Morphologie 108 (2024) 100770

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MORPHOLOGIE

GENERAL REVIEW

The mechanics of the collateral ligaments in the metacarpophalangeal joints: A scoping review

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KEYWORDS
Metacarpophalangeal ;
Collateral ligament ;
Biomechanics ;
Anatomy ;
Hand therapy

Summary
Background. — The metacarpophalangeal (MCP) joint's collateral ligaments have been extensively debated, with no clear consensus on their mechanics. Understanding their function is crucial for comprehending joint movement and stability.
Methods. — A thorough search was conducted across databases, including PubMed, Scopus, Cochrane library and grey literature. A total of 59 articles were identified, and after rigorous evaluation, six articles were included in the review.
Results. — The analysis underscores two principal findings. Firstly, the principal and accessory collateral ligaments exhibit consistent tension influenced by the MCP joint's position. This tension varies across different sections of the ligaments. Secondly, the ligaments' interaction with the joint structure plays a pivotal role in defining the range of motion of the joint.
Conclusion. — Preliminary findings from this review indicate that MCP joint collateral ligament tension varies with joint position. Increased tension in the principal collateral ligament during flexion and isometric behavior of its volar portion in extension are observed. The accessory ligament may tighten during extension. The shape of the metacarpal head appears to influence this tension. These insights, while informative, call for further detailed research to deepen our understanding of MCP joint mechanics.

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https://doi.org/10.1016/j.morpho.2024.100770

Introduction

Understanding the biomechanical properties of the metacarpophalangeal (MCP) joint and its collateral ligaments is crucial for comprehending hand function and joint stability [1,2]. The MCP joint, a pivotal element in hand mobility, is stabilized by two sets of ligaments: the principal collateral ligaments (PCL) and the accessory collateral ligaments (ACL) [3,4]. These ligaments play a vital role in allowing the joint to move through a range of motions while maintaining stability across various positions. Despite extensive research, interpretations of the biomechanical behavior of these ligaments in different joint positions vary, highlighting a gap in our collective understanding [5]. To address this gap, we present a comprehensive review focusing on the anatomical and biomechanical aspects of the MCP joint's collateral ligaments [6]. Our review aims to elucidate how these ligaments contribute to the joint's stability and motion under varus and valgus stresses, alongside other capsuloligamentous structures [7]. We propose the inclusion of a detailed figure (Fig. 1) illustrating the MCP joint and its collateral ligaments. This visual aid will provide readers with a clear understanding of the anatomical structures under review, emphasizing the significance of the PCL and ACL in joint mechanics. This introduction sets the stage for a scoping review that seeks to clarify the roles and biomechanical properties of the MCP joint's collateral ligaments, addressing the need for a more unified understanding of their function. By systematically examining the literature and synthesizing findings, we aim to contribute valuable insights into the mechanics of the MCP joint (Fig. 2), ultimately advancing both theoretical knowledge and practical applications [8] in hand therapy and surgery [3,4,9,10].

Methods

The present scoping review was conducted following the JBI methodology [11] for scoping reviews. The Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) [12] Checklist for reporting was used.

Review question

We formulated the following research question: ''How do the biomechanical properties of the metacarpophalangeal (MCP) joint respond to varus and valgus stress, and what roles do the radial and ulnar collateral ligaments, along with other capsuloligamentous structures, play in stabilizing the MCP joint in various modes of displacement?''.

Eligibility criteria

The eligibility criteria for inclusion of studies in this review were based on the Population, Concept, and Context (PCC) framework. In other words, studies were considered eligible if they met specific criteria related to the following aspects.

Population (P)

The studies focus on human cadaver samples and, in some cases, healthy adult volunteers. These subjects are relevant for understanding the anatomical and biomechanical properties of the metacarpophalangeal (MCP) joint and associated ligaments.

Concept (C)

The primary concept across these studies is the biomechanical analysis of the MCP joint, particularly under various conditions such as flexion, extension, varus, and valgus stress. The studies examine specific aspects like ligament stability, length changes, and biomechanical properties of collateral and accessory collateral ligaments.

