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Prevalence and clinical implications of median nerve variants within the carpal tunnel: A systematic review and meta-analysis



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Introduction

A precise understanding of the anatomical organization of the brachial plexus and its terminal branches is essential for the diagnosis and surgical management of upper limb neuropathies. Among the major terminal nerves supplying the hand, the median nerve (MN) plays a central

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role due to its combined motor and sensory functions in the forearm and hand. The MN arises from contributions of both the lateral cord (C5-C6) and the medial cord (C8-T1) of the brachial plexus, reflecting its complex neuroanatomical origin and extensive distal distribution.¹

Distally, the MN traverses the carpal tunnel (CT), a confined osteofibrous canal bounded dorsally by the carpal bones and volarly by the transverse carpal ligament. Within this restricted space, the nerve courses alongside the flexor tendons before dividing into its terminal branches in the hand. Histologically, at the level of the wrist, the MN contains approximately 30 fascicles and nearly 22,000 nerve fibers, highlighting its structural complexity.¹

CT syndrome (CTS), resulting from compression of the MN within this compartment, is the most common peripheral compressive neuropathy, with an estimated annual prevalence of approximately 5% worldwide.² Clinically, CTS is characterized by pain, paresthesia, and sensory disturbances affecting the radial three and a half digits, often supported by provocative maneuvers such as Tinel's and Phalen's tests. However, definitive diagnosis typically requires electrodiagnostic confirmation and increasingly incorporates imaging modalities, particularly high-resolution ultrasound and magnetic resonance imaging (MRI). Beyond confirming nerve enlargement or altered mobility, imaging plays a key role in identifying anatomical variants that may influence both clinical presentation and surgical planning.

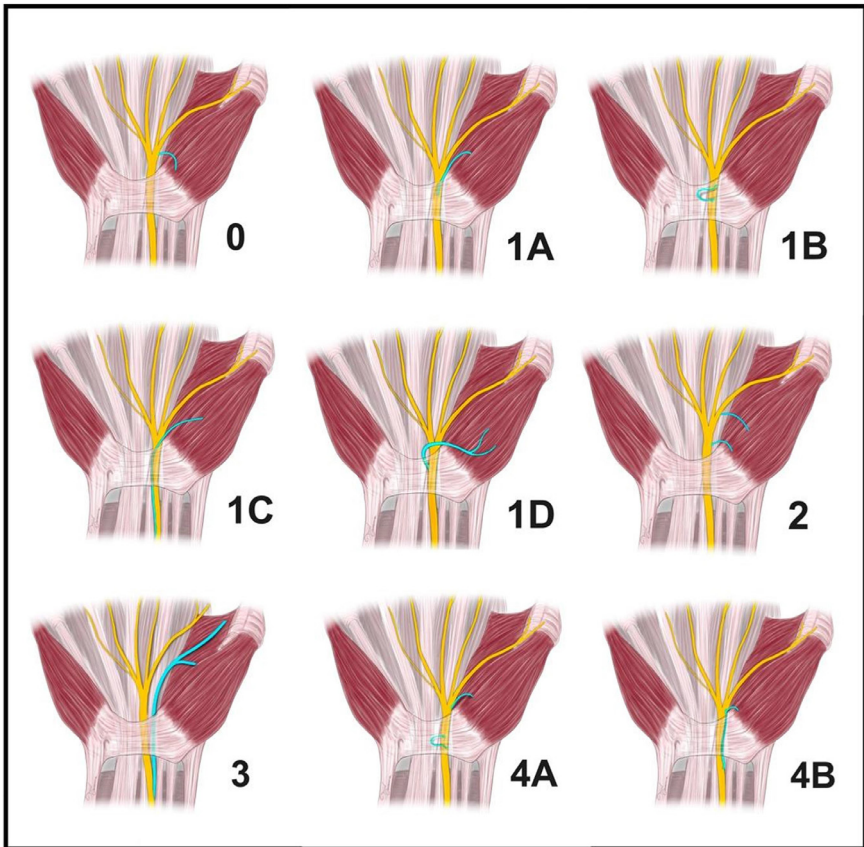


Fig. 1. Variants of the median nerve according to the Lanz classification. (1A) Subligamentous; (1B) transligamentous; (1C) ulnarwards; (1D) supraligamentous. Group 0, extraligamentous thenar branch. Group II, distal accessory thenar branch. Group IV, proximal accessory thenar branch; (4A) running directly in the thenar muscles; (4B) joining another branch. Group III, high division of the median nerve; (3A) without an artery of muscle; (3B) with artery; (3C) with lumbrical muscle.

Multiple structural variations have been described within the CT, including anomalous musculature (eg, deep palmaris longus), variants of the recurrent motor branch, persistent median artery (PMA), and bifid MN (BMN). These variants may coexist and, in some cases, form complex neurovascular configurations. For example, Piagkou et al. reported the combined presence of BMN, PMA, and an incomplete superficial palmar arch, illustrating the structural heterogeneity that may exist within the tunnel.³ To standardize the description of these anatomical patterns, Lanz proposed a classification system based on the course and branching of the MN within the CT, which remains widely used in both anatomical and clinical studies (Fig. 1).

Among these variants, BMN is one of the most frequently reported. Its prevalence ranges from approximately 2.8% to 18%, depending on population characteristics and methodological approach.⁴ BMN is defined as a partial or complete division of the MN proximal to or within the CT. In partial bifurcation, the nerve is subdivided by a septal or fascicular separation while maintaining a shared epineurial sheath. In complete bifurcation, the MN is divided into two distinct components along its course within the CT.^{5,6}

From a morphometric perspective, the cross-sectional area (CSA) of the MN at the wrist in asymptomatic individuals is typically reported to average approximately 8 to 9 mm².⁶ In the presence of BMN, individual branch measurements may be smaller; however, the combined CSA may equal or exceed that of a nonbifid nerve, potentially complicating sonographic interpretation.⁷ Whether bifurcation intrinsically increases susceptibility to compression remains uncertain. Some studies suggest that BMN may contribute to increased compartmental crowding⁴ with reports indicating that 0.8% to 18% of CTS cases are associated with bifid morphology. However, other studies have demonstrated similar BMN prevalence in CTS patients and healthy controls (15.8% vs 18.5%), challenging its role as an independent risk factor.^{8,9} Additionally, surgical outcomes in CTS patients with BMN have been inconsistently reported, with some evidence suggesting a higher risk of incomplete decompression when variants are not identified preoperatively.⁹

Given the anatomical complexity of the CT and the variability in reported prevalence and clinical implications of MN variants, a comprehensive synthesis of the available evidence is warranted. This systematic review and meta-analysis aims to estimate the pooled prevalence of morphological variants of the MN within the CT and to evaluate their laterality, geographic distribution, and clinical relevance in the context of CTS.

Methods

Protocol and registration

This systematic review was conducted in accordance with the PRISMA 2020 statement.¹⁰ The study protocol was prospectively registered in the PROSPERO International Prospective Register of Systematic Reviews (Registration No. CRD420261307914).

No major deviations from the registered protocol were identified. Minor adjustments were made in the categorization of studies and synthesis approach, particularly regarding the inclusion of descriptive reports in the qualitative synthesis and the restriction of quantitative analysis to studies providing sufficient numerical data.

Electronic search

A comprehensive search strategy was conducted across MEDLINE (via PubMed), Scopus, Web of Science, CINAHL, and LILACS from database inception to November 20, 2024. The final search was performed on November 20, 2024. The search strategy combined controlled vocabulary terms (MeSH) and free-text keywords related to *median nerve*, *carpal canal*, *carpal tunnel*, *carpal tunnel syndrome*, *bifid median nerve*, and *anatomical variations*. Boolean operators (AND, OR, NOT)

were applied as appropriate to refine the search. The complete search strategy is provided in Supplementary Table 1.

Eligibility criteria

Eligible studies included observational designs such as anatomical dissection studies, imaging-based studies (ultrasound or MRI), and surgical series reporting the prevalence of morphological variants of the MN within the CT. Descriptive studies, including case reports and case series, were also considered when they provided relevant anatomical or clinical information. Case reports and small case series were included in the qualitative synthesis to provide anatomical and clinical context; however, only studies reporting sufficient numerical data were considered eligible for quantitative synthesis (meta-analysis). Only original research articles published in peer-reviewed journals and written in English were considered. Both retrospective and prospective observational designs were eligible. Exclusion criteria comprised: (1) animal studies; (2) editorials, letters to the editor, or conference abstracts; and (3) studies focusing exclusively on anatomical variants unrelated to the MN within the CT.

