimming:	More than ½ loss of one foot or more than ¾ loss on both feet.
Para Table Tennis:	Loss of at least 1/3 of a foot.
Para Taekwondo:	Loss of big toe or all of the toes of the foot.
Para Triathlon:	Complete loss of one foot or shortened leg of similar length.
Sitting Volleyball:	Loss of ½ length of one foot.
Wheelchair Basketball:	Loss of at least the big toe on one foot.
Wheelchair Curling:	Complete absence of one leg or loss of both legs above the ankle.
Wheelchair Fencing:	Loss of one foot or shortened limb of similar length.
Wheelchair Rugby:	Limb loss in both legs AND at least one arm/hand.
Wheelchair Tennis (2021):	Complete unilateral amputation of half the length of the foot.

Table 2. Characteristics of the included studies.

Author	Country	Study Design	Aim(s)	Sample size	Experimental group	Control group	Age in years (Mean ± SD)	Gender (Male: N (%))
Amputation Level: Toe/Great Toe								
Ademoglu et al 2000	Turkey	Case-control	Present outcomes (including clinical and biomechanical markers) after replantation surgery of great toe.	9	Failed replantation of great toe following trauma	Successful replantation of the great toe	25.3±14.9	8 (89)
Beyaert et al 2003	France	Cross-sectional	Determine effects at 5 years of second toe-to-hand transfer on foot morphology and function in children.	11	Toe amputation for digital reconstruction to treat congenital hand malformation	NA	6.5 to 12.5	7 (63.6)
Chen et al 1991	Taiwan	Case report	Describe a triple toe transfer as a unit with vascular supply.	1	Triple toe amputation for finger reconstruction	NA	26	1 (100)
Lavery et al 1995	United States	Cross-sectional	Compare under foot pressure with contralateral foot after great toe and first metatarsal amputation.	11	Great toe (+ partial 1st MTA) due to diabetes	NA	65.1 (39-79)*	7 (63.6)
Lipton et al 1987	United States	Pre-post study	Evaluate gait factors during walking cycle before and after great toe amputation.	12	Great toe amputation for thumb reconstruction	NA	29.3	10 (83.3)
Mann et al 1988	United States	Cross-sectional	Evaluate clinical and biomechanical effects of great toe amputation.	10	Great toe amputation for thumb reconstruction	NA	NR	9 (90)
Poppen et al 1981	United States	Cross-sectional	Establish effect on gait of great toe amputation.	4	Great toe amputation for thumb reconstruction	NA	NR	NR
Amputation Level: Metatarsophalangeal [MTP]								
Forczek et al 2014	Poland	Case report	Investigate gait kinematics after bilateral partial amputation of toes.	1	Bilateral MTP to treat frostbite	NA	30	1 (100)
Amputation Level: Transmetatarsal [TMT]								
Andersen et al 1987	Denmark	Pre-post study	Report the results of transmetatarsal amputation.	5	TMA to treat rheumatoid arthritis	NA	54.4±5.9	NR
Czerniecki et al 2012	United States	Pre-post study	Describe changes in: [i] function due to limb disability prior to surgery, [ii] premorbid function to 12 months, and [iii] identify associations between presurgical risk factors and change in ambulation.	87	TMA due to peripheral artery diseases or diabetes	NA	62.3±8.9	NR
Friedmann et al 1987	United States	Cross-sectional	Evaluate indications for surgical, and post-surgical management of partial foot loss.	9	TMA due to diabetes, trauma, frostbite or burn	NA	NR	NR
Garbalosa et al 1996	United States	Cross-sectional	Examine effects of TMA on plantar pressure and ankle joint kinematics.	10	TMA due to diabetes	NA	58.3±17.2	8 (80)
Kelly et al 2000	United States	Cross-sectional	Determine point during gait cycle at which peak forefoot plantat pressures occur.	24	TMA due to diabetes	Healthy subjects	60.3±10.3	6 (50)
Mueller et al 1997a	United States	Cross-sectional	Determine effect of footwear, shoe inserts and ankle foot orthoses on peak plantar pressures of amputated and non-amputated feet of patients with diabetes.	30	TMA due to diabetes	NA	61.7±11.3	20 (66.7)
Mueller et al 1997b	United States	Cross-sectional	Compare function of persons with diabetes and TMA with matched controls.	30	TMA due to diabetes	Healthy subjects	62.4±9.3	18 (60)
Mueller et al 1998	United States	Cross-sectional	Compare gait characteristics of people with diabetes and TMA to matched controls.	30	TMA due to diabetes	Healthy subjects	62.4±9.3	18 (60)
Pinzur et al 1992	United States	Cross-sectional	Evaluate the metabolic demand for walking in those with amputation following peripheral vascular disease.	25	Midfoot amputation due to peripheral vascular disease	Syme, below, through and above knee amputation and peripheral vascular disease	NR	NR

Pinzur et al 1997	United States	Case-control	Establish ground reaction force and dynamic center of pressure data for those with midfoot and Syme amputation.	11	Midfoot amputation due to peripheral vascular disease	Syme and peripheral vascular disease	63	NR
Salsich et al 1997	United States	Cross-sectional	Determine correlations between strength and functional measures, in people with diabetes and TMA.	30	TMA due to diabetes	NA	61.7±11.3	20 (66.7)
Tang et al 2004	Taiwan	Case-control	Determine correlations between strength and functional measures and intercorrelation between functional measures in people with diabetes and TMA.	17	TMA due to trauma	Healthy subjects	42.3±4.9	17 (100)
Amputation Level: Chopart								
Burger et al 2009	Slovenia	Cross-sectional	Establish gait biomechanics (barefoot; silicone prosthesis with/without footwear; footwear with conventional prosthesis).	4	Amputation due to trauma	NA	42.3±17.2	4 (100)
Amputation Level: Ray								
Aprile et al 2018	Italy	Case-control	Investigate differences in gait between persons with diabetes and first ray amputation, persons with diabetes without amputation, and healthy subjects.	18	Ray amputation due to diabetes	Diabetes without amputation, healthy subjects	70.4±6.9**	12 (66.7)
Ramseier et al 2004	Switzerland	Cross-sectional	Discuss clinical reasoning in deciding, planning, and carrying out local tumor resection and reconstruction.	4	Toe and ray amputation to treat malignant tumor	NA	30±28	2 (50)
Amputation Level: Mixed								
Burnfield et al 1998	United States	Cross-sectional	Determine impact of two partial foot amputation levels on limb loading force of non-affected limb during gait.	21	Toe amputation or TMA due to diabetes	Healthy subjects	NR	15 (71.4)
Dillon et al 2006a	Australia	Case-control	[i] Examine if preserving foot length should be a primary objective to maintain normal function, [ii] Establish biomechanical data to aid selection of amputation level.	16	MPT(1), TMT(1), Lisfranc(4), Chopart(2) amputation due to trauma or gangrene	Healthy subjects	41.5±24.4	NR
Dillon et al 2006b	Australia	Case-control	Evaluate the biomechanical effects of a partial foot prostheses in normalising gait pattern.	16	MPT(1), TMT(1), Lisfranc(4), Chopart(2) amputation due to trauma or gangrene	Healthy subjects	42.1±15.9	NR
Dillon et al 2008a	Australia	Case-control	Describe the gait patterns of a range of partial foot amputees to aid understanding of the mechanical adaptations to partial foot amputation and prosthetic fitting.	7	MTP(1), TMT(1), Lisfranc(3), Chopart(2) amputation due to trauma or gangrene	Healthy subjects	40.1±14.9	NR
Greene et al 1982	United States	Cross-sectional	Review gait and function of patients with congenital and childhood-acquired partial foot amputation and Syme amputation.	14	Ray, TMT, Midtarsal, Lisfranc, Chopart, and Syme's amputation either congenital or acquired in childhood	NA	16.3	10 (71.4)
Kanade et al 2006	United Kingdom	Case-control	Investigate walking capacity, performance and impact on the plantar tissues across four groups with diabetic neuropathy.	84	TMT(5), Ray(4), Hallux(5), all five toes(1), first two toes (1) amputation due to diabetes	Diabetic neuropathy / diabetic foot ulcer / trans-tibial amputation	62.3±7.6	74 (88)

* Only range reported.
** SD not reported for all groups.
NA: Not Applicable; NR: Not Reported; SD: Standard Deviation; MTA: Metatarsal amputation; MTP: Metatarsophalangeal; TMA: Transmetatarsal Amputation; TMT: Transmetatarsal.

Table 3. Assessment methods and outcome measures used in the included studies.

