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

Fábio Carlos Lucas de Oliveira [1,2] Samuel Williamson [3] Clare L Ardern [4,5] Kristina Fagher [6] Neil Heron [7,8] Dina Christina (Christa) Janse van Rensburg [9,10] Marleen G T Jansen [11,12] Nikki Kolman [12,13] Sean Richard O'Connor [14] Tobias Saueressig [15] Linda Schoonmade [16] Jane S Thornton [17,18] Nick Webborn [19,20] Babette M Pluim [9,21,22]

► Additional supplemental material is published online only. To view, please visit the journal online (http://dx.doi.org/10.1136/bjsports-2022-105650).

For numbered affiliations see end of article.

Correspondence to
Dr Fábio Carlos Lucas de Oliveira, Faculty of Medicine, Université Laval, Quebec, Quebec, Canada; fclud@ulaval.ca

Accepted 17 November 2022
Published Online First 5 December 2022

To cite: de Oliveira FCL, Williamson S, Ardern CL, *et al. Br J Sports Med* 2023;**57**:237–248.

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 Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews.

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. 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 include or exclude great toe, ray (two to five) and metatarsophalangeal amputations.

Trial registration The protocol of this scoping review was previously registered at the Open Science Framework Registry (https://osf.io/8gh9y) and published.

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 ARE THE FINDINGS?

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

HOW MIGHT IT IMPACT ON CLINICAL PRACTICE IN THE FUTURE?

- ⇒ Results of this 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.

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

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 ⅓ 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.

programmes. 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 must 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 (eg, Para judo requires a visual impairment) to be eligible to participate.

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 (ie, 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.
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, whereas 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 sixstep 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 1 February 2021 was developed by one reviewer (FCLO) in collaboration with a medical librarian (LS). Database searches were then carried out by two reviewers (BMP, MGTJ). 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 9 February 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 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 online supplemental file 1.

Before screening the search results, duplicate articles were identified and removed using Endnote X V.19.2 (Clarivate, USA). The search yield was imported into Rayyan software,[15] and two independent reviewers (FCLO and 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 (BMP). 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 online supplemental file 2. Reasons for exclusion are reported in the PRISMA flowchart in figure 1.[16]

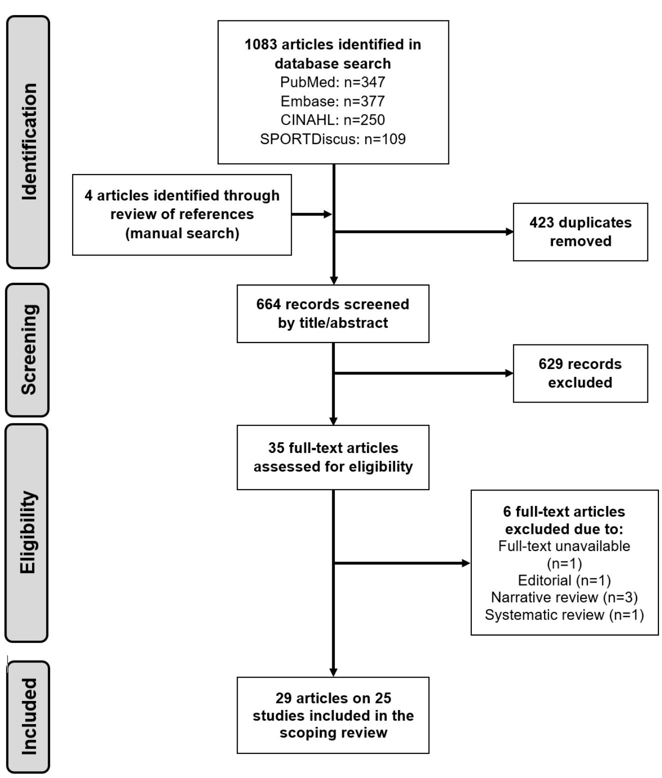

Figure 1 Flowchart of the article selection process conducted according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews (PRISMA-ScR).