Study selection

Three authors conducted independent analyses to select studies thoroughly. Two authors (Valenzuela, JJ and Orellana, M) initially reviewed the titles and abstracts of references retrieved from the database searches. The full texts of these references were obtained for the studies they deemed potentially relevant. If the two reviewers could not reach a consensus, a third reviewer (Sanchis, J) was involved in the decision-making process. Additionally, we performed an agreement test among the authors using the kappa statistic to evaluate reliability and the risk of bias among the reviewers. The calculated kappa value was 0.72, indicating good agreement.

Data collection process

Two authors (Nova, P and Bruna, A) independently extracted data on the outcomes of each study. The following information was collected from the included studies: (1) authors and year of publication, (1) *n* and type of example, (3) age and sex of participants, (4) type variants and prevalence, (5) geographical region, (6) symptoms, and (7) clinical considerations.

Assessment of the methodological quality of the included studies

To assess the risk of bias of the included studies, we utilized the Anatomical Quality Assessment (AQUA) tool proposed by the International Working Group on Evidence-Based Anatomy (IEBA).^{11,12} Two reviewers (Valenzuela, JJ and Loaiza, JP) independently evaluated the five domains outlined by the AQUA tool. Discrepancies were resolved by consensus, and the results were summarized in a risk-of-bias table and graphical representation. To assess publication bias and heterogeneity among the included studies, funnel plot analysis was performed. This method visualizes the relationship between each study's effect size and its precision, allowing the identification of potential small-study effects. A formal assessment of certainty of evidence (eg, GRADE) was not performed, as this review focuses on anatomical prevalence data derived from observational and descriptive studies, for which such frameworks are not typically applicable. Only studies with sufficient methodological detail and appropriate design (eg, anatomical dissection, imaging-based studies, or surgical series) were included in the AQUA assessment. Descriptive reports, including case reports and small case series, were not subjected to methodological quality appraisal due to their inherent limitations for structured risk-of-bias evaluation.

Statistical methods

The extracted data were analyzed using RStudio (R Foundation for Statistical Computing) to estimate the prevalence of morphological variants of the MN. Pooled prevalence was calculated using a DerSimonian–Laird random-effects model with Freeman–Tukey double arcsine transformation. This approach was selected due to its widespread use in prevalence meta-analyses and its ability to stabilize variance when dealing with proportions close to 0 or 1. A random-effects model was applied, given the anticipated clinical and methodological heterogeneity among the included studies.

Between-study heterogeneity was assessed using the chi-square (χ^2) test and the I^2 statistic. For the χ^2 test, a P value < 0.10 was considered indicative of significant heterogeneity, as recommended by the Cochrane Collaboration. The magnitude of heterogeneity was interpreted according to I^2 values as follows: 0% to 40% (low), 30% to 60% (moderate), 50% to 90% (substantial), and 75% to 100% (considerable).¹³⁻¹⁵

Sensitivity analyses were performed to evaluate the influence of high-weight studies on pooled estimates.

Although the DerSimonian–Laird method with Freeman–Tukey transformation is widely used in prevalence meta-analyses, it has recognized limitations, particularly in the presence of substantial heterogeneity and when dealing with extreme proportions. Alternative approaches, such as generalized linear mixed models or logit transformations, have been proposed as more robust under certain conditions. However, the selected method was considered appropriate for this analysis due to its consistency with prior anatomical prevalence studies and its stability in handling proportion data across a wide range of values.

Sensitivity analysis

Sensitivity analysis by data exclusion is a statistical test that eliminates confounding variables, variables that may underestimate or overestimate the data. In this study, we performed one sensitivity analysis test: to eliminate studies with n greater than 1000 subjects, which allows us to identify influential points and validate the robustness of the conclusions.

Results

Selection of articles

The database search identified 1096 records, and an additional 2 records were identified through other sources. After removal of duplicates ($n = 198$), 898 records were screened. After removal of duplicates ($n = 198$), 898 records were screened. Of these, 510 were excluded based on titles and abstracts. A total of 388 reports were sought for retrieval, of which 245 were not retrieved. Consequently, 143 full-text articles were assessed for eligibility. Of these, 80 were excluded based on predefined eligibility criteria, resulting in 63 studies included in the qualitative synthesis. Among these, 19 studies ($n = 9045$ subjects) were included in the primary prevalence meta-analysis. The study selection process is summarized in the PRISMA flow diagram (Fig. 2).

Characteristics of included studies

A total of 63 studies were included in the qualitative synthesis.¹⁶⁻⁷⁹ These studies comprised anatomical dissections, imaging-based evaluations (ultrasound or MRI), and surgical series investigating morphological variants of the MN within the CT. Among the studies included in the quantitative synthesis ($n = 19$), seven were conducted in Europe,^{41,44,45,47,49,53,73} six in

PRISMA 2020 flow diagram for updated systematic reviews which included searches of databases, registers and other sources

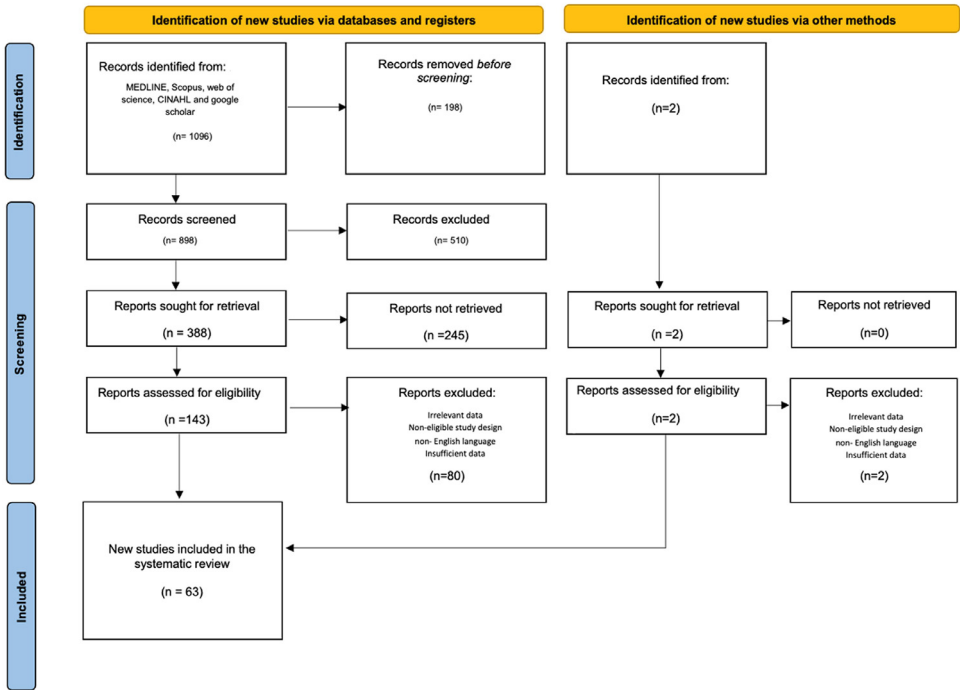


Fig. 2. PRISMA 2020 flow diagram of study selection.

Asia,^{16,19,26,32,33,72} and three in America.^{30,67,75} No eligible studies were identified from Africa or Oceania. Sex distribution was inconsistently reported across studies. Fifty-one studies provided sex-specific data, comprising 2319 female and 1206 male participants. The remaining studies did not report sex distribution. It should be noted that some studies reported demographic characteristics exclusively for participants presenting with BMN, which may limit the representativeness of pooled sex-based comparisons (Table 1).

Prevalence of morphological variants of the MN and subgroups analysis

A total of 19 studies ($n = 9045$ subjects) were included in the primary prevalence meta-analysis.^{16,19,22,26,30,32,33,41,44,45,47,49,53,63,67,72,73,75,79} The pooled prevalence of MN variants within the CT was 12% (95% CI: 9%-15%), with substantial heterogeneity ($I^2 = 87\%$) (Fig. 3). The high degree of heterogeneity suggests considerable variability across study populations, methodologies, and diagnostic approaches, consistent with the use of a random-effects model. The LFK index was 0.353, indicating minor asymmetry.

Prevalence in imaging-based and surgical studies

For the subgroup of living subjects evaluated through imaging or surgical reports, 17 studies were included (Fig. 4), yielding a pooled prevalence of 12% (95% CI: 9%-15%) with high heterogeneity ($I^2 = 87.8\%$). Two cadaveric studies were excluded from this subgroup analysis, resulting in a total sample of 8975 subjects. The persistence of high heterogeneity suggests that variability is not solely attributable to study type, but also to differences in population characteristics and diagnostic criteria. The Doi plot demonstrated symmetry, and the LFK index was 0.212, indicating no major asymmetry.

Table 1

Characteristics of studies included in the qualitative synthesis, including observational studies, case series, and case reports, of median nerve variants within the carpal tunnel.