Context (C)

The context for these studies is largely biomechanical and anatomical research, with a focus on understanding the MCP joint's functionality and stability. The methodologies involve cadaveric analysis, microcomputed tomography, load-displacement tests, and other biomechanical testing techniques.

Exclusion criteria

Studies that did not meet the specific PCC criteria were excluded.

Search strategy

The literature search for this review was meticulously conducted using prominent databases including PubMed, ScienceDirect, Google Scholar, and the Cochrane Library. To broaden our search and include unpublished or ongoing studies, we also explored grey literature through ClinicalTrials.gov and the Prospero databases. The search was initiated in January 2022 and was inclusive of all relevant works, irrespective of their date of publication. Our search focused on gathering comprehensive data regarding the anatomy and biomechanics of the metacarpophalangeal (MCP) joint, with a specific emphasis on its collateral ligaments. We aimed to understand both the structural anatomy and the mechanical properties of these ligaments to get a complete picture of their function and significance in joint stability and motion.

(''metacarpophalangeal joint'' OR ''MCP joint'') AND (''collateral ligaments'' OR ''principal collateral ligament'' OR ''PCL'' OR ''accessory collateral ligament'' OR ''ACL'') AND (''mechanics'' OR ''ligament tension'' OR ''joint stability'' OR ''flexion-extension'' OR ''abduction-adduction'' OR ''axial rotation'' OR ''ligament function'' OR ''joint conformation'' OR ''ligament length'' OR ''ligament dynamics'')

Study selection

From our extensive database search, we initially retrieved 59 papers. Implementing a duplicate elimination strategy streamlined this pool to 33 relevant papers. Our evaluation of these papers involved a two-tiered process. Initially, we

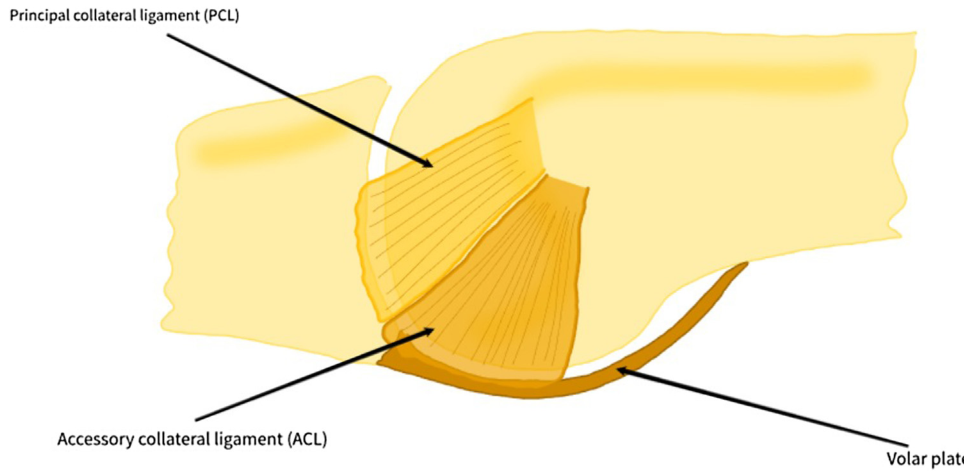

Figure 1 Metacarpophalangeal (MCP) joint.