Author	Assessment Methods	Outcome measures
Amputation Level: Toe/Great Toe		
Ademoglu et al 2000	Physical Examination, Standard Weightbearing Dorsoplantar and Lateral X-Ray, Pedography Measurement Platform	Plantar Callus Formation, Joint ROM, Navicular Index, Cuboid Index, Height of First Metatarsal Head, Intermetatarsal Angles, Sesamoid Migration, Peak Plantar Pressure, Regional Plantar Pressure, Regional Pressure Ratios, CoP Excursion
Beyaert et al 2003	Physical Examination, Podoscope Assessment, Anteroposterior and Lateral X-Rays, Postural Balance via Force Platform, 3D Gait Analysis	Gait Speed, Cadence, Stride Length, Single Stance Duration of Gait Cycle, Plantar Imprint, Toe Position, Forefoot Deformation, Alignments, Balance Time, CoP Displacement, Angular Joint Movements,
Chen et al 1991	Postural Balance via Force Platform	CoP Excursion
Lavery et al 1995	In-Shoe Pressure Measurement System	Peak Plantar Pressure
Lipton et al 1987	Physical Examination, Gait Analysis using High Speed Cameras, Electromyography	Gait Speed, Cadence, Stride Length, Step Length, Single and Double Limb Stance Times, Step Width
Mann et al 1988	Physical Examination, Harris Mat Print, Anteroposterior and Lateral X-Rays and Photographs, Gait Analysis using Force Plates and High Speed Cameras	Gait Speed, Cadence, Step Length, Percent of Stance and Swing Phase, Heel-Rise Time, Plantar Callus Formation, ROM, Shoe Wear, Motion of the Pelvis, Hip, Knee, and Ankle; CoP
Poppen et al 1981	Physical Examination, X-Rays, Harris Mat, Gait Analysis	Plantar Callus Formation, ROM, Navicular Index, Cuboid Index, Pressure Distribution, Shoe Wear, Stance Phase, Heel Rise, Step Length
Amputation Level: Metatarsophalangeal [MTP]		
Forczek et al 2014	3D Gait Analysis using a Motion Analysis System	Gait Speed, Step Frequency, Single and Double Leg Support, Step Length, Step Time, Angular Motion in of Lower Limb Joints.
Amputation Level: Transmetatarsal [TMT]		
Andersen et al 1987	Physical Examination, Visual Observation	Walking Distance, Ability to Wear Shoes
Czerniecki et al 2012	Locomotor Capability Index-5	Ambulatory Function
Friedmann et al 1987	Questionnaire, Physical Examination, Gait Analysis, Electrodynograph (force data collector)	Duration of Gait Phases, Plantar Pressure
Garbalosa et al 1996	3D Gait Analysis via Cameras; Force Platform data	Peak Plantar Pressure, Regional Plantar Pressure, Static and Dynamic ROM Motion of the Ankle
Kelly et al 2000	In-Shoe Pressure Measurement System, 6.8m Walkway	Gait Velocity, Peak Plantar Pressure, Peak Force, Area in contact at Peak Plantar Pressure
Mueller et al 1997a	6.8m Walkway; In-Shoe Pressure Measurement System	Gait Speed, Peak Plantar Pressure
Mueller et al 1997b	Functional Reach Test, Physical Performance Test (PPT), Sickness Impact Profile (SIP)	Gait Speed, Reaching Distance, PPT: writing a sentence, simulated eating, lifting a book to put on a shelf, putting on and removing a jacket, picking up a penny from the floor, turning 360 degrees, walking 15.2 m (50 ft), and climbing a single flight of stairs (12 steps), SIP: emotional behaviour, mobility, body care and movement, ambulation, recreation and pastimes, social behaviour, and home management

Mueller et al 1998	3D Gait Analysis using a motion analysis system; Force Platform	Gait Speed, Step Length, Peak Plantarflexion Angle, Peak Ankle, Hip & Knee Moments and Power, Onset of Hip Flexion Moment, Hip & Knee ROM Excursion
Pinzur et al 1992	25m Walkway, Douglas Air Bag, Gas Chromatography, Telemetry EKG,	Gait speed (self-selected and maximum), Stride Length, Cadence, VO_2max, relative and functional energy cost
Pinzur et al 1997	Force Data using In-Shoe Pressure Measurement System	Ground Reaction Force, CoP Excursion
Salsich et al 1997	15.2 m Walkway and Stopwatch, Hand Held Dynamometry, Functional Reach Test, Physical Performance Test, Sickness Impact Profile,	Gait Speed, Lower Extremity Strength, Reaching Distance, PPT: writing a sentence, simulated eating, lifting a book to put on a shelf, putting on and removing a jacket, picking up a penny from the floor, turning 360 degrees, walking 15.2 m (50 ft), and climbing a single flight of stairs (12 steps), SIP: emotional behaviour, mobility, body care and movement, ambulation, recreation and pastimes, social behaviour, and home management,
Tang et al 2004	10m Walkway, 3D Gait Analysis using a Motion Analysis System, Force Platform	Gait Speed, Step Length, Cadence, Single- and Double-Leg Support Time, Ankle Joint Moments and Powers, Gait Symmetry
Amputation Level: Chopart		
Burger et al 2009	10M Walkway, 3D Gait Analysis using Motion Analysis System, Force Plates	Gait Speed, Step Length, Stride Length, Cadence, Joint Angles, Joint Moments, Joint Power
Amputation Level: Ray		
Aprile et al 2018	3D Gait Analysis using a Stereophotogrammetric System, Short-Form 36-item Health Survey Score, North American Spine Society Questionnaire, Neuropathic Pain Symptom Inventory, Numeric Rating Scale, ID-Pain	Gait Speed, Step Length, Step Width, Cadence, Stance, Percentage of Duration of Swing Phase, Percentage of Duration of Double Leg Support, Joint ROM during Gait, Quality of Life, Pain Score
Ramseier et al 2004	Gait Analysis using a Pedobarograph	Plantar Pressure Distribution
Amputation Level: Mixed		
Burnfield et al 1998	10 m Walkway, Force Platform, Dynamometrey	Gait Speed, Cadence, Stride Length, Peak Ground Reaction Force, Plantar Flexion Torque
Dillon et al 2006a	3D Gait Analysis using a Motion Analysis System; Force Platform	Ankle Power and Moment, Hip Power, Work across the Ankle
Dillon et al 2006b	3D Gait Analysis using a Motion Analysis System; Force Platform	CoP Excursion, Ground Reaction Force
Dillon et al 2008	3D Gait Analysis using a Motion Analysis System, Goniometry, Force Platform, Manual Muscle Testing	Gait Speed, Cadence, Stride Length, Duration of Swing and Stance Phase, Single and Double Leg Support, Joint ROM, Muscle Strength, Ground Reaction Force, CoP Excursion, Joint Moments and Power, Angular Velocity
Greene et al 1982	7.62 m Walkway, Physical Examination, Goniometry, Manual Muscle Testing, Weightbearing Lateral X-ray, Gait Analysis and Functional Activity via Visual Observation	Gait speed, Gait Mechanics
Kanade et al 2006	Heart Rate Monitor, Step Activity Monitor, Force Data using In-Shoe Pressure Measurement System	Gait Speed, Walking Capacity via Total Heart Beat Index, Daily Strides, Peak Plantar Pressure

3D: Three Dimensional; CoP: Center of Pressure; EKG: electrocardiogram; MTA: Metatarsal amputation; MTP: Metatarsophalangeal; MTT: Metatarsal; PPT: Physical Performance Test; ROM: range of motion; SIP: Sickness Impact Profile; TMA: Transmetatarsal Amputation; TMT: Transmetatarsal.

Table 4. Proposed recommendations for the Minimum Impairment Criteria for limb deficiency for wheelchair tennis according to amputation type.

Amputation type	Recommendation	Level of Evidence	Grade of recommendation	Rationale
Toe amputation(s) (excluding great toe)	Exclude	5	D	It is unlikely that running speed and acceleration/deceleration will be highly affected, but more research is needed
Great toe amputation	Exclude	5	D	Loss of power on pushing off, lateral movements, and serving. More research is needed on the extent that fundamental tennis activities are affected.
Ray amputation (excluding 1st ray)	Unclear	5	D	Acceleration/deceleration and running speed may be affected. More research is needed.*
1st Ray amputation	Include	5	D	Loss of power on pushing off, lateral movements, and serving. Acceleration/deceleration and running speed may be reduced.
Metatarsophalangeal amputation	Unclear	5	D	Minor limitations on acceleration/deceleration. More research is needed.**
Transmetatarsal amputation	Include	4	C	Major limitations on acceleration/deceleration.
Lisfranc amputation	Include	5	D	Major limitations on acceleration/deceleration.
Chopart amputation	Include	5	D	Major limitations on acceleration/deceleration.

*Based on three patients. **Based on two patients.

Grade of recommendation for the minimum impairment criteria rated according to the Centre of Evidence-Based Medicine (CEBM):[25]

A = Consistent level 1 studies. B = Consistent level 2 or 3 studies or extrapolations from level 1 studies. C = Level 4 studies or extrapolations from level 2 or 3 studies. D = Level 5 evidence or troublingly inconsistent or inconclusive studies at any level.