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Moeller et al. (2024)	40 patients, 41 wrists	30 female, 10 male 21-78 (56.5) y	TMB origin	USA	-	The US adds safety to CTR surgery, so it could be useful in the preoperative period. US, as a diagnosis, is equivalent to specificity and sensitivity of electrodiagnosis.
Guangxiang et al. (2016)	49 patients, 70 wrists	32 female wrists and 4 male, 57.08 y ± 8.968. 31 female wrists and 3 male 51.8 y ± 10.8	TMB origin	China	CTS Symptoms are more severe with a larger cross-sectional area of the MN	CTS was correlated with body weight. Cross-sectional area was the most appropriate measurement for CTS diagnosis. US is a useful tool for the detection and severity of CTS and for monitoring.
Stavros et al. (2016)	1 patient	47-y-old male	Left MN penetrated by a PMA and vein, and reattachment of nerve fibers in a nerve distal to penetration site	USA	CTS Ultrasound Tinel (+). No Phalen-Tinel's sign	The US may be the preferred imaging technique for peripheral neuropathies. Consider anatomical variations when investigating CTS symptoms with inconsistent electrodiagnostic results.
Gassner et al. (2002)	2 patients with CTS 50 healthy patients (100 wrists)	29 and 49-y-old male with CTS. 18 male and 32 female volunteers, 22-54-y-old	PMA was associated BMN	Austria	CTS. Both patients were asymptomatic after surgery	PMA is a common condition in healthy individuals and can be detected by US and computed tomography. PMA greater than 1.5 mm appears to be uncommon in asymptomatic individuals. Since the PMA has a superficial, preoperative diagnosis may be important.
Ahn et al. (2000)	192 patients (354 wrists)	8 male, 184 female; ages between 30 and 82-y-old	Variants according to Lanz: Group 0: 340 cases; Group I-A: 10 cases (2.8%); Group I-B: 4 cases Origin of the motor branch: radial Border, radial third, anterior zone, ulnar side Number of branches: 1 branch, 2 branches, 3 or more branches	Korea	CTS	These results may contribute to better surgical outcome and complete decompression of the MN during surgery, while preventing inadvertent injuries to the motor branch of the MN in Korean patients.

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Table 1 (continued)

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Al-Qattan (2010)	100 patients	Not specified	Variants according to Lanz: Group 0: 56 cases, Group I-A: 34 cases, Group I-B: 9 cases, preligamentous: 1 case. Association with hypertrophic muscle: 26/56 extraligamentous, 9/9 transligamentous, 1/1 preligamentous	Saudi Arabia	CTS	The presence of hypertrophic muscle over the transverse carpal ligament is associated with transligamentous and preligamentous types. The motor branch may be located within this muscle, so it is recommended to incise carefully on the ulnar side to avoid nerve injury.
Iijima and Tajiri (2024)	85 patients (100 wrists)	26 male and 59 female, 44-87-y-old (mean 66.8)	Variants according to Lanz: Group 0: 10 cases, Group I-B: 6 cases, Group I-D: 1 case, Group III-A: 1 case, Group IV-A: 1 case	Japan	CTS	Direct visualization allowed the preservation of anomalous motor branches and the prevention of complications. Useful technique to completely release the antebrachial fascia and avoid MN injuries.
Al-Qattan et al. (2009)	1 patient	Female, 18-y-old	BMN with PMA pathological with aneurysm and venous malformation (Lanz III-B/Al-Qattan III-D)	Saudi Arabia	Acute CTS due to PMA thrombosis between branches of the BMN	It highlights the importance of recognizing neurovascular variants before surgery or for differential diagnosis.
Asghar et al. (2022)	Meta-analysis 29 studies: 2186 wrists STC 1311 without STC 3497 total wrists	Not specified	Variants according to Lanz: Group 0, Group III, Group Ib, Group IIIb of Lanz, Group II Group I and IV of Al-Qattan	Global	CTS	The study demonstrates a higher prevalence of BMN and the combination BMN + PMA in patients with CTS, suggesting that these variants may act as predisposing factors. The importance of preoperative evaluation in suspected CTS is highlighted.
Akgun et al. (2017)	1 patient	35-y-old female	BMN in right wrist, thrombosed PMA passing between branches of BMN Lanz Group III-B and Al-Qattan Group III-c	Turkey	Acute CTS	First documented clinical case of acute CTS caused by thrombosis of a PMA traversing the bifurcated MN. The case highlights the importance of diagnosis by Doppler US in the context of atypical acute pain and suspected neurovascular variants.

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Table 1 (continued)

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Barr et al. (2022)	1 patient	41-y-old, female	Lanz type III-B, Al-Qattan tipo IV-A	USA	Acute CTS, asymptomatic after surgery	It highlights the clinical importance of recognizing these variants to avoid surgical errors.
Becciolini et al. (2025)	Not specified	Not specified	Not specified	Italy, Switzerland, Austria	CTS	The relevance of identifying anatomical variants to prevent iatrogenic complications in carpal tunnel surgery is highlighted. In addition, the use of US is emphasized as a functional diagnostic tool, which allows for the evaluation of MN mobility within the tunnel and differentiation between normal and pathological conditions.
Cartwright et al. (2017)	20 patients, 40 wrists	Average age 48.5-y-old; 12 female, 8 male.	BMN in 2 cases (Group III of Lanz), PMA in 2 cases (Group II de Al-Qattan)	USA	Asymptomatic	High-resolution US allowed for the identification of variants. Fewer fascicles were observed in wrists with variants, suggesting a possible structural relationship with CTS predisposition. The US is a useful noninvasive tool for anatomical study and preventive diagnosis.
Dag et al. (2021)	300 patients (300 wrists): 157 right wrists 143 left wrists	142 male, 158 female, average age: 38-y-old (Range 18-85)	BMN proximal, 38 cases Group III-A/Al-Qattan Group I, BMN 35 cases Lanz Group I-B, BMN + PMA: 44 cases Lanz Group III-B, Al-Qattan Group II. Trifurcation: 1 case	Turkey	Wrist pain, with and without CTS	PMA was common and coexisted with BMN in most cases. The use of preoperative MRI is recommended to detect these variants and improve surgical safety in carpal tunnel release.
De Maeseneer et al. (2015)	Not specified	Not specified	Variants of MN entrapment at multiple levels (Struthers' ligament, lacertus fibrosus, pronator teres head, Sublimis pons)	Belgium	Compression of the MN and its branches, including anterior interosseous nerve syndrome	Detailed US evaluation of MN entrapment zones is diagnostically useful. Relevant for identifying anatomical causes of compressive neuropathy.

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Table 1 (continued)

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Dhal et al. (2020)	1 patient	Teenager male, 15-y-old.	BMN Group III of Lanz, Group VI of Al-Qattan, PMA	India	CTS	US and MRI detected BMN and PMA, but not the aberrant muscle, which was found during surgery. The importance of preoperative imaging is emphasized to avoid diagnostic and surgical errors.
Di Cosmo et al. (2022)	103 patients; 246 US images	Not specified	BMN PMA Accessory Muscle	Italy	CTS	A deep learning model was developed for automatic MN detection in US. The algorithm achieved high accuracy (DSC = 0.868). Although effective with normal anatomy, it showed limitations with rare variants. The system can standardize cross-sectional area (CSA) measurement, reduce operator errors, and support CTS diagnosis.
Eachempati et al. (2024)	1 patient	Male, 47-y-old, orthopedic surgeon	Bilateral BMN + Bilateral PMA thrombosis of the left PMA with focal occlusion (Lanz Group III/Al-Qattan Group III-c)	India	Sharp pain in the left wrist, mild paresthesia in the index and middle fingers. No weakness or motor deficit. Pain exacerbated by dorsiflexion	First reported case of PMA thrombosis coexisting with BMN in a surgeon with prolonged exposure to vibrating tools. It resolved with aspirin in 3 wk. It is associated with hand-arm vibration syndrome (HAVS). It is recommended to consider this syndrome as a differential diagnosis in professionals with vascular symptoms and high-risk occupations.
Gruber et al. (2025)	432 patients (447 wrists) + 103 patients (200 wrists)	CTS: Average age: 63-y-old (28-96) 294 female, 153 male. Controls: Average age: 58-y-old (24-89), 67 female, 36 male	BMN: 64 cases in CTS, 22 in controls, PMA: 46 in CTS, 26 in controls, BMN + PMA: 22 in CTS, 16 in controls, Lanz Group III-B, Al-Qattan Group II	Austria	CTS	Although anatomical variants were more frequent in CTS, no statistically significant differences were observed. The MN cross-sectional area (CSA) was significantly larger in CTS but was not directly correlated with variants. This study highlights the role of US for anatomical diagnosis and surgical planning.