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 (ie, 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% CIs between patients with an amputation and the corresponding control group. We quantitatively analysed the variables gait speed in metres 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-metre (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 the study design, we followed the definitions of a case-control and cross-sectional study 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, IQR, and/or range, we transformed the values with an online tool that applied the quantile estimation method of McGrath *et al*.[20] Where data were 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 (FCLO and BMP) 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, postintervention clinical condition, adverse events and take-away lessons (online supplemental file 3). 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 (online supplemental file 4). 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 subgroup 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.[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.

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]

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 (ranging 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 men. Four studies did not report age,[34 37 39 40] and seven did not report sex.[19 30 32 36 39–43]

Methodological quality assessment

Quality assessment of the included studies is presented in online supplemental files 3 and 4. 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 and Barker[30–32] and Greene and Cary[36] reported gait-related outcomes specific to amputation types, and those data are discussed.

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 online supplemental file 5. 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]

Gait speed

The MD in gait speed between individuals with an amputation, and the corresponding control groups, is presented as a forest plot in online supplemental file 6. Data from 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

MDs 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 online supplemental files 7–12.

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 4 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]

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*[51]	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*[38]	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*[33]	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*[49]	United States	Cross-sectional	Compare under foot pressure with contralateral foot after great toe and first metatarsal amputation.	11	Great toe (+ partial first MTA) due to diabetes	NA	65.1 (39–79)*	7 (63.6)
Lipton *et al*[37]	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*[50]	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*[40]	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*[34]	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*[35]	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*[39]	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*[41]	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*[47]	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*[48]	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*[26]	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*[27]	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*[28]	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*[42]	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

Continued

Table 2 Continued

Author	Country	Study design	Aim(s)	Sample size	Experimental group	Control group	Age in years (mean±SD)	Gender (male: N (%))
Pinzur *et al*[43]	United States	Case–control	Establish ground reaction force and dynamic centre 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*[29]	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*[53]	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*[52]	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*[45]	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*[54]	Switzerland	Cross-sectional	Discuss clinical reasoning in deciding, planning, and carrying out local tumour resection and reconstruction.	4	Toe and ray amputation to treat malignant tumour	NA	30±28	2 (50)
Amputation level: mixed								
Burnfield *et al*[46]	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*[30]	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*[31]	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*[32]	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*[36]	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*[44]	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.
MTA, metatarsal amputation; MTP, metatarsophalangeal; NA, not applicable; NR, not reported; TMA, transmetatarsal amputation; TMT, transmetatarsal.

de Oliveira FCL, *et al*. *Br J Sports Med* 2023;**57**:237–248. doi:10.1136/bjsports-2022-105650