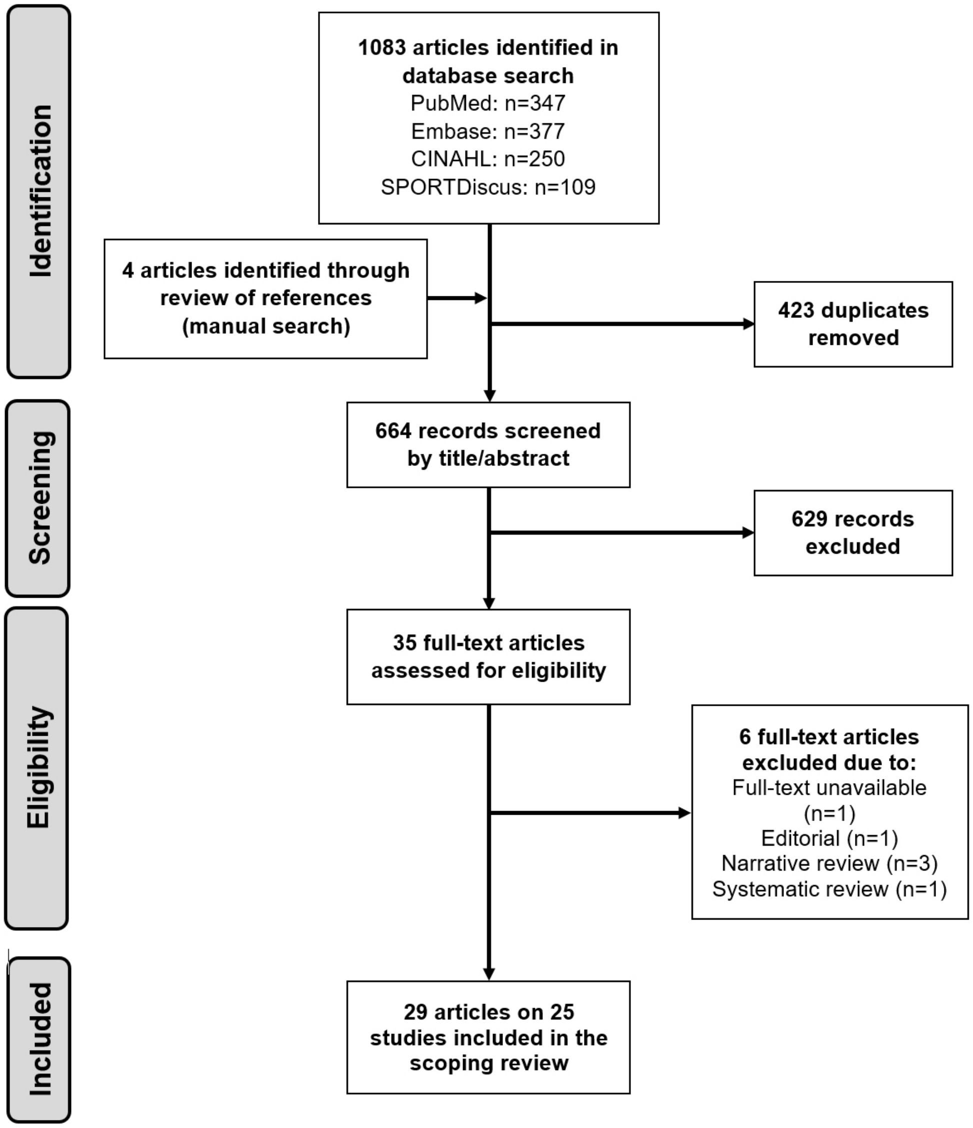


Figure 1. Flowchart of the article selection process conducted according to PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews).

101x116mm (300 x 300 DPI)

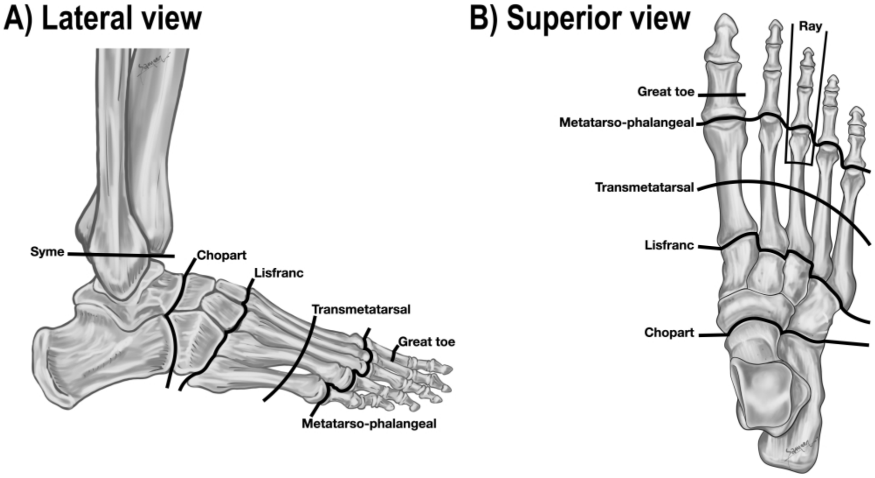


Figure 2. Partial foot amputation types. The exact level of the amputation may vary slightly. A) Lateral view. B) Superior view.

494x254mm (300 x 300 DPI)

Supplementary file S1. The search strategies for all databases.

PubMed History and Search Details February 19th 2022

Search	PubMed Query – February 19th 2022	Results
#4	#1 AND #2 AND #3	347
#3	"Physical Functional Performance"[Mesh] OR "Gait"[Mesh] OR "Gait Analysis"[Mesh] OR "gait*"[tiab] OR biomechanics[tiab] OR "functional performance"[tiab] OR "functional test*"[tiab] OR ((motion[tiab] OR movement[tiab] OR moving[tiab] OR locomotion[tiab] OR walk*[tiab] OR ambulati*[tiab]) AND analys*[tiab])	244,579
#2	"Forefoot, Human"[Mesh] OR "Foot Joints"[Mesh] OR "forefoot"[tiab] OR "midfoot"[tiab] OR "toe"[tiab] OR "toes"[tiab] OR "hallux"[tiab] OR "metatars*"[tiab] OR "intertars*"[tiab] OR "midtars*"[tiab] OR "transtars*"[tiab] OR "intermetatars*"[tiab] OR "transmetatars*"[tiab] OR "tarsometatars*"[tiab] OR "foot joint*"[tiab] OR "tarsal joint*"[tiab] OR "ray"[tiab] OR "lisfranc"[tiab] OR "chopart*"[tiab]	460,320
#1	"Amputation"[Mesh] OR "amputat*"[tiab] OR "disarticulat*"[tiab]	54,449

Embase.com History and Search Details February 19th 2022

Search	Embase.com Query – February 19th 2022	Results
#5	#4 NOT ('conference abstract'/it OR 'conference review'/it)	377
#4	#1 AND #2 AND #3	449
#3	'physical performance'/exp OR 'gait analysis system'/exp OR 'biomechanics'/exp OR 'gait'/exp OR ('gait' OR 'biomechanics' OR 'functional performance' OR 'functional test*' OR (('motion' OR 'movement' OR 'moving' OR 'locomotion' OR 'walk*' OR 'ambulati*') AND 'analys*')):ti,ab,kw	514,315
#2	'forefoot'/exp OR 'midfoot'/exp OR 'toe'/exp OR 'foot joint'/exp OR ('forefoot' OR 'midfoot' OR 'toe' OR 'toes' OR 'hallux' OR 'metatars*' OR 'intertars*' OR 'midtars*' OR 'transtars*' OR 'intermetatars*' OR 'transmetatars*' OR 'tarsometatars*' OR 'foot joint*' OR 'tarsal joint*' OR 'ray' OR 'lisfranc' OR 'chopart*'):ti,ab,kw	522,978
#1	'amputation'/exp OR (amputat* OR disarticulat*):ti,ab,kw	78,474

Cinahl (Ebsco) History and Search Details February 19th 2022

Search	Cinahl (Ebsco) Query – February 19th 2022	Results
S5	S4 AND Limit to: Academic Journals	250
S4	S1 AND S2 AND S3	298
S3	MH ("Psychomotor Performance" OR "Physical Performance" OR "Gait+" OR "Gait Analysis" OR "Biomechanics+") OR TI (gait OR biomechanics OR “functional performance” OR “functional test*” OR ((motion OR movement OR moving OR locomotion OR walk* OR ambulati*) AND analys*)) OR AB(gait OR biomechanics OR “functional performance” OR “functional test*” OR ((motion OR movement OR moving OR locomotion OR walk* OR ambulati*) AND analys*))	153,629
S2	MH ("Foot" OR "Toes" OR "Toe Joint+" OR "Tarsal Joint+") OR TI (forefoot OR midfoot OR toe OR toes OR hallux OR metatars* OR intertars* OR midtars* OR transtars* OR intermetatars* OR transmetatars* OR tarsometatars* OR “foot joint*” OR “tarsal joint*” OR ray OR lisfranc OR chopart*) OR AB (forefoot OR midfoot OR toe OR toes OR hallux OR metatars* OR intertars* OR midtars* OR transtars* OR intermetatars* OR transmetatars* OR tarsometatars* OR “foot joint*” OR “tarsal joint*” OR ray OR lisfranc OR chopart*)	54,404

Search	Cinahl (Ebsco) Query – February 19th 2022	Results
S1	MH "Amputation+" OR TI (amputat* OR disarticulat*) OR AB (amputat* OR disarticulat*)	16,129