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Table 1 (continued)

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Knarr et al. (2021)	1 patient	Female, 37-y-old	BMN with partial radial branch neuritis, accompanied by PMA, Lanz Group III-B, Al-Qattan Group III-c	Germany	Severe pain in the right thumb with allodynia, without nocturnal symptoms. Isolated involvement of the radial branch of the MN	First documented case of partial neuritis of a BMN, diagnosed by MRI with gadolinium. NCS were normal. This study highlights the usefulness of contrasted MRI in atypical neurological conditions and the importance of anatomical knowledge to avoid errors.
Piagkou et al. (2023)	1 donor	Male, 80-y-old	Bilateral PMA, bilateral BMN with superficial and deep branches (Lanz Group III-B, Al-Qattan Group II)	Greece	Not applicable	The bilateral coexistence of PMA, MN, and interconnections between MN and ulnar nerves is rare and of high clinical value. It can cause difficulties in electrophysiological interpretation and complicate carpal tunnel surgery. PMA can cause CTS if it is pathological (thrombosis, dilation) and is crucial for blood flow in the hand. Preoperative evaluation with US and angiography is recommended in complex cases.
Propeck et al. (2000)	1 patient with CTS and 2 donors	Female, 16-y-old 2 Male and 1female donors, both with 70-y-old	BMN confirmed by US, MRI, and surgery in a living patient Lanz Group III-b/Al-Qattan Group II-III-c and partial MNB (bilobed), without PMA	USA	CTS	First study to correlate US and MRI images with anatomical and histological findings of BMN. The diagnosis of CTS may be missed in the presence of BMN.
Savage and McKell (2024)	468 patients, 665 wrists	Average age: 54.6 ± 16.8-y-old 276 female, 192 male	BMN in 92 wrist, Lanz Group III-A, Al-Qattan Group I	USA	CTS	Binary classification using cutoffs of CSA ≥ 11 mm ² or ΔCSA ≥ 5 mm ² was more effective in confirming CTS in patients with BMN than in patients with type 2 diabetes. Diagnostic accuracy was higher with BMN. It is recommended not to use CSA to categorize severity in these populations. Structural US was highlighted as a useful tool for diagnosis and planning in the presence of bifurcated variants.

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Table 1 (continued)

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Seyyedini et al. (2024)	1 donor	Male, 45-y-old (donor)	Bilateral palmar PMA, bilateral BMN. Unilateral variation of the palmar cutaneous nerve arises from the ulnar side and passes under the left flexor retinaculum. Lanz Group III-B and Group IV-B, Al-Qattan Group II and Group VI	Iran	Not applicable	First description of this coexisting anatomical triad. The combination of PMA, BMN, and an aberrant branch of the palmar cutaneous nerve poses a high risk of iatrogenic injury during CTS surgery. Preoperative evaluation with US or MRI is recommended. It highlights the importance of anatomy in the surgical safety of the wrist and hand.
Trachani et al. (2018)	58 patients with CTS (100 wrists) + 56 controls (112 wrists)	CTS: 44 females, 14 males; average age 52.2 ± 11.5-y-old Controls: 44 females, 12 males; average age 49.0 ± 11.6-y-old	BMN 7 bilateral, 20 unilateral Lanz Group III-A, Al-Qattan Group I 1 unilateral trifurcation in a control	Greece	CTS	Although no statistical significance was found, BMN was more frequent in CTS. It is noted that bifurcation can reduce the area of the nerve evaluable by US, leading to false negatives. The study highlights the importance of detecting these anatomical variants using US as a support for electrophysiological diagnosis, especially in CTS with ambiguous findings.
Triguero et al. (2022)	1 patient	Male, 71-y-old	Bilateral BMN, thrombosed PMA in the right wrist, Lanz Group III-B Al-Qattan: right III-c, left I	Spain	Postsurgical recurrent bilateral CTS	First documented case of bilateral CTS with combined diagnosis of BMN and wild-type transthyretin. Biopsy revealed transthyretin-positive amyloid deposits. The importance of biopsying during CTS surgery is emphasized in recurrent, bilateral cases or cases with anatomical variants.
Yerasu et al. (2022)	1 patient	Male, 30-y-old	Bilateral BMN, PMA bilateral Lanz Group III-B, Al-Qattan Group II	India	CTS	First documented case of right CTS with bilateral BMN and PMA diagnosed by US. The usefulness of US for preoperative anatomical detection and postoperative follow-up in cases of anatomical variants is emphasized.

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Table 1 (continued)

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Zitek et al. (2023)	Review of 614 studies (88 cases)	Not specified	10 cases of BMN, Lanz III-B/Al-Qattan III-b palmaris profundus muscle insertion: in palmar aponeurosis, origin in ventral aspect of the radius, coexistence with palmaris longus	Global (USA, Europe, Asia, Africa, Oceania)	CTS	The importance of resection is emphasized when the muscle is encountered during carpal tunnel surgery to avoid persistent symptoms. The muscle can cause direct compression of the MN and requires careful presurgical differential diagnosis, especially using dynamic imaging such as US or MRI.
Elsaftawy et al. (2013)	20 adult donor wrists.	Not specified	A transligamentous variant of the recurrent motor branch of the MN and two cases of a recurrent motor branch of the ulnar nerve were found Two recurrent motor branches of the MN supplying the thenar muscles	Poland	Not applicable	Dangerous variants of the motor branch of the MN (such as the transligamentous type) are rare in the general population. However, it is important to consider in clinical practice to minimize the risk of injury when performing CTS surgeries.
Amadio and Minn (1987)	1 patient	67-y-old, male	BMN, the nerve was found to send sensory and motor branches to the thumb	USA	CTS	Knowledge of anomalous branching of the MN allows for more effective preoperative planning.
Bagatur et al. (2013)	3 patients	3 males, average age 38-y-old	BMN associated with a PMA	Turkey	CTS. All patients reported relief of symptoms after surgery	Imaging studies are generally not requested to diagnose CTS; however, they should be requested to rule out variants of MN.
Bale et al. (2018)	1 donor	Male, 48-y-old	BMN. Single digital neural loop in the right palm of the donor	USA	Not applicable	No possible developmental relationship between the BMN and the single digital neural loop is speculated.

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Table 1 (continued)

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Bayrak et al. (2008)	170 patients with CTS (320 wrists), 170 patients with CTS, 120 healthy patients (240 wrists)	42 males 248 females. Age not specified	BMN in patents with SCT	Turkey	CTS	BMN occurs relatively frequently in patients with CTS. This BMN is characterized by its high cross-sectional area, greater than that of a nonbifid nerve. US is a noninvasive and effective method for evaluating MN abnormalities, such as the bifid nerve.
Bhat et al. (2018)	1 patient	Male, 52-y-old	Bilateral BMN	India	CTS. Asymptomatic postoperatively	US is a valuable tool for detecting CTS and structural abnormalities, as these can lead to surgical failure if not detected.
Chen et al. (2017)	80 patients, 160 wrists	30 females, 50 males. Age not specified.	BMN was observed in 15 wrists, and PMA in 12 wrists. A persistent median vein in 9 wrists, which was associated with PMA	China	CTS	These three anatomical variants were not associated with an additional risk of developing CTS. However, more attention should be paid to persistent medium-sized arteries and veins that could present pathogenic factor for CTS when thrombi form.
De Franco et al. (2013)	2 patients	2 females, 56-y-old and 58-y-old	Presentation of BMN and reverse palmaris longus	Italy	CTS	The importance of US evaluations to assess anatomy when diagnosing and operating wrist pathologies is highlighted In decompressive surgery, it was essential to know the anatomy due to the risk of incomplete decompression or even nerve damage.

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Table 1 (continued)

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Duymus et al. (2012)	1 patient	Female, 46-y-old	Bifurcation and trifurcation of the MN were observed in both wrists	Turkey	CTS.	Variations in the MN allow the surgeon to avoid damaging the perineurium, epineurium, or other branches to ensure an optimal patient outcome. The US is an easy and inexpensive radiological method for diagnosing CTS.
Ekiz et al. (2016)	1 patient	Male, 30-y-old	PMA and two medium-sized veins with BMN	Turkey	Asymptomatic	Artery/vein and MN involvement may predispose to CTS due to the relative increase in cross-sectional area and space occupation. US is a convenient imaging modality for visualizing peripheral nerves and anatomy.
Gutowski et al. (2000)	1 patient	Male, 12-y-old	Venous malformation, PMA with BMN	USA	CTS	An arteriovenous malformation is associated with the presence of BMN. Surgeons should be aware of the possible presence of BMN, particularly when an NMN is identified, and remember that additional structures could lead to nerve compression in the carpal tunnel.
Jones et al. (2006)	1 patient	Female, 57-y-old	Anomaly of the tendon of the deep palmar muscle that runs along the anterior surface of the MN and divides it into two branches (BMN), on both wrists	New Zealand	CTS. Symptomatic postoperatively	The importance of clear visualization of the BMN in this type of surgery and knowledge of the anatomical variations in the area are emphasized.
Kele et al. (2002)	1 patient	Male, 37-y-old	BMN and thrombosis of PMA	Germany	CTS	US directly influenced the surgical strategy and approach.