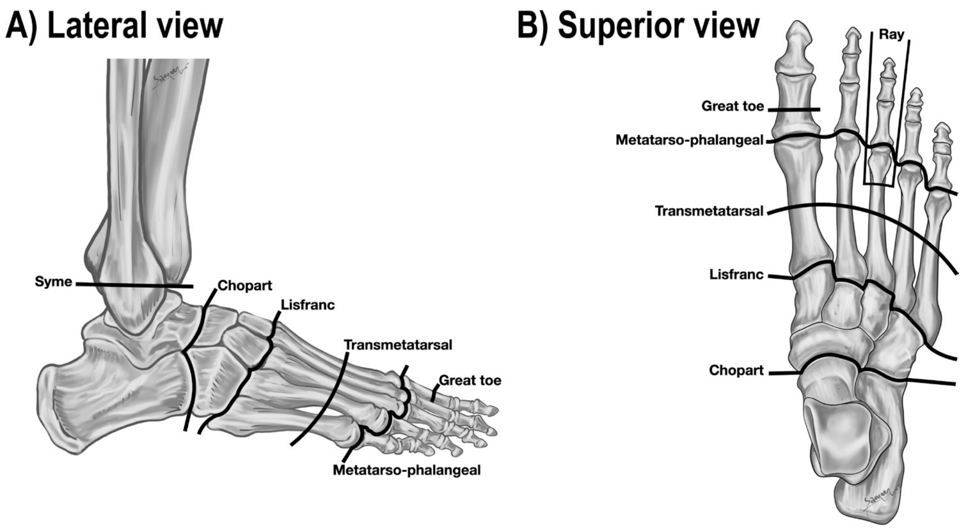

Figure 2 Partial foot amputation types. The exact level of the amputation may vary slightly. (A) Lateral view. (B) Superior view.

Toe amputation (digits 2 to 5)

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 1 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 with 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 with 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.

MTP 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 and Barker[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]

TMT 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 with 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 with the intact foot. A considerably decreased maximum dynamic dorsiflexion ROM (70% vs 90%)

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*[51]	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*[38]	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*[33]	Postural Balance via Force Platform	CoP Excursion
Lavery *et al*[49]	In-Shoe Pressure Measurement System	Peak Plantar Pressure
Lipton *et al*[37]	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*[50]	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*[40]	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*[34]	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*[35]	Physical Examination, Visual Observation	Walking Distance, Ability to Wear Shoes
Czerniecki *et al*[39]	Locomotor Capability Index-5	Ambulatory Function
Friedmann *et al*[41]	Questionnaire, Physical Examination, Gait Analysis, Electrodynograph (force data collector)	Duration of Gait Phases, Plantar Pressure
Garbalosa *et al*[47]	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*[48]	In-Shoe Pressure Measurement System, 6.8 m Walkway	Gait Velocity, Peak Plantar Pressure, Peak Force, Area in contact at Peak Plantar Pressure
Mueller *et al*[26]	6.8 m Walkway; In-Shoe Pressure Measurement System	Gait Speed, Peak Plantar Pressure
Mueller *et al*[27]	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*[28]	3D Gait Analysis using a motion analysis system; Force Platform	Gait Speed, Step Length, Peak Plantarflexion Angle, Peak Ankle, Hip and Knee Moments and Power, Onset of Hip Flexion Moment, Hip & Knee ROM Excursion
Pinzur *et al*[42]	25 m 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*[43]	Force Data using In-Shoe Pressure Measurement System	Ground Reaction Force, CoP Excursion
Salsich *et al*[29]	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*[53]	10 m 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*[52]	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*[45]	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*[54]	Gait Analysis using a Pedobarograph	Plantar Pressure Distribution

Continued

Table 3 Continued

Author	Assessment methods	Outcome measures
Amputation level: mixed		
Burnfield *et al*[46]	10 m Walkway, Force Platform, Dynamometrey	Gait Speed, Cadence, Stride Length, Peak Ground Reaction Force, Plantar Flexion Torque
Dillon *et al*[30]	3D Gait Analysis using a Motion Analysis System; Force Platform	Ankle Power and Moment, Hip Power, Work across the Ankle
Dillon *et al*[31]	3D Gait Analysis using a Motion Analysis System; Force Platform	CoP Excursion, Ground Reaction Force
Dillon *et al*[32]	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*[36]	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*[44]	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

CoP, center of pressure; 3D, three dimensional; 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.

and a similar static ROM were measured in the ankles of the amputated feet compared with 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 and Barker[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 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 preswing phase was only 28% compared with 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 with 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 with 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 with 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. MTP 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). TMT 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 with 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 men (43 per 100 000 women) in Australia to 31.3 per 100 000 men (20.1 per 100 000 women) 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 with patients with type 2 diabetes without 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 one in six 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.