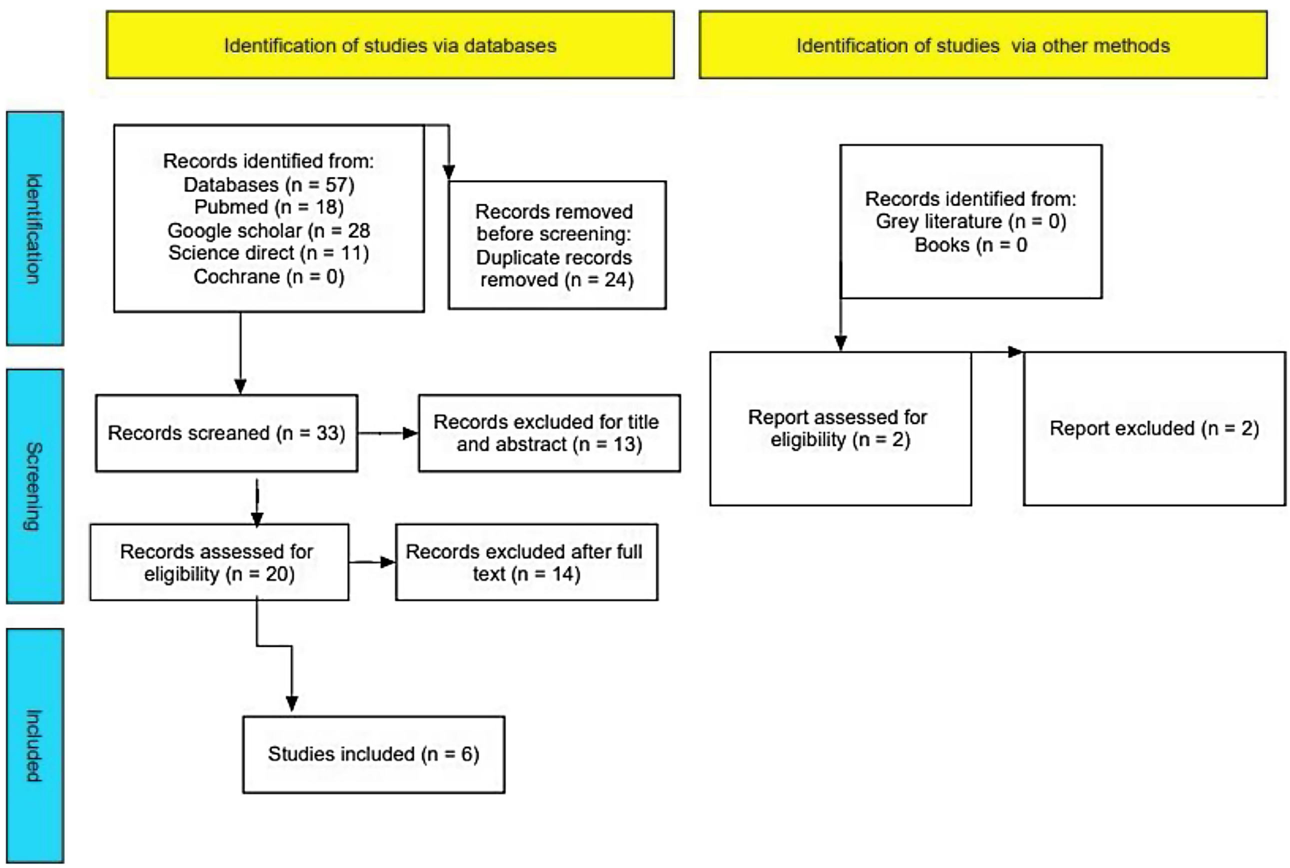

Figure 2 This graph amalgamates findings from three pivotal studies (Sun et al., Kataoka et al., Minami et al.) to illustrate the elongation patterns of the main collateral ligament's dorsal and intermediate portions under varus and valgus stresses. Each point represents mean elongation measurements in millimeters, derived from dynamic assessments during MCP joint flexion and extension. The studies utilized advanced imaging and biomechanical testing to quantify ligament elongation, offering insights into the MCP joint's response to stress. This figure aims to visually summarize the complex interplay between ligament tension and joint position, highlighting the critical role of collateral ligaments in joint stability.

reviewed titles and abstracts, focusing on their alignment with our research objectives. This step led to the exclusion of 13 papers, primarily due to their lack of specificity to our study's focus.