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Table 1 (continued)

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Klauser et al. (2010)	Analyzes clinical tools for the diagnosis of CTS	Not specified	BMN; PMA; variant of the deep palmar muscle tendon; accessory muscles of the carpal tunnel; variants in the transverse carpal tunnel ligament; palmar cutaneous branch of the MN	Austria, France, Italy	CTS	US and MRI provide detailed anatomical information for these cases, allowing for a better clinical and surgical approach. US is essential as an initial diagnostic tool.
Kostoris et al. (2019)	1 patient	Male, 79-y-old	BMN accompanied by an anomalous tendon of the deep palmaris muscle	Italy	CTS	Carpal tunnel release surgery is a simple, rapid, and well-standardized procedure that can be complicated by anatomical abnormalities. The surgeon must be familiar with the variations in nerve, tendon, and vascular structures to avoid major complications.
McClelland and Means (2012)	1 patient	Female, 47-y-old	BMN and PMA, and deep palmar muscle	USA	CTS	It is essential to consider the anatomy of the carpal tunnel and its possible variations when modifying a surgical plan. Although the endoscopic approach is less invasive, an open approach is necessary if there are concerns about the safety of the procedure.
Petrover et al. (2017)	15 donors, 30 wrists	Not specified	The dissection revealed variants of the MN and its TMB. According to Lanz type 1, type II, and type 3 in 1	France	Not applicable	High-frequency US was accurate in identifying anatomical variants of the MN and its TMB, as well as hypertrophic muscles. Ultrasound mapping should be performed before carpal tunnel release surgery.

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Table 1 (continued)

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Spagnoli et al. (2017)	1 patient	Not specified	BMN (Lanz III)	Italy	CTS	The BMN can facilitate compression of the MN in the carpal tunnel due to its larger cross-sectional area. These uncommon variants should be taken into consideration to avoid further complications.
Yildirim et al. (2001)	1 patient	Not specified	BMN (Lanz III)	Turkey	Not specified	Consideration in carpal tunnel release surgery. Separate decompression for each branch
Walker et al. (2013)	1026 wrists of 513 patients with US and electromyography (518 just with US)	283 males and 235 females Average age 34.5-37.2-y-old	88 wrists with BMN, 10 patients bilateral, 38 patients with PMA, 4 patients with bilateral PMA	USA	Not specified	No association was found with the prevalence of CTS in participants with an ipsilateral PMA or a bifid MN. Anatomical variations of the median artery can be determined by ultrasound. PMA and bifid MN tend to coexist, but they do not increase the risk of developing CTS in manual workers.

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Table 1 (continued)

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Schlaflly and Lister (1987)	1 patient	Female, 35-y-old	The palmaris longus muscle belly was bifid, with the radial portion inserting into the normal insertion area of the palmaris longus, superficial to the transverse carpal ligament, and the ulnar portion on the deep surface of this ligament	USA	Pain and swelling in the right wrist with paresthesia in the thumb, index finger, and middle finger were aggravated by her sales activities. Examination revealed mild, diffuse bluish swelling on the anterior aspect of the distal forearm. Abductor pollicis brevis weakness. Static two-point discrimination sensitivity was intact, although cogwheel sensitivity on the palmar aspect of the index finger was decreased. Phalen + Tinel + Asymptomatic after surgery	Normal electromyogram with slowed MN conduction. MN compression in the distal forearm secondary to an abnormality of the palmaris longus mimics CTS. Suspect if swelling or abnormal discoloration occurs in the distal forearm. If carpal tunnel release does not reveal an abnormality, further proximal examination is required.
Negm et al. (2017)	1 patient	Female, 43-y-old	BMN and PMA	Egypt	Bilateral CTS	Multisystem US is a simple, noninvasive, low-cost, and rapid tool with novel diagnostic capabilities that could modify the treatment of CTS with careful preoperative evaluation.

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Table 1 (continued)

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Pierre-Jerome et al. (2009)	194 patients, 194 wrists	77 males, 117 females, 12-80 y	BMN and PMA	USA	CTS	No significant differences were found in the prevalence of BMN within the tunnel between subgroups based on age, sex, or wrist side.
Kornberg et al. (1983)	1 patient	Male, 23-y-old	BMN and PMA, radial portion with 3 transligamentous TMB	USA	Hypoesthesia	BMN in the distal third of the forearm is important for the surgeon because it can injure a branch. Due to the numerous variations in the course, the surgeon should approach it from the ulnar side.
Klauser et al. (2011)	49 patients with BMN and CTS. 27 healthy volunteers with BMN	17 males and 32 females (24-78 y). Healthy volunteers: 13 males and 14 females (24-86 y).	BMN	Austria	CTS	The use of CSA is a noninvasive US technique for the accurate diagnosis of CTS in the presence of a BNM. US with electrodiagnostic testing is the reference standard for CTS diagnosis.
Kasius et al. (2014)	259 patients with STC (259 wrists) 54 healthy patients (108 wrists)	209 females, 50 males with CTS, average age 39.8 29 healthy females, 25 healthy males. Average age: 50	BMN	The Netherlands	CTS	The US can effectively disclose the presence of a BMN. Measuring the summated CSA, however, does not add any additional data for diagnosis of CTS and may lead to false negative findings.
Karahmet al. (2016)	1 patient	Male, 21-y-old	BMN and PMA	Turkey	CTS	Increased risk of CTS and advised to avoid heavy lifting or repetitive activities involving the hand or wrist.
Ibrahim et al. (2015)	1 patient	Male, 50-y-old	BMN and PMA	Japan	CTS	Imaging revealed an old hamate fracture and a rupture of the flexor tendons of the little finger. Findings of the MN and artery were incidental and unrelated to the pathology.
Iannicelli et al. (2000)	50 patients	25 males, 25 females between 18 and 60-y-old)	6 BMN Lanz Group III	Italy	CTS. Twenty days after surgery, the patients remained asymptomatic	In the six patients with anatomical variation of the MN, axial US showed two closed oval formations with a hypoechoic fascicular structure.

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Table 1 (continued)

Authors (y)	N and sample	Age and sex	Variant	Region	Symptomatology	Clinical consideration
Granec et al. (2012)	1 patient	Female, 29-y-old	BMN	Croatia	CTS	US is used as a noninvasive, effective, and accessible method for diagnosing BMN.
Granata et al. (2011)	89 symptomatic (162 wrists), 52 patients (104 wrists)	27 males, 62 females; 20-65-y-old. Control: 16 males, 36 females; 22-48-y-old.	16 BMN in the control group and 30 BMN in the CTS group	Italy	CTS	BMN is common, not always bilateral, more often incomplete, and has a similar prevalence in the CTS group and the control group. It is not a risk factor for the development of CTS.
Fernández-García et al. (2011)	1 patient	31-y-old female	BMN	Spain	CTS	Electrodiagnostic examination at a proximal level revealed the abnormality, leading to successful surgical treatment.
Erol et al. (2004)	1 patient	45-y-old female	BMN	Turkey	Asymptomatic	US is useful in asymptomatic individuals, and its preoperative necessity in patients with CTS, for anatomical guidance.
Checa and Hussain (2011)	3 patients	80-, 55- and 62-y-old females	BMN, one of them with PMA	USA	Arthrosis and CTS Rheumatoid arthritis and CTS	US is a tool increasingly used in rheumatology, should be used to identify different variants of the MN at the level of the carpal tunnel, such as the identification of a BMN and a PMA.
Berry et al. (2003)	1 patient	4-y-old female	BMN. Each tunnel contained two superficial and two deep flexor tendons	United Kingdom	Glass laceration at the base of the dominant right palm. Both nerve branches had were repaired, with good clinical progress	Surgeons treating hand injuries must also be aware of these anatomical variants and dissect outside the obvious area of injury to avoid missing a major structure with significant consequences.
Artico et al. (1995)	2 patients	55- and 48-y old females	BMN with two equal branches	Austria	CTS	It is necessary to approach the MN from the ulnar side by releasing the carpal tunnel to carefully identify and protect the TMB

AI, artificial intelligence; Al-Qattan classification, Al-Qattan classification of median nerve variants; CSA, cross-sectional area; CTR, carpal tunnel release; DSC, dice similarity coefficient; EDX, electrodiagnostic studies; EMG, electromyography; HAVS, hand-arm vibration syndrome; Lanz classification, Lanz classification of median nerve variants; NCS, nerve conduction studies; Phalen (+), positive Phalen test; RBMN, recurrent branch of the median nerve; SPA, superficial palmar arch; TCL, transverse carpal ligament; Tinel (+), positive Tinel sign; TMB origin, thenar motor branch origin pattern; Δ CSA, difference in cross-sectional area between proximal and distal measurements.