MTP 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]

TMT amputation

Amputation proximal to the MTP 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 with 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-three-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-three-sets) last around 1 hour and a half.[64 65] Players cover 8 m to 10 m per point and 550 m to 700 m per set,[66 67] with a peak running speed of 20 km/hour in elite male and 17 km/hour in elite female players.[59 68–70] During a best-of-three-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 (ie, wheelchair tennis). Factors that need to be considered to develop minimum impairment criteria are the extent to which the impairment (ie, 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 first ray, TMT, Chopart and Lisfranc amputations in the minimum impairment criteria for wheelchair tennis (table 4). It is unclear whether great toe, ray and MTP amputations should be included 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.

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	Unclear	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 first ray)	Unclear	5	D	Acceleration/deceleration and running speed may be affected. More research is needed.*
First 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.

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

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 9 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 multicentric studies.

Author affiliations
[1]Faculty of Medicine, Université Laval, Quebec City, Quebec, Canada
[2]Research Unit in Sport and Physical Activity (CIDAF), University of Coimbra, Coimbra, Portugal
[3]English Institute of Sport, London, UK
[4]Department of Family Practice, The University of British Columbia, Vancouver, British Columbia, Canada
[5]Sport and Exercise Medicine Research Centre, La Trobe University, Melbourne, Victoria, Australia
[6]Rehabilitation Medicine Research Group, Department of Health Sciences, Lund University, Lund, Sweden
[7]Center for Public Health, Queen's University Belfast, Belfast, UK
[8]School of Medicine, Keele University, Staffordshire, UK
[9]Section Sports Medicine, Faculty of Health Sciences, University of Pretoria, Pretoria, South Africa
[10]Medical Board member, World Netball, Manchester, UK
[11]Toptennis Department, Royal Netherlands Lawn Tennis Association (KNLTB), Amstelveen, The Netherlands
[12]Center for Human Movement Sciences, University Medical Centre Groningen, Groningen, The Netherlands
[13]Knowledge Centre for Sport & Physical Activity, Utrecht, The Netherlands
[14]School of Psychology, Queen's University Belfast, Belfast, UK
[15]Physio Meets Science GmbH, Leimen, Germany
[16]Medical Library, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands
[17]Department of Family Medicine, Schulich School of Medicine & Dentistry, University of Western Ontario, London, Ontario, Canada
[18]Department of Epidemiology & Biostatistics, Schulich School of Medicine & Dentistry, University of Western Ontario, London, Ontario, Canada
[19]IPC Medical Committee, Bonn, Germany
[20]School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, UK
[21]Amsterdam Collaboration on Health & Safety in Sports (ACHSS), AMC/VUmc IOC Research Center of Excellence, Amsterdam, The Netherlands
[22]Medical Department, Royal Netherlands Lawn Tennis Association (KNLTB), Amstelveen, The Netherlands

Twitter Fábio Carlos Lucas de Oliveira @fabiophysio, Clare L Ardern @clare_ardern, Kristina Fagher @KristinaFagher, Neil Heron @neilSportDoc, Sean Richard O'Connor @seanoc_QUB, Jane S Thornton @janesthornton, Nick Webborn @SportswiseUK and Babette M Pluim @docpluim

Acknowledgements We thank Dr Mohd Sameer Qureshi, MBBS, DNB Orthopaedics, for creating the illustrations.

Contributors FCLO, SW, CLA and BMP contributed to the conception and study design. LS contributed to the search strategy. FCLO, SW and BMP conducted the data extraction, analysis and interpretation. TS performed the statistical analysis. FCLO, NH, CJvR, SW and BMP drafted the manuscript. All authors contributed to the manuscript with critical reviews and approved the final version of this paper.

Funding All authors thank the International Tennis Federation and the Royal Dutch Lawn Tennis Association (KNLTB) for supporting this research. We thank Dr Mohd Sameer Qureshi, MBBS, DNB Orthopaedics, for creating the illustrations.

Competing interests CA is Editor-in-Chief for JOSPT and JST is Editor for BJSM. 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.

Patient consent for publication Not applicable.

Provenance and peer review Not commissioned; externally peer reviewed.