SportDiscus (Ebsco) History and Search Details February 19th 2022

Search	SportDiscus (Ebsco) Query – February 19th 2022	Results
S4	S1 AND S2 AND S3	109
S3	DE ("PERFORMANCE" OR "BIOMECHANICS" OR "BIOMECHANICS in sports" OR "SEGMENTAL analysis technique (Biomechanics)") OR TI (gait OR biomechanics OR “functional performance” OR “functional test*” OR ((motion OR movement OR moving OR locomotion OR walk* OR ambulati*) AND analys*)) OR AB (gait OR biomechanics OR “functional performance” OR “functional test*” OR ((motion OR movement OR moving OR locomotion OR walk* OR ambulati*) AND analys*)) OR KW (gait OR biomechanics OR “functional performance” OR “functional test*” OR ((motion OR movement OR moving OR locomotion OR walk* OR ambulati*) AND analys*))	81,418
S2	DE ("FOOT" OR "TOES" OR "METATARSUS" OR "TARSOMETATARSUS" OR "TARSAL joint" OR "TOE joint" OR "LISFRANC joint") OR TI (forefoot OR midfoot OR toe OR toes OR hallux OR metatars* OR intertars* OR midtars* OR transtars* OR intermetatars* OR transmetatars* OR tarsometatars* OR “foot joint*” OR “tarsal joint*” OR ray OR lisfranc OR chopart*) OR AB (forefoot OR midfoot OR toe OR toes OR hallux OR metatars* OR intertars* OR midtars* OR transtars* OR intermetatars* OR transmetatars* OR tarsometatars* OR “foot joint*” OR “tarsal joint*” OR ray OR lisfranc OR chopart*) OR KW (forefoot OR midfoot OR toe OR toes OR hallux OR metatars* OR intertars* OR midtars* OR transtars* OR intermetatars* OR transmetatars* OR tarsometatars* OR “foot joint*” OR “tarsal joint*” OR ray OR lisfranc OR chopart*)	22,878
S1	TI (amputat* OR disarticulat*) OR AB (amputat* OR disarticulat*) OR KW (amputat* OR disarticulat*)	3,610

Supplementary file S2. Criteria for inclusion/exclusion of studies after the full-text screening.

	Inclusion criteria	Exclusion criteria
Population	Individuals (aged ≤16 years and >16 years), who underwent a PFA.	Cadaveric, animals, non-human studies
Types of PFA	Partial foot amputation: - (great) toe - metatarsophalangeal - ray amputation - transmetatarsal - tarsometatarsal (Lisfranc) - transtarsal (Chopart)	Level of amputation more proximal than transtarsal (e.g., Pirigoff, Boyd, and Symes) Use of mobility aids such as: - crutches - walking stick - cane - Nordic walking poles
Outcomes	- gait/walking speed - cadence - stride length - step length - step width - stance step duration - peak GRF - center of pressure excursion	- stair climbing - self-care
Study design	- peer-reviewed original articles - quantitative, qualitative, mixed, and multimethod design - dissertation or thesis - grey literature	Books, chart reviews, opinion papers, news and magazine articles, study protocols, narrative and systematic reviews, meta-analyses, editorials, annals of congresses, conference proceedings, presentations, posters,
Study availability	Full-text available	

GRF: ground reaction force; PFA, partial foot amputation.

Supplementary file S3. Joanna Briggs Institute (JBI) checklist score of the case reports included in this review (n=2).

Author	**Item number and corresponding score**								**Yes**	**No**	**Unclear**	**Not Applicable**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**				
Chen et al. (2007)	Y	Y	Y	N	Y	Y	Y	Y	7	1	0	0
Forczek et al. (2000)	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	0
Number of studies applying the item	2	2	2	1	2	2	2	2				
								Mean	7.5			
								SD	0.7			

Y = Yes; N = No; U = Unclear; NA = Not Applicable.

Questions from the JBI Checklist: 1. Were patient's demographic characteristics clearly described? 2. Was the patient's history clearly described and presented as a timeline? 3. Was the current clinical condition of the patient on presentation described in detail? 4. Were diagnostics tests or assessment methods and the results clearly described? 5. Was the intervention(s) or treatment procedure(s) clearly described? 6. Was the post-intervention clinical condition clearly described? 7. Were adverse events (harms) or unanticipated events identified and described? 8. Does the case report provide take-away lessons?

Supplementary file S4. Joanna Briggs Institute (JBI) checklist score of the analytical cross-sectional studies included in this review (n=27).

Author	Item number and corresponding score								Yes	No	Unclear	Not applicable
	1	2	3	4	5	6	7	8				
Amputation Level: Toe / Great toe												
Ademoglu et al. (2000)	Y	Y	Y	Y	N	N	U	N	4	3	1	0
Beyaert et al. (2003)	Y	Y	Y	Y	Y	N	Y	Y	7	1	0	0
Lavery et al. (1995)	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	0
Lipton et al. (1987)	Y	Y	Y	Y	Y	N	Y	N	6	2	0	0
Mann et al. (1988)	N	Y	Y	Y	N	N	Y	U	4	3	1	0
Poppen et al. (1981)	N	N	Y	Y	N	N	N	NA	2	5	0	1
Amputation Level: Transmetatarsal												
Andersen et al (1987)	Y	Y	Y	Y	Y	N	N	NA	5	2	0	1
Czerniecki et al. (2012)	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	0
Friedmann et al. (1987)	Y	N	Y	Y	Y	N	Y	NA	5	2	0	1
Garbalosa et al. (1996)	N	Y	Y	Y	N	N	Y	Y	5	3	0	0
Kelly et al. (2000)	Y	Y	Y	Y	Y	N	Y	Y	7	1	0	0
Mueller et al. (1997a)	Y	Y	Y	Y	N	N	Y	Y	6	2	0	0
Mueller et al. (1997b)	Y	Y	Y	Y	N	N	Y	Y	6	2	0	0
Mueller et al. (1998)	Y	Y	Y	Y	Y	N	Y	Y	7	1	0	0
Pinzur et al. (1992)	N	Y	Y	Y	Y	Y	Y	U	6	1	1	0
Pinzur et al. (1997)	N	Y	Y	Y	Y	Y	Y	NA	6	1	0	1
Salsich et al. (1997)	Y	Y	Y	Y	Y	N	Y	Y	7	1	0	0
Tang et al. (2004)	Y	Y	Y	Y	Y	N	N	Y	6	2	0	0
Amputation Level: Chopart												
Burger et al. (2009)	Y	Y	Y	Y	N	N	Y	y	6	2	0	0
Amputation Level: Ray												
Aprile et al. (2018)	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	0
Ramseier et al. (2004)	Y	Y	Y	Y	N	N	Y	NA	5	2	0	1
Amputation Level: Mixed												
Burnfield et al. (1998)	Y	Y	Y	Y	N	N	Y	Y	6	2	0	0
Dillon et al. (2006a)	Y	Y	Y	Y	N	N	Y	U	5	2	1	0
Dillon et al. (2006b)	Y	Y	Y	Y	N	N	Y	U	5	2	1	0
Dillon et al. (2008a)	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	0
Greene and Cary (1982)	Y	Y	Y	Y	N	N	N	NA	4	3	0	1
Kanade et al. (2006)	Y	Y	Y	Y	Y	Y	Y	Y	8	0	0	0
Number of studies applying the item	22	25	27	27	15	7	22	15				
								Mean	6.00	1.50	0.33	0.17
								SD	1.67	1.22	0.52	0.41

Y = Yes; N = No; U = Unclear; NA = Not Applicable.

Questions from the JBI Checklist: 1. Were the criteria for inclusion in the sample clearly defined? 2a. Were the study subjects and setting described in detail? 3. Was the exposure measured in a valid and reliable way? 4. Were objective, standard criteria used for measurement of the condition? 5. Were confounding factors identified? 6. Were strategies to deal with confounding factors stated? 7. Were the outcomes measured in a valid and reliable way? 8. Was appropriate statistical analysis used?

Supplementary file S5. Summary of key findings from the included studies.

Author	Level of amputation	Comparison	Key findings	Study limitations	Conclusions
Amputation Level: Toe/Great Toe					
Ademoglu et al 2000	Great toe	Successful replanted toe vs. failed replantation	↓ MTP and IP ROM in replanted toes. No significant difference in navicular index, cuboid index, height of first MT head, interMT angles, sesamoid migration. ↑ loading of 2nd-5th MT heads and laterally displaced CoP.	Small sample size. Only one female participant. Limited explanation of statistical analysis.	Amputation of great toe does not appear to effect gait compared to replantation, but changes pressure distribution in foot.
Beyaert et al 2003	Second toe	Operated vs. non-operated contralateral foot	↓ balance duration and ↑ rate of CoP displacement and sway in standing. ↑ gait speed and cadence. Normal kinematics, stride length and single-stance time.	Only includes participants under 13 years. No detail on treatment in first 5 years post-surgery. Both feet operated on in 8/15 so no comparisons with non-operated foot.	Removal of second toe ↓ balance but has no apparent effect on gait.
Chen et al 1991	Second, third and fourth toe	Operated vs non-operated contralateral foot	No significant difference in weightbearing and walking.	Single case study, no quantitative data, measurement device not described, non-operated foot damaged by trauma.	Despite removal of three toes and original transverse arch collapse, ability to walk/run, walk upstairs and stand on one foot remain.
Lavery et al 1995	Great toe (and partial first MT)	Operated vs. non-operated contralateral foot	Peak pressure ↑ under MT heads and 2nd-5th toes. ↑ peak pressure under contralateral heel.	Comparison with contralateral foot only. Diabetic participants only.	Pressure distribution changes ↑ complications including ulceration risk.
Lipton et al 1987	Great toe	Pre-operative vs. post-amputation gait	↓ velocity post-amputation, due to ↓ stride length/cadence. ↓ step length of non-operated foot. Average velocity, cadence, step length of the operated foot, and single/double limb stance times, and step width did not significantly change. No change in EMG activity post-surgery.	High number of male participants. Wide range in time since surgery.	Gait changes following great toe replantation were mild.
Mann et al 1988	Great toe	Operated vs. non-operated contralateral foot	↑ pressure under 3rd MT head on operated side and ↓ velocity of movement of CoP (↑ loading). CoP progression noted beneath 3rd MT head on operated side, instead of medially and distally towards first web space.	High number of male participants. Gait analysis performed in only 7/10 participants, EMG in 3/10.	Hallux removal at MTP joint causes medial instability due to loss of windlass mechanism, ↑ pressure at MT heads and ↓ gait speed.
Poppen et al 1981	Great toe	Operated vs. non-operated contralateral foot	Second MT joint in 8° varus. ↑ dorsiflexion of 2nd MTP joint. ↓ Navicular and cuboid index. ↑ pressure under 2nd/3rd MT heads. No change in gait pattern.	Small sample size. Large range in time since amputation. No detail on gait analysis techniques.	Pressure distribution changes (2nd and 3rd MT heads) but gait unchanged with unilateral great toe amputation.
Amputation Level: Metatarsophalangeal [MTP]					