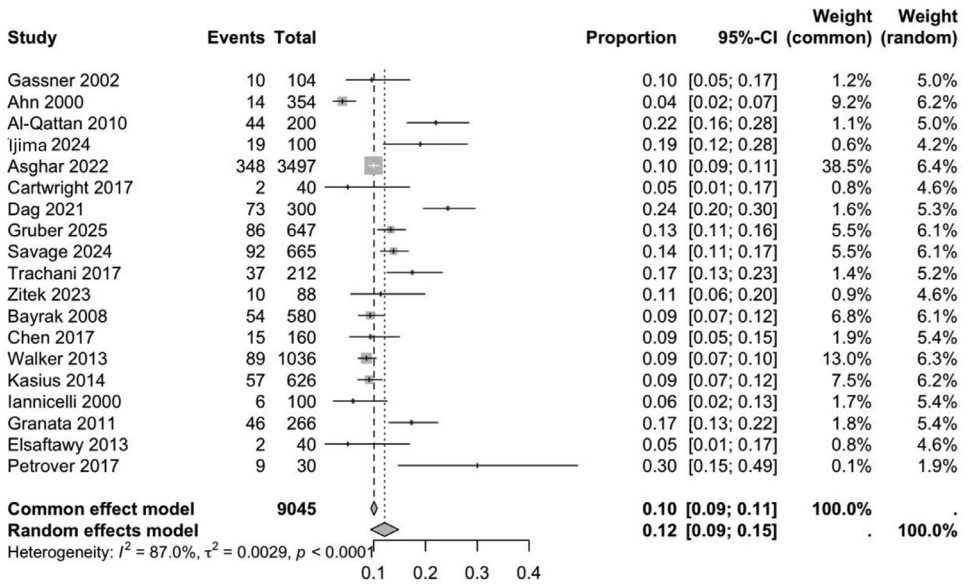


Fig. 3. Forest plot prevalence MN variants.

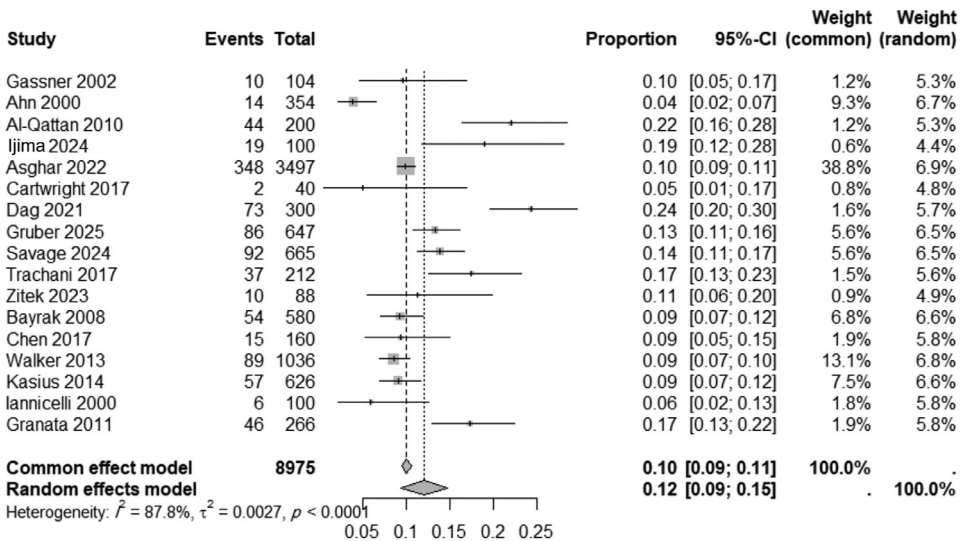


Fig. 4. Forest plot of prevalence of median nerve variants in imaging-based and surgical studies.

Laterality analysis

Laterality analysis included four studies.^{53,67,73,75} Right-sided variants showed a pooled prevalence of 46% (95% CI: 40%-52%) with no observed heterogeneity ($I^2 = 0.0\%$) (Fig. 5), while left-sided variants demonstrated a pooled prevalence of 53% (95% CI: 48%-59%), also with no heterogeneity ($I^2 = 0.0\%$) (Fig. 6). The absence of heterogeneity suggests high consistency across studies, although the limited number of included studies restricts the strength of these estimates. Bilateral presentation showed a pooled prevalence of 21% (95% CI: 6%-36%) with con-

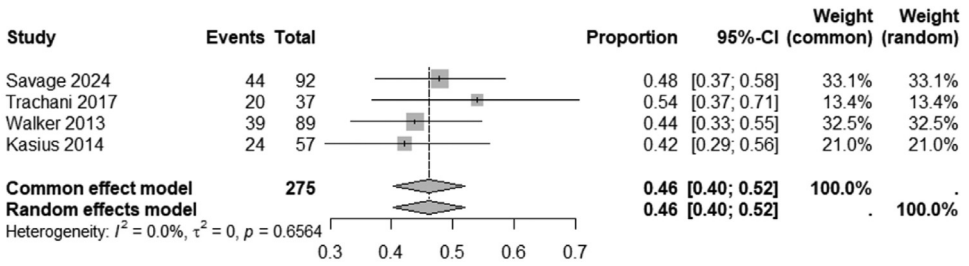


Fig. 5. Forest plot prevalence right example MN variants.

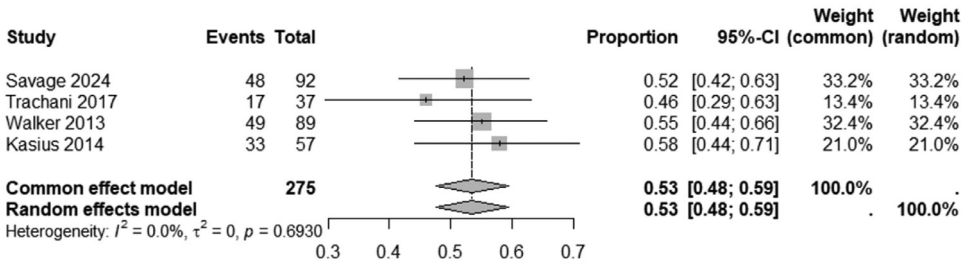


Fig. 6. Forest plot prevalence left example MN variants.

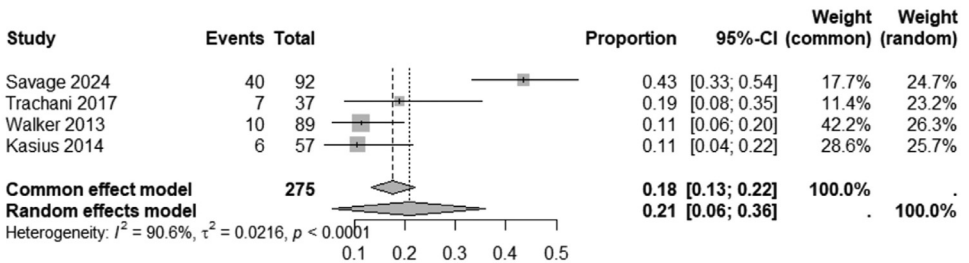


Fig. 7. Forest plot prevalence bilateral example MN variants.

siderable heterogeneity ($I^2 = 90.6\%$) (Fig. 7), indicating substantial variability and limiting the interpretability of this subgroup.

Geographic subgroup analysis

Geographic subgroup analysis demonstrated a pooled prevalence of 22% in Asia (95% CI: 13%-31%; $P = 92.6\%$) based on six studies^{16,19,26,32,33,72} (Fig. 8), 20% in Europe (95% CI: 14%-27%; $P = 79.2\%$) based on seven studies^{41,44,45,47,49,53,73} (Fig. 9), and 18% in America (95% CI: 16%-20%; $P = 19.4\%$) based on three studies ($n = 1006$)^{30,67,75} (Fig. 10). The substantial heterogeneity observed in Asian and European subgroups suggests considerable variability in study design, population characteristics, and diagnostic approaches. In contrast, the lower heterogeneity in American studies indicates greater methodological consistency, although the smaller number of studies limits the robustness of this comparison. No eligible prevalence studies were identified from Africa or Oceania, limiting the global generalizability of the findings.