ORCID iDs
Fábio Carlos Lucas de Oliveira http://orcid.org/0000-0002-7127-6560
Samuel Williamson http://orcid.org/0000-0002-3533-0603
Clare L Ardern http://orcid.org/0000-0001-8102-3631
Kristina Fagher http://orcid.org/0000-0002-9524-7553
Neil Heron http://orcid.org/0000-0002-4123-9806
Dina Christina (Christa) Janse van Rensburg http://orcid.org/0000-0003-1058-6992
Marleen G T Jansen http://orcid.org/0000-0002-8441-7748
Nikki Kolman http://orcid.org/0000-0002-3865-7695
Sean Richard O'Connor http://orcid.org/0000-0001-6805-8899
Tobias Saueressig http://orcid.org/0000-0002-3332-3856
Linda Schoonmade http://orcid.org/0000-0002-2407-5977
Jane S Thornton http://orcid.org/0000-0002-3519-7101
Nick Webborn http://orcid.org/0000-0003-3636-5557
Babette M Pluim http://orcid.org/0000-0003-0655-8980

REFERENCES

1 Davie-Smith F, Coulter E, Kennon B, *et al*. Factors influencing quality of life following lower limb amputation for peripheral arterial occlusive disease: a systematic review of the literature. *Prosthet Orthot Int* 2017;41:537–47.
2 Quigley M, Dillon MP. Quality of life in persons with partial foot or transtibial amputation: a systematic review. *Prosthet Orthot Int* 2016;40:18–30.
3 Robbins CB, Vreeman DJ, Sothmann MS, *et al*. A review of the long-term health outcomes associated with war-related amputation. *Mil Med* 2009;174:588–92.
4 Stern JR, Wong CK, Yerovinkina M, *et al*. A meta-analysis of long-term mortality and associated risk factors following lower extremity amputation. *Ann Vasc Surg* 2017;42:322–7.
5 Bragaru M, Dekker R, Geertzen JHB, *et al*. Amputees and sports: a systematic review. *Sports Med* 2011;41:721–40.
6 Jaarsma EA, Dijkstra PU, Geertzen JHB, *et al*. Barriers to and facilitators of sports participation for people with physical disabilities: a systematic review. *Scand J Med Sci Sports* 2014;24:871–81.
7 International Paralympic Committee. International standard for athlete evaluation, 2016. Available: https://www.paralympic.org/sites/default/files/document/161007092547338_Sec+ii+chapter+1_3_2_subchapter+2_International+Standard+for+Athlete+Evaluation.pdf [Accessed 31 Oct 2022].
8 Paralympic Australia. Paralympic sports, 2022. Available: https://www.paralympic.org.au/play-para-sport/ [Accessed 24 Jun 2022].
9 International Tennis Federation (ITF). Wheelchair tennis classification rules, 2020. Available: https://www.itftennis.com/media/7289/itf-wheelchair-tennis-classification-rules-updated-15may2020.pdf [Accessed 21 Jan 2022].
10 Mann DL, Tweedy SM, Jackson RC, *et al*. Classifying the evidence for evidence-based classification in Paralympic sport. *J Sports Sci* 2021;39:1–6.
11 Munn Z, Peters MDJ, Stern C, *et al*. Systematic review or scoping review? guidance for authors when choosing between a systematic or scoping review approach. *BMC Med Res Methodol* 2018;18:143.
12 Arksey H, O'Malley L. Scoping studies: towards a methodological framework. *Int J Soc Res Methodol* 2005;8:19–32.
13 Levac D, Colquhoun H, O'Brien KK. Scoping studies: advancing the methodology. *Implement Sci* 2010;5:69.
14 de Oliveira FCL, Williamson S, Ardern CL, *et al*. Associations between partial foot amputation level, gait parameters, and minimum impairment criteria in para-sport: a research study protocol. *Sports Med Health Sci* 2022;4:70–3.