Forczek et al 2014	MTP (bilateral)	Barefoot walking vs shod walking	Walking velocity ↑ during shod walking than barefoot. Step frequency/length ↓ during gait without shoes. Single/double support and step time similar. Larger ROM used during shod walking.	Single case study. Bilateral amputation, precluding comparison with non-operated foot.	Changes in gait from forefoot amputation are ↓ when walking shod compared to barefoot. Walking shod utilises larger ROM.
Amputation Level: Transmetatarsal [TMT]					
Andersen et al 1987	TMT	Pre-post surgery	Walking distance improved after surgery in 4 out of 5 patients; they achieved almost normal heel-toe gait. None complained of imbalance.	Sex not reported, small study. No objective gait analysis. 3 out of 5 bilateral amputations, precluding comparison with non-operated foot.	TMT amputation to reduce pain and improve walking distance recommended in patients with deformed feet due to RA.
Czerniecki et al 2012	TMT	Pre-post surgery	Ambulation improved after surgery but did not return to premorbid levels. Little difference in ambulation outcome between TT and TMT amputees.	Sex not reported, final numbers with partial amputation that finished study not reported.	Importance of salvaging the TMT amputation level to preserve ambulation questioned in situations where revascularisation is required to enable healing.
Friedmann et al 1987	TMT	Operated vs. non-operated contralateral foot	Single-stance duration ↓ on amputated and non-amputated foot, compared with non-amputated reference. ↓ heelstrike to forefoot contact, ↑ midstance and ↓ propulsive phase in amputated feet, with ↑ contralateral swing phase. ↑ pressure in MT heads compared to non-amputated feet.	Low response rate and few participants fully assessed. No age data. Absolute pressure levels not included. No SD or CIs. Persons with diabetes compared to healthy population, no controls.	TMA leads to lateral, forefoot and midfoot instability and compromised propulsion through the amputated foot.
Garbalosa et al 1996	TMT	Operated vs. non-operated contralateral foot	↑ peak mean plantar pressure, ↓ heel and ↑ forefoot peak plantar pressure in the amputated feet Significantly ↑ maximum dynamic dorsiflexion (90% vs 70%) and similar static ankle ROM in intact feet.	No control group. Heterogeneity in the relative lengths of the residual MTs did not allow any further insight into the issue of the optimal contour of the residual MTs.	↓ heel and ↑ forefoot peak plantar pressure in TMA feet due to lack of dynamic dorsiflexion ROM causing heel to not be fully loaded ("functional equinus").
Kelly et al 2000	TMT	Participants with TMA vs controls	Persons with diabetes and TMA walked more slowly than controls. Peak Plantar Pressure and timing were similar. Peak force occurred earlier on amputated side and gait speed significantly ↓. No difference in peak force between groups.	Diabetes may be a confounding factor. Large range of time since amputation. Different walking speeds ↓ ability to compare peak plantar pressures.	Participants with TMA walk more slowly than non-amputated participants and may explain similar peak pressures between groups.
Mueller et al 1997a	TMT	Comparison between five different footwear combinations	Experimental footwear combinations produced ↓ peak plantar pressure on amputated foot compared with regular shoe with toe-filler. No differences in peak plantar pressure between experimental footwear conditions found.	No control group used. Only forefoot measurements were gathered. Large range of time since last amputation (2-132 months).	Therapeutic footwear ↓peak plantar pressure compared to normal shoes. Total contact area of footwear with foot appears important for ↓ peak plantar pressure.

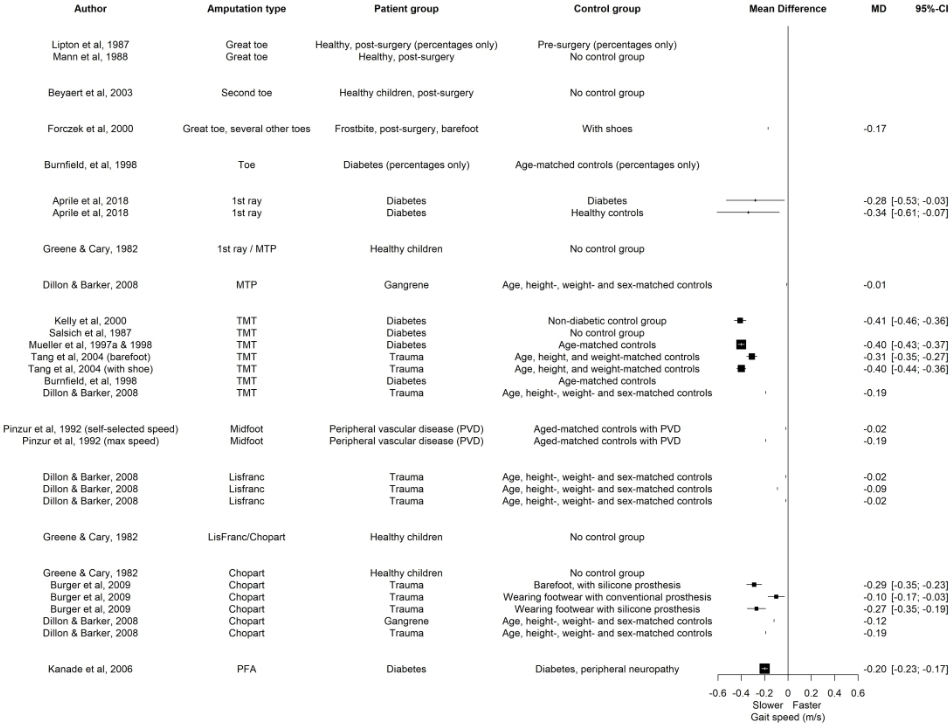
			Long shoe with rigid rocker bottom sole, and both short shoe combinations produced faster walking speeds than normal shoes with toe filler.		
Mueller et al 1997b	TMT	Participants with TMA vs controls	↓ functional reach scores, and Physical Performance Test scores versus controls (walking with a turn, picking up a penny and climbing stairs). Participants with amputation walked at 68% speed of controls.	Presence of diabetes itself may be a confounding factor. High presence of neuropathy in amputation group.	Participants with TMA showed deficits in functional tasks versus controls, due to shortened foot length or co-morbidities.
Mueller et al 1998	TMT	Participants with TMA vs control participants	↓ plantar flexion ROM, peak plantar flexor moment, and peak plantar flexor power in the late stance phase after amputation. Hip flexor moment initiated earlier in stance phase and slower gait speeds and step lengths noted compared to controls.	Presence of diabetes may be a confounding factor. High presence of neuropathy in amputation group. Only assessed sagittal plane movement.	Participants with diabetes and TMA had ↓ contribution to gait from plantar flexors and hip compensation may be used to advance the leg.
Pinzur et al 1992	Midfoot(5), Syme(5), BKA(5), TKA(5), AKA(5)	Midfoot amputation vs. Syme amputation vs. BKA vs. TKA vs AKA vs. diabetic participants without amputation	Walking speed, stride length and cadence ↓ with more proximal amputation. Metabolic cost of walking ↑ with more proximal amputation and at ↑ energy demand than non-amputated controls.	No testing for statistical significance of results, or significance of difference between groups.	Walking capacity related to level of amputation, therefore preservation of limb via more distal amputation levels may lead to better function.
Pinzur et al 1997	Midfoot(5), Syme(6)	Midfoot amputation vs. participants with Syme amputation	Syme amputation linked to initial loading through centre of prosthetic heel, progressing along midline of prosthetic foot. GRF corresponded with push off. Midfoot amputation had similar early CoP distribution to healthy participants and initial floor contact at lateral border of heel, with CoP moving to midline before progressing distally, then moving medially to area under the residual first MT.	No numerical data given. Presence of diabetes and severe peripheral vascular disease may be confounding factors. Does not report control subject data.	Pressure data may explain ↑ energy cost of walking with midfoot amputation due to shortened lever versus rigid complete prosthetic foot. Level of walking and function should be considered when selecting amputation level.
Salsich et al 1997	TMT	None	Hip extension strength correlated with walking speed and physical performance scores. Functional reach correlated with hip extension, flexion and abduction. Physical test scores correlated with hip flexion, knee flexion and extension and ankle dorsiflexion. Walking speed correlated with hip flexion, abduction, knee flexion and extension and ankle dorsiflexion.	Does not detail testing position for strength testing. No controls, therefore unable to say if correlations are different in amputated population.	Hip extension strength is important in controlling gait speed as well as other functional tasks after TMA. There is a correlation with lower limb muscle strength and gait speed / function.
Tang et al 2004	TMT	(1) Participants with amputation vs control	Participants with amputation did not differ from controls in walking velocity and step	Only males included. Adequate control group (healthy	TMA significantly ↓ plantar flexion power during gait. Use