Sensitivity analysis

In addition to statistical heterogeneity, variability across studies was influenced by the markedly large sample size of two included investigations. To evaluate the potential impact of

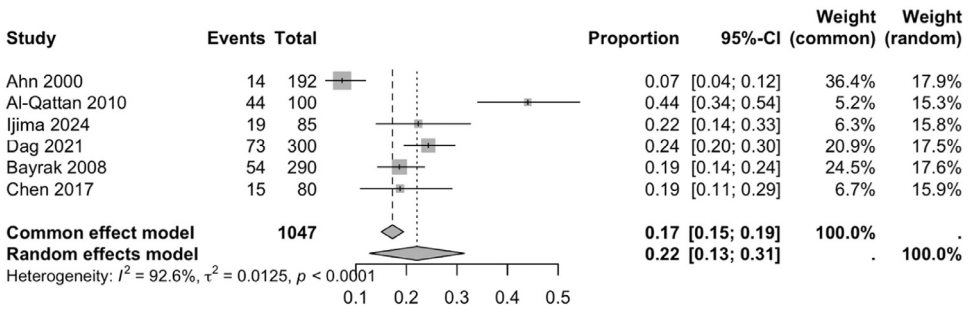


Fig. 8. Forest plot prevalence Asia region example MN variants.

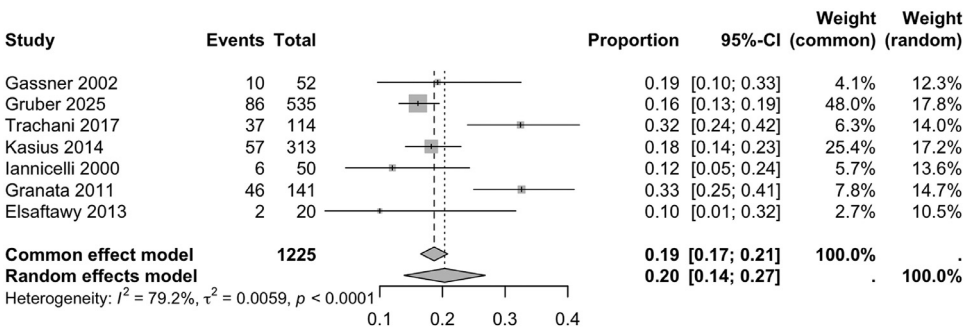


Fig. 9. Forest plot prevalence Europe region example MN variants.

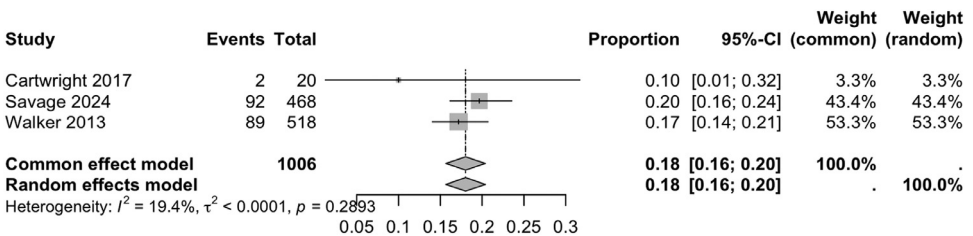


Fig. 10. Forest plot prevalence America region example MN variants.

these high-weight studies on the pooled estimate, a sensitivity analysis was conducted excluding studies with more than 1000 participants. After exclusion of these large-sample studies, the pooled prevalence of MN variants was 13% (95% CI: 9%-16%), with persistent substantial heterogeneity ($P = 88.9\%$). The resulting estimate was comparable to the overall pooled prevalence of 12%, indicating that the exclusion of high-sample studies did not materially alter the effect size. These findings suggest that the large population-based studies did not disproportionately influence the overall prevalence estimate. Therefore, the robustness of the meta-analytic results is supported (Supplementary Fig. 1).

Publication bias analysis

Publication bias was assessed using funnel plot visualization and Egger's regression test. Visual inspection of the funnel plot suggests mild asymmetry (Fig. 11). Egger's test was statistically significant ($P = 0.01$), indicating potential small-study effects. However, these findings should be interpreted with caution, as the substantial heterogeneity observed across studies may contribute to funnel plot asymmetry and increase the likelihood of a significant Egger test.

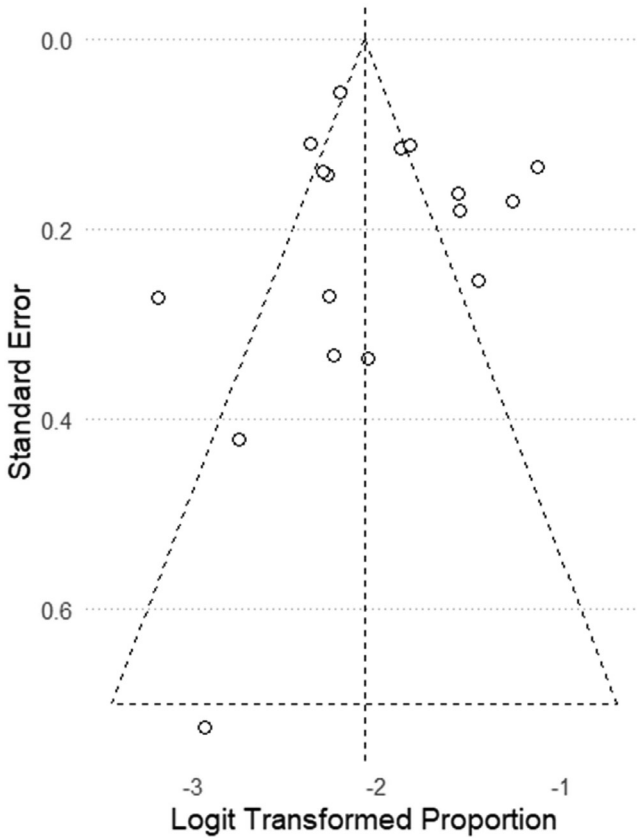


Fig. 11. Funnel plot prevalence MN variants.

Risk of bias of included articles

Of the 63 studies included in the qualitative synthesis, 37 met the criteria for methodological quality assessment using the AQUA tool, which evaluates risk of bias across five predefined domains. In the methodology and subject characterization domain, four studies^{33,39,54,59} were classified as high risk. In the descriptive anatomy domain, five studies^{56,58,61,63,64} were classified as high risk. In the results reporting domain, 11 studies^{1,20,30,32,34,37,52,55,58,62,68} were classified as high risk. These findings indicate that a proportion of the included studies presented methodological limitations that may affect interpretability and should be considered when contextualizing the pooled estimates (Fig. 12).

Discussion

This systematic review and meta-analysis provide a comprehensive synthesis of the available evidence on morphological variants of the MN within the CT. To our knowledge, this represents one of the largest pooled analyses addressing this topic, integrating anatomical, imaging, and surgical data within a unified quantitative framework. The pooled prevalence of 12% indicates that these variants are relatively common anatomical findings rather than rare anomalies and may be encountered in both asymptomatic individuals and patients undergoing evaluation for CTS. The substantial heterogeneity observed across studies likely reflects methodological differences and population variability rather than random variation alone.⁴⁴

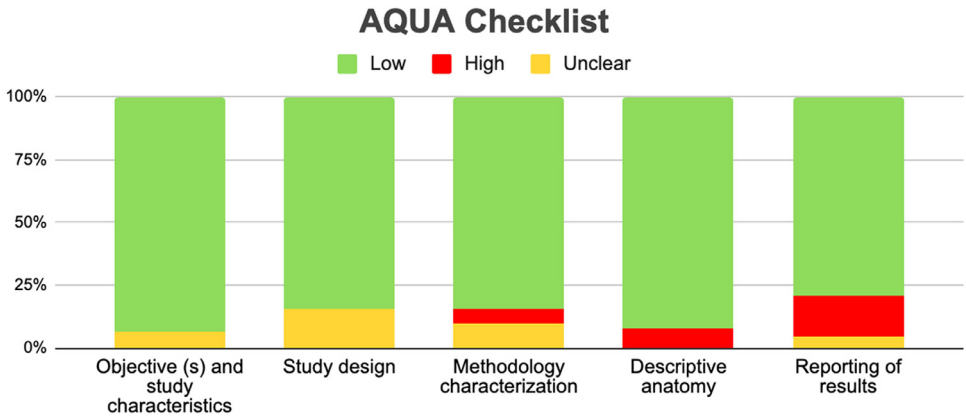


Fig. 12. Risk of bias with AQUA checklist.

Previous studies on median bifid nerve

Previous meta-analyses have evaluated anatomical variants of the MN in relation to CTS, primarily focusing on BMN and PMA. Asghar et al. and Zitek et al.^{22,79} reported a higher prevalence of BMN and PMA in CTS populations compared with controls, suggesting a potential anatomical contribution to nerve compression. These studies also highlighted the role of accessory musculature as a possible contributor to increased compartmental content.

In contrast, Henry et al.¹¹ focused on variations of the thenar motor branch, emphasizing their surgical relevance, particularly in relation to iatrogenic injury during CT release. However, their analysis was limited to branching patterns and did not address the broader spectrum of MN morphological variability.

Compared with prior studies, the present analysis expands the scope by incorporating a wider range of morphological variants and by providing subgroup analyses based on laterality and geographic distribution. This broader approach allows for a more comprehensive anatomical and epidemiological characterization derived from 63 studies included in the qualitative synthesis.