15 Ouzzani M, Hammady H, Fedorowicz Z, *et al*. Rayyan-a web and mobile APP for systematic reviews. *Syst Rev* 2016;5:210.
16 Tricco AC, Lillie E, Zarin W, *et al*. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. *Ann Intern Med* 2018;169:467–73.
17 McKenzie JE, Brennan SE. Chapter 12: Synthesising and presenting findings using other methods. Section 12.1: Why a meta-analysis of effect estimates may not be possible. In: Higgins J, Thomas J, Chandler J, *et al*, eds. *Cochrane Handbook for systematic reviews of interventions*. London: The Cochrane Collaboration, 2022.
18 McKenzie JE, Brennan SE. Chapter 12: Synthesising and presenting findings using other methods. Section 12.2: Statistical synthesis when meta-analysis of effect estimates is not possible. In: Higgins J, Thomas J, Chandler J, *et al*, eds. *Cochrane Handbook for systematic reviews of interventions*. London: The Cochrane Collaboration, 2022.
19 Dillon MP, Fatone S, Hodge MC. Biomechanics of ambulation after partial foot amputation: a systematic literature review. *J Prosthet Orthot* 2007;19:2–61.
20 McGrath S, Zhao X, Steele R, *et al*. Estimating the sample mean and standard deviation from commonly reported quantiles in meta-analysis. *Stat Methods Med Res* 2020;29:2520–37.
21 GetData graph Digitizer, 2013. Available: http://getdata-graph-digitizer.com/index.php [Accessed 19 Jun 2022].
22 Vucic K, Jelicic Kadic A, Puljak L. Survey of Cochrane protocols found methods for data extraction from figures not mentioned or unclear. *J Clin Epidemiol* 2015;68:1161–4.
23 Joanna Briggs Institute. Critical appraisal tools, 2022. Available: https://jbi.global/critical-appraisal-tools [Accessed Acessed 16 Jun 2022].
24 Moola S, Munn Z, Tufanaru C. Chapter 7: Systematic reviews of etiology and risk. In: Aromataris E, Munn Z, eds. *Joanna Briggs Institute Reviewer's Manual*. Adelaide: The Joanna Briggs Institute, 2017. https://jbi.global/critical-appraisal-tools
25 Centre for Evidence-Based Medicine (CEBM). OCEBM level of evidence, 2021. Available: https://www.cebm.ox.ac.uk/resources/levels-of-evidence/ocebm-levels-of-evidence [Accessed 28 Oct 2022].
26 Mueller MJ, Salsich GB, Strube MJ. Functional limitations in patients with diabetes and transmetatarsal amputations. *Phys Ther* 1997;77:937–43.
27 Mueller MJ, Strube MJ, Allen BT. Therapeutic footwear can reduce plantar pressures in patients with diabetes and transmetatarsal amputation. *Diabetes Care* 1997;20:637–41.
28 Mueller MJ, Salsich GB, Bastian AJ. Differences in the gait characteristics of people with diabetes and transmetatarsal amputation compared with age-matched controls. *Gait Posture* 1998;7:200–6.
29 Salsich GB, Mueller MJ. Relationships between measures of function, strength and walking speed in patients with diabetes and transmetatarsal amputation. *Clin Rehabil* 1997;11:60–7.
30 Dillon MP, Barker TM. Preservation of residual foot length in partial foot amputation: a biomechanical analysis. *Foot Ankle Int* 2006;27:110–6.
31 Dillon MP, Barker TM. Can partial foot prostheses effectively restore foot length? *Prosthet Orthot Int* 2006;30:17–23.
32 Dillon MP, Barker TM. Comparison of gait of persons with partial foot amputation wearing prosthesis to matched control group: observational study. *J Rehabil Res Dev* 2008;45:1317–34.
33 Chen HC, Tang YB, Wei FC, *et al*. Finger reconstruction with triple toe transfer from the same foot for a patient with a special job and previous foot trauma. *Ann Plast Surg* 1991;27:272–7.