		participants; (2) amputated foot vs non-amputated foot; (3) barefoot vs walking with shoe vs walking with prosthesis	length. Walking barefoot ↓ ankle ROM compared with walking with footwear or prosthesis. Better gait symmetry was achieved with prosthesis than when barefoot. Ankle power ↓ versus controls, and lower when barefoot than shod.	participants with traumatic amputation vs healthy controls)	of footwear can improve this but reductions may still exist and be more pronounced during high demand activities.
Amputation Level: Chopart					
Burger et al 2009	Chopart	Barefoot vs. silicone prosthesis vs. footwear with conventional prosthesis vs. footwear with silicone prosthesis	Use of a silicone prosthesis ↑ step length of amputated foot and gait velocity when compared to barefoot walking. Cadence and step length of the intact foot were ↑ but not significantly. Use of silicone prosthesis when wearing footwear ↑ all parameters compared to conventional foot prostheses. Silicone prosthesis ↑ ankle ROM, hip ab/adduction ankle moment and ankle power compared to barefoot walking.	Small sample size. No control group for comparison of results to normal data.	Use of a silicone prosthesis ↑ gait speed, step length, ankle range and ankle power as well as other parameters compared to barefoot walking or conventional prosthesis.
Amputation Level: Ray					
Aprile et al 2018	First Ray	Participants with diabetes and amputation vs. participants with diabetes and no amputation vs. healthy controls	Amputated participants with diabetes showed ↓ quality of life, ↓ ROM, ↑ pain scores versus diabetic participants, greater variability in, and shorter step length, larger step width, and slower walking speeds than non-amputated participants with diabetes or healthy participants.	Small sample size per group.	First ray amputation leads to negative changes in gait parameters compared to healthy subjects and those with diabetes without amputation.
Ramseier et al 2004	Ray	Operated vs. non-operated foot of participants	All participants show almost normal gait, with the centre of pressure shifting laterally in the foot in two of the four cases.	Small sample size. Wide age range in participants. Lack of justification as to how 'normal gait' was defined.	Ray resection causes mild changes to pressure distribution during gait, but functionally has little effect on gait.
Amputation Level: Mixed					
Burnfield et al 1998	Toe, TMT	Participants with toe amputation vs. participants with TMA vs. healthy participants	Participants with TMA showed ↑ peak load forces for non-amputated foot, and ↓ isometric plantar flexion torque for amputated foot. Participants with toe amputation had no differences in peak load force or isometric plantar flexion torque. Both amputated groups had ↓ walking velocities, cadence and stride length compared to healthy control.	Data not provided as absolute values but as percentages. Presence of diabetes could be a confounding factor when control group consisted of healthy subjects without diabetes.	Forefoot rocker preservation may ↓ limb loading and ↓ risk of skin breakdown.
Dillon et al 2006a	MTP(1), TMT(1), Lisfranc(4), Chopart(2)	Participants with partial foot amputation vs. healthy participants	In participants with MT head amputation, power generation was negligible in affected limbs. This was compensated for	High variability in terms of amputation level and small sample size. Wide variance in	Amputation that preserves the MT heads does not affect power generation at ankle

			by ↑ hip force generation. Participants with preserved MT heads did not demonstrate differences in power at ankle compared to non-amputated controls.	years since amputation. Gait of evaluated while wearing prosthetic replacement. Type of prosthetic may be confounding factor.	compared to non-amputated gait. With MT heads amputated, power generation at ankle was negligible regardless of foot length.
Dillon et al 2006b	MTP(1), TMT(1), Lisfranc (4), Chopart (2)	Participants with partial foot amputation vs. healthy participants	In participants with MTP, TMT and Lisfranc amputation, CoP progressed in intact foot at initial swing phase. After loading, CoP did not progress distally. In TMT and Lisfranc amputated feet, GRF did not continue along length of foot but at distal end through stance phase. Chopart amputation allowed progression of CoP similar to intact foot.	Variable amputation levels and small sample size. Wide variance in years since amputation. Gait evaluated while wearing prosthetic replacement. Type of prosthetic may be confounding factor.	Participants with TMA and Lisfranc amputation are unable to effectively utilise forefoot prosthetics to restore normal gait parameters.
Dillon et al 2008	MTP(1), TMT(1), Lisfranc (3), Chopart (2)	Partial foot amputation vs. healthy participants	Significant ↓ in walking velocity observed in subjects with amputation (TMT and Chopart). No change noted in gait cycle duration compared to controls. With MTP amputation there was delay in progression of CoP following midstance, and ↓peak ankle moments during late stance.	Variable amputation level. Small sample size. Variance in years since amputation. Number of controls not provided. Gait evaluated while wearing their prosthetic replacement. Type of prosthetic may be confounding factor.	TMT/ Lisfranc amputation and toe fillers/slipper sockets linked to inability to progress CoP beyond end of residuum commensurate with peak GRF or generate ankle power. Despite effective forefoot length, with Chopart amputation and clamshell devices power generation negligible at ankle.
Greene et al 1982	Ray, TMT, midtarsal, Lisfranc, Chopart, Syme	Ray or TMA vs. participants with Lisfranc, midtarsal & Chopart amputations vs. participants with Chopart amputations with equinus contracture vs. participants with Syme amputation	Syme amputations linked to ↑ function and mild gait alterations at pelvis and knee. TMT or ray amputations had ↑ function with prolonged knee extension at heel off and ↑ knee flexion at toe off. Lisfranc, midtarsal or Chopart amputations demonstrated acceptable gait mechanics but ↓ co-ordination and gait smoothness. Chopart amputation with equinus contracture had ↓ functional activity, and gait speed compared to other groups.	No control group. One participant with Lisfranc amputation in group 1 not group 2. No analysis. Gait analysis via subjective methods.	Conversion to Syme may benefit patients with Chopart amputation with equinus contracture but is unlikely to benefit those without equinus contracture or more distal amputation.
Kanade et al 2006	First two toes(1), all five toes(1), great toe(5), ray(1), TMT(5)	Diabetic neuropathy and no ulcer vs. participants with diabetic foot ulcer vs. participants with diabetes and partial foot amputation vs. participants with diabetes	Total HBI as an indicator of energy expenditure showed an ↑ across groups from participants with diabetes but without ulcer, to trans-tibial amputation. Daily strides and gait velocity ↓ suggesting lower activity levels. Participants with partial foot amputation showed ↑ plantar pressure than	Cross-sectional design rather than longitudinal study. Groups were matched; however, the distribution of type 1 and type 2 diabetes does not appear matched.	Measures of energy expenditure, daily activity, walking speed and peak pressure show less desirable outcomes as participants with diabetes progress from neuropathy alone, through ulceration, partial foot

	and trans-tibial amputation	participants with neuropathy and active ulceration.		amputation and trans-tibial amputation.

AKA: Above Knee Amputation; BKA: Below knee Amputation; CIs: Confidence Intervals; CoP: Centre of pressure; EMG: Electromyography; GRF: Ground Reaction Force; HBI: Heart Beat Index; IP: Interphalangeal; MT: Metatarsal; MTP: Metatarsophalangeal; RA: Rheumatoid Arthritis; ROM: Range of Motion; SD: Standard Deviation; TKA: Through Knee Amputation; TMA: Transmetatarsal amputation; TMT: Transmetatarsal; TT: Transtibial.