Prevalence and characteristics

The pooled prevalence of MN variants was 12% (95% CI: 9%-15%) based on 19 studies included in the quantitative synthesis. Although this estimate suggests that these variants are relatively common, the high heterogeneity ($I^2 = 87\%$) limits the precision of the pooled estimate and should be considered when interpreting the results. The observed heterogeneity likely reflects differences in study design, imaging modalities, anatomical dissection techniques, population characteristics, and diagnostic criteria for variant classification. Geographic variability and differences in sample size may have further contributed to statistical dispersion. The use of a random-effects model was therefore appropriate to account for between-study variability. Prevalence estimates were consistent across imaging-based and surgically evaluated populations, supporting the clinical detectability of these variants. As most imaging studies were conducted in living populations,^{17,19} these findings indicate that MN variants are not limited to cadaveric observations. No clear laterality predominance was identified (right: 46%; left: 53%; $I^2 = 0.0\%$), suggesting consistent findings across studies.^{53,67,73,75} In contrast, bilateral variants demonstrated substantial variability (21%; $I^2 = 90.6\%$), which should be interpreted cautiously given the limited number of studies specifically addressing bilaterality. Geographic subgroup analysis showed

higher prevalence estimates in Asia and Europe compared with America, although these findings are limited by high heterogeneity within subgroups. Importantly, the absence of data from Africa and Oceania restricts the global generalizability of the results.

Anatomical and topographic considerations beyond BMN

Although BMN is among the most frequently described variants, the anatomical complexity of the CT extends beyond neural bifurcation. This region represents a constrained osteofibrous compartment in which neural, vascular, and tendinous structures coexist in close proximity, making detailed topographic knowledge essential for both interpretation and surgical safety. Recent studies emphasize the importance of reproducible anatomical landmarks. Mizia et al.⁸⁰ demonstrated that fixed relationships between the MN and surrounding tendons may provide reliable intraoperative guidance. Similarly, Duzgun et al.⁸¹ showed that the recurrent branch of the MN exhibits considerable variability relative to bony landmarks, challenging traditional anatomical assumptions. Distal division patterns further contribute to variability. Smith et al.⁸² reported proximal splitting of the MN with nonclassical trajectories through the CT, supporting the concept of anatomical variation as a continuum rather than discrete categories. From a surgical perspective, Ajayi et al.⁸³ proposed a “safe-zone” model based on bony landmarks, offering quantifiable parameters to reduce procedural risk. Additionally, Wysiadeci et al.⁸⁴ highlighted the need for standardized reporting frameworks in anatomical research to improve reproducibility and comparability. Taken together, these findings suggest that MN variability should be interpreted within a broader anatomical context rather than being limited to bifurcation patterns alone.

Vascular coexistence and PMA

The coexistence of vascular and neural variants further contributes to the structural variability of the CT. The PMA is a well-described but heterogeneous structure with variable anatomical patterns. A large meta-analysis by Solewski et al.⁸⁵ demonstrated that the antebrachial PMA is more prevalent than the palmar variant in general populations. Notably, the prevalence of palmar PMA in surgical CTS cohorts appears relatively low (approximately 2%-3%), suggesting a limited etiological role in most cases. This interpretation is supported by surgical data from Osiaik et al.⁸⁶ who reported a PMA prevalence of 2.8% in patients undergoing CT release. Although PMA frequently coexists with BMN, its presence alone does not appear to be disproportionately increased compared with general anatomical populations. However, pathological changes such as thrombosis or arterial enlargement may contribute to localized increases in compartmental content. In such cases, spatial relationships within the tunnel may be altered, particularly when PMA courses between bifid nerve components. Overall, current evidence supports interpreting PMA as a variable anatomical structure with context-dependent clinical relevance rather than a consistent independent risk factor for CTS.^{87,88}

Clinical and surgical implications

CTS remains the most common compressive neuropathy of the upper extremity, and its adequate evaluation requires a thorough understanding of potential anatomical variants within the CT. Although the BMN has not been consistently demonstrated to represent an independent risk factor for CTS (Pierre-Jerome et al.)⁶⁵ its coexistence with additional variants, particularly PMA or accessory musculature, may alter spatial relationships and theoretically increase susceptibility to compression.^{22,33}

Several studies have examined the relationship between BMN and nerve CSA. Bayrak et al.²⁶ reported that BMN may be associated with a larger CSA, which could influence sonographic interpretation. However, other investigations have demonstrated inconsistent associations between CSA enlargement and the presence of anatomical variants,^{46,47} suggesting that CSA alone should not be interpreted as a surrogate marker of morphological variation. High-resolution ultrasound has emerged as a valuable tool for both the diagnosis of CTS and the identification of anatomical variants. Studies by Klauser et al. and Stavros et al.^{56,71} support the complementary use of ultrasound alongside electrodiagnostic testing, particularly in cases with discordant clinical findings. Emerging artificial intelligence-based segmentation models, such as Mask R-CNN algorithms, have demonstrated promising diagnostic accuracy³⁷; however, their performance may be reduced in cases involving rare or complex anatomical variants, reinforcing the continued importance of expert interpretation and multimodal imaging. Importantly, a considerable proportion of the included studies reported that the presence of BMN may influence surgical planning or increase the theoretical risk of incomplete decompression if not recognized preoperatively.^{16,19,22,33,41,53,63,72,79} Consequently, individualized anatomical assessment rather than reliance on standard surgical assumptions appears warranted in selected patients.

Relation with CTS

The etiological role of MN variants in CTS remains uncertain. While some studies suggest a potential association²² most evidence does not demonstrate a consistent independent relationship.^{30,32,47,73,79} Additional structures, including vascular and muscular variants, may contribute to local crowding; however, their overall prevalence in surgical populations appears low. Importantly, no study identified in this review implemented standardized imaging protocols specifically targeting variant detection. Although preoperative imaging may assist surgical planning,^{26,30,32,47,67,72} high-quality prospective evidence demonstrating improved clinical outcomes is lacking. Further studies are needed to determine whether systematic identification of anatomical variants translates into meaningful clinical benefit.

Embryological considerations

From an embryological perspective, the MN originates from fibers of the lateral (C5-C6) and medial (C8-T1) cords of the brachial plexus, which converge during early development.⁸⁹ Normally, the nerve continues as a single trunk through the CT before distal division. Variations in axonal fusion or differentiation may result in proximal bifurcation patterns.⁹⁰ These processes may be influenced by local developmental factors, including vascular persistence or accessory musculature, which can alter nerve trajectory and organization. Such mechanisms may contribute to the development of BMN, supporting its interpretation as a developmental variant rather than an acquired anatomical anomaly.⁹¹

Limitations

This review has several limitations that should be considered when interpreting the findings. First, the substantial heterogeneity observed across studies ($I^2 = 87\%$) reduces the precision of pooled prevalence estimates and reflects variability in study design, imaging modalities, anatomical dissection protocols, and population characteristics. Second, the absence of uniformly standardized definitions for BMN and other morphological variants may have introduced classification bias and limited cross-study comparability. Third, only English-language publications indexed in selected databases were included, which may have introduced language and publication bias. Although funnel plot inspection suggested only mild asymmetry, the statistically significant

Egger's regression test indicates the possibility of small-study effects; however, interpretation is limited in the presence of high heterogeneity. Finally, the absence of eligible prevalence data from Africa and Oceania restricts the global generalizability of the findings and highlights the need for geographically diverse anatomical investigations. Additionally, the use of the Freeman-Tukey transformation has been debated in recent methodological literature, which may influence interpretation of extreme prevalence estimates. Future studies adopting standardized reporting frameworks, such as recent recommendations in translational anatomy, may improve methodological consistency and strengthen future pooled analyses.

Conclusion

This systematic review and meta-analysis demonstrates that morphological variants of the MN within the CT are relatively common anatomical findings, with a pooled prevalence of 12%. Although these variants do not appear to constitute an independent risk factor for CTS, their coexistence with vascular or muscular anomalies may influence local anatomical relationships and surgical complexity. These findings underscore the importance of careful anatomical assessment and may assist in preoperative planning; however, their impact on clinical outcomes and intraoperative complications remains uncertain. Future studies adopting standardized reporting frameworks and incorporating clinical outcome measures are warranted to improve comparability and strengthen the evidence base.

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Data availability

The data supporting the findings of this study are available within the article and its Supplementary Materials. Additional extracted data are available from the corresponding author upon reasonable request.

Declaration of Generative AI and AI-assisted technologies in the manuscript preparation process

The authors used AI-assisted tools for language editing. All content was critically reviewed and approved by the authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article. All authors approved the final version of the manuscript.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.cpsurg.2026.102027](https://doi.org/10.1016/j.cpsurg.2026.102027).

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