34 Forczek W, Ruchlewicz T, Gawęda A. Kinematic gait analysis of a young man after amputation of the toes. *Biomed Hum Kinet* 2014;6:40–6.
35 Andersen JA, Klåborg KE. Forefoot amputation in rheumatoid arthritis. *Acta Orthop Scand* 1987;58:394–7.
36 Greene WB, Cary JM. Partial foot amputations in children. A comparison of the several types with the Syme amputation. *J Bone Joint Surg Am* 1982;64:438–43.
37 Lipton HA, May JW, Simon SR. Preoperative and postoperative gait analyses of patients undergoing great toe-to-thumb transfer. *J Hand Surg Am* 1987;12:66–9.
38 Beyaert C, Henry S, Dautel G, *et al*. Effect on balance and gait secondary to removal of the second toe for digital reconstruction: 5-year follow-up. *J Pediatr Orthop* 2003;23:60–4.
39 Czerniecki JM, Turner AP, Williams RM, *et al*. Mobility changes in individuals with dysvascular amputation from the presurgical period to 12 months postamputation. *Arch Phys Med Rehabil* 2012;93:1766–73.
40 Poppen NK, Mann RA, O'Konski M, *et al*. Amputation of the great toe. *Foot Ankle* 1981;1:333–7.
41 Friedmann LW, Padula PA, Weiss JM, *et al*. Studies on the survival of transmetatarsal amputation stumps. *Vasc Surg* 1989;23:34–42.
42 Pinzur MS, Gold J, Schwartz D, *et al*. Energy demands for walking in dysvascular amputees as related to the level of amputation. *Orthopedics* 1992;15:1033–7.
43 Pinzur MS, Wolf B, Havey RM. Walking pattern of midfoot and ankle disarticulation amputees. *Foot Ankle Int* 1997;18:635–8.
44 Kanade RV, van Deursen RWM, Harding K, *et al*. Walking performance in people with diabetic neuropathy: benefits and threats. *Diabetologia* 2006;49:1747–54.
45 Aprile I, Galli M, Pitocco D, *et al*. Does first ray amputation in diabetic patients influence gait and quality of life? *J Foot Ankle Surg* 2018;57:44–51.
46 Burnfield JM, Boyd LA, Rao S, *et al*. The effect of partial foot amputation on sound limb loading force during barefoot walking. *Gait Posture* 1998;7:178–9.
47 Garbalosa JC, Cavanagh PR, Wu G, *et al*. Foot function in diabetic patients after partial amputation. *Foot Ankle Int* 1996;17:43–8.
48 Kelly VE, Mueller MJ, Sinacore DR. Timing of peak plantar pressure during the stance phase of walking. A study of patients with diabetes mellitus and transmetatarsal amputation. *J Am Podiatr Med Assoc* 2000;90:18–23.
49 Lavery LA, Lavery DC, Quebedeax-Farnham TL. Increased foot pressures after great toe amputation in diabetes. *Diabetes Care* 1995;18:1460–2.
50 Mann RA, Poppen NK, O'Konski M. Amputation of the great toe. A clinical and biomechanical study. *Clin Orthop Relat Res* 1988;226:192–205.
51 Ademoğlu Y, Ada S, Kaplan I. Should the amputations of the great toe be replanted? *Foot Ankle Int* 2000;21:673–9.
52 Burger H, Erzar D, Maver T, *et al*. Biomechanics of walking with silicone prosthesis after midtarsal (Chopart) disarticulation. *Clin Biomech* 2009;24:510–6.
53 Tang SFT, Chen CPC, Chen MJL, *et al*. Transmetatarsal amputation prosthesis with carbon-fiber plate: enhanced gait function. *Am J Phys Med Rehabil* 2004;83:124–30.
54 Ramseier LE, Jacob HAC, Exner GU. Foot function after ray resection for malignant tumors of the phalanges and metatarsals. *Foot Ankle Int* 2004;25:53–8.
55 Kasović M, Štefan L, Štefan A. Normative data for gait speed and height norm speed in ≥ 60-year-old men and women. *Clin Interv Aging* 2021;16:225–30.