Author	Amputation type	Patient group	Control group	MD	95%-CI
Lipton et al, 1987	Great toe	Healthy, post-surgery (percentages only)	Pre-surgery (percentages only)		
Mann et al, 1988	Great toe	Healthy, post-surgery	No control group		
Beyaert et al, 2003	Second toe	Healthy children, post-surgery	No control group		
Forczek et al, 2000	Great toe, several other toes	Frostbite, post-surgery, barefoot	With shoes	-0.17	
Burnfield, et al, 1998	Toe	Diabetes (percentages only)	Age-matched controls (percentages only)		
Aprile et al, 2018	1st ray	Diabetes	Diabetes	-0.28	[-0.53; -0.03]
Aprile et al, 2018	1st ray	Diabetes	Healthy controls	-0.34	[-0.61; -0.07]
Greene & Cary, 1982	1st ray / MTP	Healthy children	No control group		
Dillon & Barker, 2008	MTP	Gangrene	Age, height-, weight- and sex-matched controls	-0.01	
Kelly et al, 2000	TMT	Diabetes	Non-diabetic control group	-0.41	[-0.46; -0.36]
Salsich et al, 1987	TMT	Diabetes	No control group		
Mueller et al, 1997a & 1998	TMT	Diabetes	Age-matched controls	-0.40	[-0.43; -0.37]
Tang et al, 2004 (barefoot)	TMT	Trauma	Age, height, and weight-matched controls	-0.31	[-0.35; -0.27]
Tang et al, 2004 (with shoe)	TMT	Trauma	Age, height, and weight-matched controls	-0.40	[-0.44; -0.36]
Burnfield, et al, 1998	TMT	Diabetes	Age-matched controls		
Dillon & Barker, 2008	TMT	Trauma	Age, height-, weight- and sex-matched controls	-0.19	
Pinzur et al, 1992 (self-selected speed)	Midfoot	Peripheral vascular disease (PVD)	Aged-matched controls with PVD	-0.02	
Pinzur et al, 1992 (max speed)	Midfoot	Peripheral vascular disease (PVD)	Aged-matched controls with PVD	-0.19	
Dillon & Barker, 2008	Lisfranc	Trauma	Age, height-, weight- and sex-matched controls	-0.02	
Dillon & Barker, 2008	Lisfranc	Trauma	Age, height-, weight- and sex-matched controls	-0.09	
Dillon & Barker, 2008	Lisfranc	Trauma	Age, height-, weight- and sex-matched controls	-0.02	
Greene & Cary, 1982	LisFranc/Chopart	Healthy children	No control group		
Greene & Cary, 1982	Chopart	Healthy children	No control group		
Burger et al, 2009	Chopart	Trauma	Barefoot, with silicone prosthesis	-0.29	[-0.35; -0.23]
Burger et al, 2009	Chopart	Trauma	Wearing footwear with conventional prosthesis	-0.10	[-0.17; -0.03]
Burger et al, 2009	Chopart	Trauma	Wearing footwear with silicone prosthesis	-0.27	[-0.35; -0.19]
Dillon & Barker, 2008	Chopart	Gangrene	Age, height-, weight- and sex-matched controls	-0.12	
Dillon & Barker, 2008	Chopart	Trauma	Age, height-, weight- and sex-matched controls	-0.19	
Kanade et al, 2006	PFA	Diabetes	Diabetes, peripheral neuropathy	-0.20	[-0.23; -0.17]

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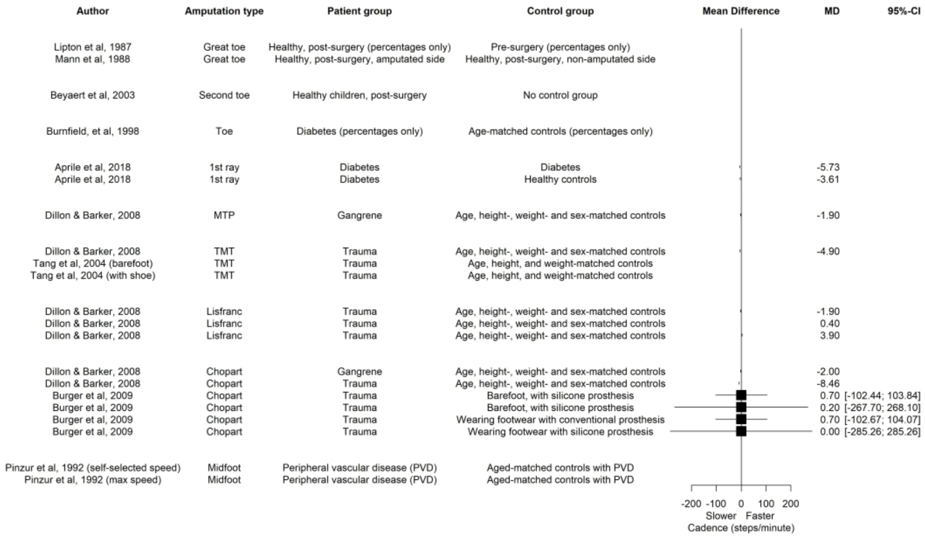

Author	Amputation type	Patient group	Control group	Mean Difference	MD	95%-CI
Lipton et al, 1987	Great toe	Healthy, post-surgery (percentages only)	Pre-surgery (percentages only)			
Mann et al, 1988	Great toe	Healthy, post-surgery, amputated side	Healthy, post-surgery, non-amputated side			
Beyaert et al, 2003	Second toe	Healthy children, post-surgery	No control group			
Burnfield, et al, 1998	Toe	Diabetes (percentages only)	Age-matched controls (percentages only)			
Aprile et al, 2018	1st ray	Diabetes	Diabetes		-5.73	
Aprile et al, 2018	1st ray	Diabetes	Healthy controls		-3.61	
Dillon & Barker, 2008	MTP	Gangrene	Age, height-, weight- and sex-matched controls		-1.90	
Dillon & Barker, 2008	TMT	Trauma	Age, height-, weight- and sex-matched controls		-4.90	
Tang et al, 2004 (barefoot)	TMT	Trauma	Age, height, and weight-matched controls			
Tang et al, 2004 (with shoe)	TMT	Trauma	Age, height, and weight-matched controls			
Dillon & Barker, 2008	Lisfranc	Trauma	Age, height-, weight- and sex-matched controls		-1.90	
Dillon & Barker, 2008	Lisfranc	Trauma	Age, height-, weight- and sex-matched controls		0.40	
Dillon & Barker, 2008	Lisfranc	Trauma	Age, height-, weight- and sex-matched controls		3.90	
Dillon & Barker, 2008	Chopart	Gangrene	Age, height-, weight- and sex-matched controls		-2.00	
Dillon & Barker, 2008	Chopart	Trauma	Age, height-, weight- and sex-matched controls		-8.46	
Burger et al, 2009	Chopart	Trauma	Barefoot, with silicone prosthesis		0.70	[-102.44; 103.84]
Burger et al, 2009	Chopart	Trauma	Barefoot, with silicone prosthesis		0.20	[-267.70; 268.10]
Burger et al, 2009	Chopart	Trauma	Wearing footwear with conventional prosthesis		0.70	[-102.67; 104.07]
Burger et al, 2009	Chopart	Trauma	Wearing footwear with silicone prosthesis		0.00	[-285.26; 285.26]
Pinzur et al, 1992 (self-selected speed)	Midfoot	Peripheral vascular disease (PVD)	Aged-matched controls with PVD			
Pinzur et al, 1992 (max speed)	Midfoot	Peripheral vascular disease (PVD)	Aged-matched controls with PVD			

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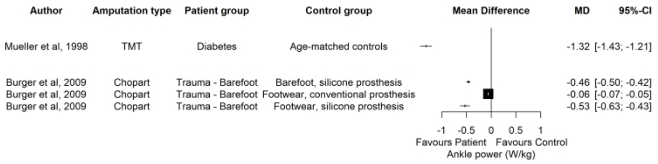

Author	Amputation type	Patient group	Control group	MD	95%-CI
Mueller et al, 1998	TMT	Diabetes	Age-matched controls	-1.32	[-1.43; -1.21]
Burger et al, 2009	Chopart	Trauma - Barefoot	Barefoot, silicone prosthesis	-0.46	[-0.50; -0.42]
Burger et al, 2009	Chopart	Trauma - Barefoot	Footwear, conventional prosthesis	-0.06	[-0.07; -0.05]
Burger et al, 2009	Chopart	Trauma - Barefoot	Footwear, silicone prosthesis	-0.53	[-0.63; -0.43]

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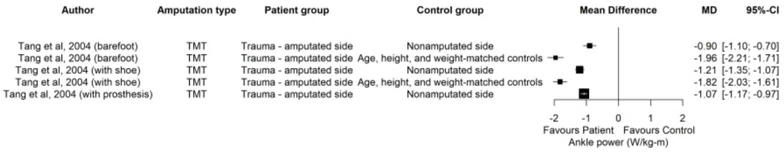

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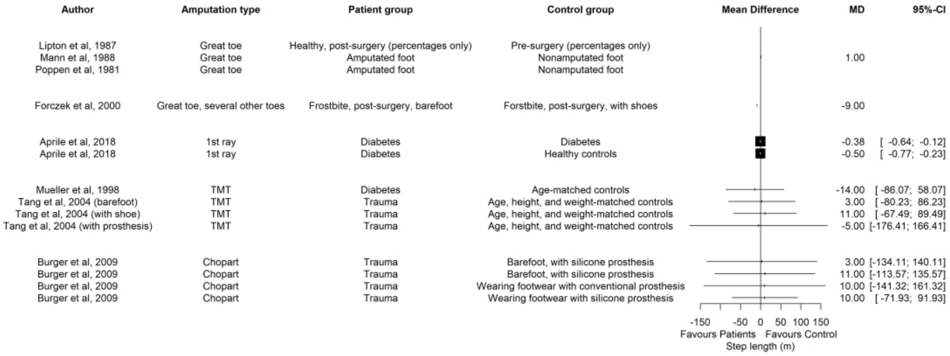