56 Hughes W, Goodall R, Salciccioli JD, *et al*. Editor's Choice - Trends in Lower Extremity Amputation Incidence in European Union 15+ Countries 1990-2017. *Eur J Vasc Endovasc Surg* 2020;60:602–12.
57 Harlow E, Khambete P, Ina J, *et al*. Use of a second ray amputation for foot salvage in a collegiate athlete with Proteus syndrome. *Int J Foot Ankle* 2021;5:1–5.
58 Carboch J, Plachá K. Development of rally pace and other match characteristics in women's matches in the Australian Open 2017. *J Phys Educ Sport* 2018;18:1079–83.
59 Carboch J, Siman J, Sklenarik M, *et al*. Match characteristics and rally pace of male tennis matches in three grand SLAM tournaments. *Phys. Act. Rev.* 2019;7:49–56.
60 Kovalchik SA, Reid M. Comparing Matchplay characteristics and physical demands of junior and professional tennis athletes in the era of big data. *J Sports Sci Med* 2017;16:489–97.
61 Giles B, Kovalchik S, Reid M. A machine learning approach for automatic detection and classification of changes of direction from player tracking data in professional tennis. *J Sports Sci* 2020;38:106–13.
62 Pereira TJC, Nakamura FY, de Jesus MT, *et al*. Analysis of the distances covered and technical actions performed by professional tennis players during official matches. *J Sports Sci* 2017;35:361–8.
63 Girard O, Eicher F, Micallef J-P, *et al*. Plantar pressures in the tennis serve. *J Sports Sci* 2010;28:873–80.
64 Lisi F, Grigoletto M. Modeling and simulating durations of men's professional tennis matches by resampling match features. *JSA* 2021;7:57–75.
65 Sánchez-Pay A, Ortega-Soto JA, Sánchez-Alcaraz BJ. Notational analysis in female grand SLAM tennis competitions. *Kinesiology* 2021;53:154–61.
66 Cui Y, Gómez Miguel-Ángel, Gonçalves B, *et al*. Performance profiles of professional female tennis players in grand slams. *PLoS One* 2018;13:e0200591.
67 Cui Y, Zhao Y, Liu H, *et al*. Effect of a seeding system on competitive performance of elite players during major tennis tournaments. *Front Psychol* 2020;11:1294.
68 Filipcic A, Leskosek B, Crespo M, *et al*. Matchplay characteristics and performance indicators of male junior and entry professional tennis players. *Int J Sports Sci Coach* 2021;16:768–76.
69 Reid M, Morgan S, Whiteside D. Matchplay characteristics of grand SLAM tennis: implications for training and conditioning. *J Sports Sci* 2016;34:1791–8.
70 Whiteside D, Bane MK, Reid M. Differentiating top-ranked male tennis players from lower-ranked players using Hawk-Eye data: an investigation of the 2012-2014 Australian open tournaments. In: 33rd *International Society of Biomechanics in Sports Conference*. Poitiers, France, 2015.
71 Whiteside D, Reid M. External match workloads during the first week of Australian open tennis competition. *Int J Sports Physiol Perform* 2017;12:756–63.
72 International Paralympic Committee. International Paralympic Committee athlete classification code, 2015. Available: https://www.paralympic.org/sites/default/files/document/151218123255973_2015_12_17+Classification+Code_FINAL.pdf [Accessed 17 Feb 2022].
73 Tweedy SM, Beckman EM, Connick MJ. Paralympic classification: conceptual basis, current methods, and research update. *Pm R* 2014;6:S11–17.
74 Tweedy SM, Vanlandewijck YC. International Paralympic Committee position stand--background and scientific principles of classification in Paralympic sport. *Br J Sports Med* 2011;45:259–69.