Author	Amputation type	Patient group	Control group	Mean Difference	MD	95%-CI
Lipton et al, 1987	Great toe	Healthy, post-surgery (percentages only)	Pre-surgery (percentages only)			
Mann et al, 1988	Great toe	Amputated foot	Nonamputated foot		1.00	
Poppen et al, 1981	Great toe	Amputated foot	Nonamputated foot			
Forczek et al, 2000	Great toe, several other toes	Frostbite, post-surgery, barefoot	Forstbite, post-surgery, with shoes		-9.00	
Aprile et al, 2018	1st ray	Diabetes	Diabetes		-0.38	[-0.64; -0.12]
Aprile et al, 2018	1st ray	Diabetes	Healthy controls		-0.50	[-0.77; -0.23]
Mueller et al, 1998	TMT	Diabetes	Age-matched controls		-14.00	[-86.07; 58.07]
Tang et al, 2004 (barefoot)	TMT	Trauma	Age, height, and weight-matched controls		3.00	[-80.23; 86.23]
Tang et al, 2004 (with shoe)	TMT	Trauma	Age, height, and weight-matched controls		11.00	[-67.49; 89.49]
Tang et al, 2004 (with prosthesis)	TMT	Trauma	Age, height, and weight-matched controls		-5.00	[-176.41; 166.41]
Burger et al, 2009	Chopart	Trauma	Barefoot, with silicone prosthesis		3.00	[-134.11; 140.11]
Burger et al, 2009	Chopart	Trauma	Barefoot, with silicone prosthesis		11.00	[-113.57; 135.57]
Burger et al, 2009	Chopart	Trauma	Wearing footwear with conventional prosthesis		10.00	[-141.32; 161.32]
Burger et al, 2009	Chopart	Trauma	Wearing footwear with silicone prosthesis		10.00	[-71.93; 91.93]

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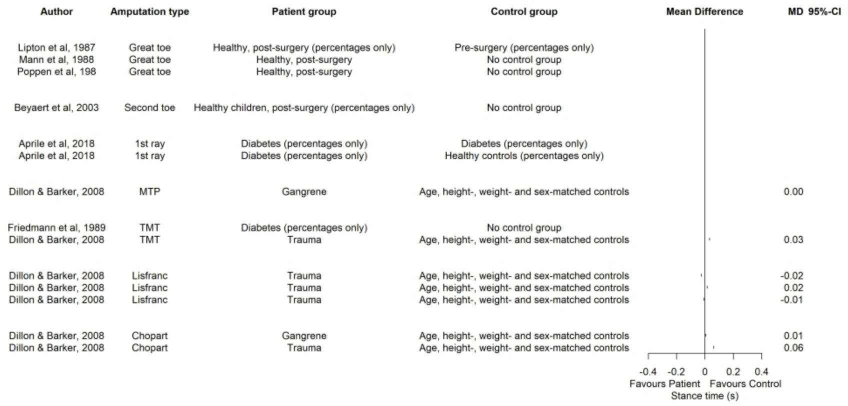
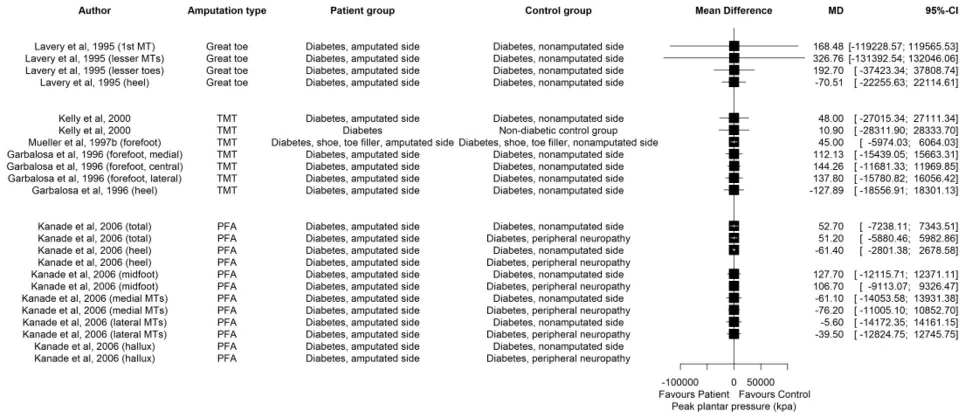


Author	Amputation type	Patient group	Control group	Mean Difference	MD 95%-CI
Lipton et al, 1987	Great toe	Healthy, post-surgery (percentages only)	Pre-surgery (percentages only)		
Mann et al, 1988	Great toe	Healthy, post-surgery	No control group		
Poppen et al, 198	Great toe	Healthy, post-surgery	No control group		
Beyaert et al, 2003	Second toe	Healthy children, post-surgery (percentages only)	No control group		
Aprile et al, 2018	1st ray	Diabetes (percentages only)	Diabetes (percentages only)		
Aprile et al, 2018	1st ray	Diabetes (percentages only)	Healthy controls (percentages only)		
Dillon & Barker, 2008	MTP	Gangrene	Age, height-, weight- and sex-matched controls		0.00
Friedmann et al, 1989	TMT	Diabetes (percentages only)	No control group		
Dillon & Barker, 2008	TMT	Trauma	Age, height-, weight- and sex-matched controls		0.03
Dillon & Barker, 2008	Lisfranc	Trauma	Age, height-, weight- and sex-matched controls		-0.02
Dillon & Barker, 2008	Lisfranc	Trauma	Age, height-, weight- and sex-matched controls		0.02
Dillon & Barker, 2008	Lisfranc	Trauma	Age, height-, weight- and sex-matched controls		-0.01
Dillon & Barker, 2008	Chopart	Gangrene	Age, height-, weight- and sex-matched controls		0.01
Dillon & Barker, 2008	Chopart	Trauma	Age, height-, weight- and sex-matched controls		0.06

423x338mm (300 x 300 DPI)



Author	Amputation type	Patient group	Control group	MD	95%-CI
Lavery et al, 1995 (1st MT)	Great toe	Diabetes, amputated side	Diabetes, nonamputated side	168.48	[-119228.57; 119565.53]
Lavery et al, 1995 (lesser MTs)	Great toe	Diabetes, amputated side	Diabetes, nonamputated side	326.76	[-131392.54; 132046.06]
Lavery et al, 1995 (lesser toes)	Great toe	Diabetes, amputated side	Diabetes, nonamputated side	192.70	[-37423.34; 37808.74]
Lavery et al, 1995 (heel)	Great toe	Diabetes, amputated side	Diabetes, nonamputated side	-70.51	[-22255.63; 22114.61]
Kelly et al, 2000	TMT	Diabetes, amputated side	Diabetes, nonamputated side	48.00	[-27015.34; 27111.34]
Kelly et al, 2000	TMT	Diabetes	Non-diabetic control group	10.90	[-28311.90; 28333.70]
Mueller et al, 1997b (forefoot)	TMT	Diabetes, shoe, toe filler, amputated side	Diabetes, shoe, toe filler, nonamputated side	45.00	[-5974.03; 6064.03]
Garbalosa et al, 1996 (forefoot, medial)	TMT	Diabetes, amputated side	Diabetes, nonamputated side	112.13	[-15439.05; 15663.31]
Garbalosa et al, 1996 (forefoot, central)	TMT	Diabetes, amputated side	Diabetes, nonamputated side	144.26	[-11681.33; 11969.85]
Garbalosa et al, 1996 (forefoot, lateral)	TMT	Diabetes, amputated side	Diabetes, nonamputated side	137.80	[-15780.82; 16056.42]
Garbalosa et al, 1996 (heel)	TMT	Diabetes, amputated side	Diabetes, nonamputated side	-127.89	[-18556.91; 18301.13]
Kanade et al, 2006 (total)	PFA	Diabetes, amputated side	Diabetes, nonamputated side	52.70	[-7238.11; 7343.51]
Kanade et al, 2006 (total)	PFA	Diabetes, amputated side	Diabetes, peripheral neuropathy	51.20	[-5880.46; 5982.86]
Kanade et al, 2006 (heel)	PFA	Diabetes, amputated side	Diabetes, nonamputated side	-61.40	[-2801.38; 2678.58]
Kanade et al, 2006 (heel)	PFA	Diabetes, amputated side	Diabetes, peripheral neuropathy		
Kanade et al, 2006 (midfoot)	PFA	Diabetes, amputated side	Diabetes, nonamputated side	127.70	[-12115.71; 12371.11]
Kanade et al, 2006 (midfoot)	PFA	Diabetes, amputated side	Diabetes, peripheral neuropathy	106.70	[-9113.07; 9326.47]
Kanade et al, 2006 (medial MTs)	PFA	Diabetes, amputated side	Diabetes, nonamputated side	-61.10	[-14053.58; 13931.38]
Kanade et al, 2006 (medial MTs)	PFA	Diabetes, amputated side	Diabetes, peripheral neuropathy	-76.20	[-11005.10; 10852.70]
Kanade et al, 2006 (lateral MTs)	PFA	Diabetes, amputated side	Diabetes, nonamputated side	-5.60	[-14172.35; 14161.15]
Kanade et al, 2006 (lateral MTs)	PFA	Diabetes, amputated side	Diabetes, peripheral neuropathy	-39.50	[-12824.75; 12745.75]
Kanade et al, 2006 (hallux)	PFA	Diabetes, amputated side	Diabetes, nonamputated side		
Kanade et al, 2006 (hallux)	PFA	Diabetes, amputated side	Diabetes, peripheral neuropathy		

423x338mm (300 x 300 DPI)