We then conducted a thorough analysis of the full texts of the remaining 20 papers. This deeper dive resulted in the exclusion of 14 more papers, mainly due to their peripheral focus on the general mechanics of the MCP joint

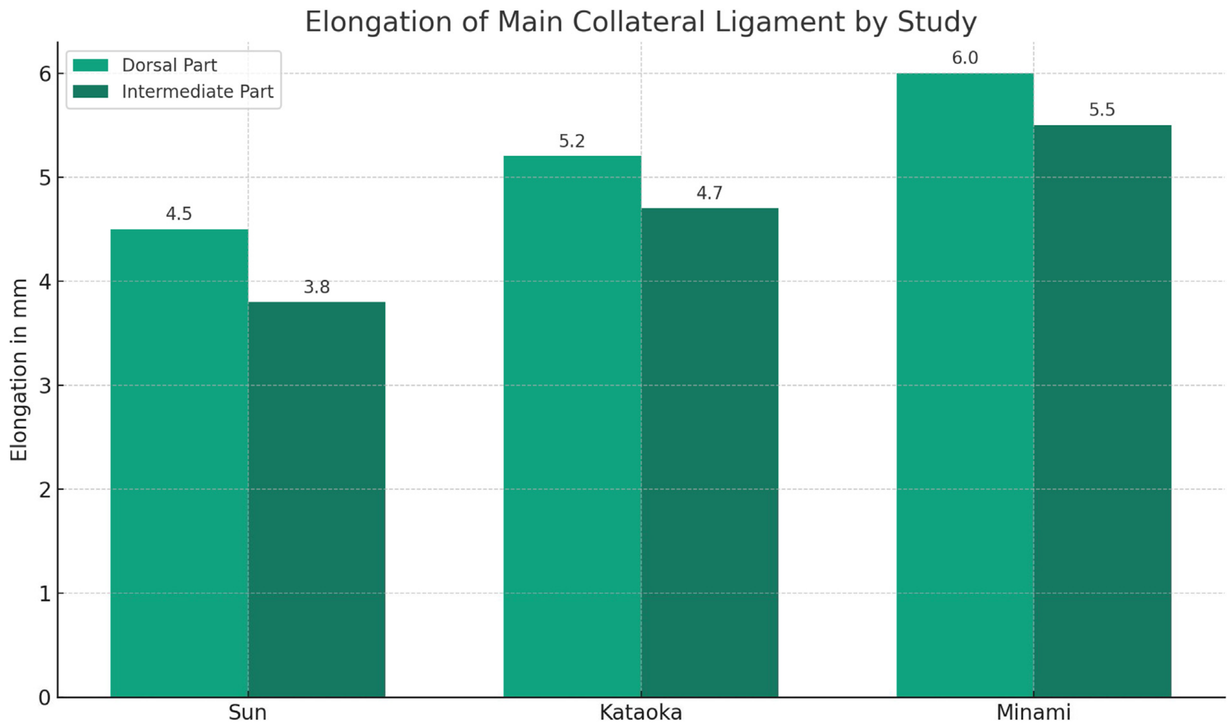

Figure 3 Prisma-SRC flowchart.

or load dynamics of peri-articular structures. After this comprehensive and stringent selection process, six studies were identified that thoroughly met our criteria and were thus included in our review. These selected studies collectively provide an in-depth understanding of the MCP joint's anatomical and biomechanical properties and the critical functional roles and interactions of its collateral ligaments (refer to Fig. 3 for a summary).

Results

As presented in the PRISMA 2020-flow diagram (Fig. 3), from 57 records identified by the initial literature searches, 51 were excluded and 6 articles were included (Table 1).

Sun et al. (2017)

This study utilized computed tomography scans of fingers from six healthy volunteers. It found that the dorsal and middle portions of both the radial and ulnar collateral ligaments lengthened during flexion, reaching their maximum length at 90° of flexion. The volar portion of these ligaments increased in length from 0° to 30° of flexion and then decreased, reaching its minimum length at 90° of flexion.

Schultz et al. (1987)

Employing a triaxial spatial goniometer, computer modeling, and anatomical studies, this research concluded that the MCP joint possesses an instant axis with two degrees of freedom. The study observed that the collateral ligament remains taut in all joint positions, thus supporting joint motion and stability.

Werner et al. (2003)

Through testing MCP joints from nine cadaver hands, the study revealed that the index and long fingers showed a significant decrease in collateral ligament laxity between 0° and 90° of flexion. However, there was no notable change in collateral ligament stiffness across MCP joint flexion, except for a late increase in radial collateral ligament stiffness in the long finger between 0° and 60° of flexion.

Minami et al. (1985)

This biomechanical study involved load-displacement tests on joints from 15 human cadavers. It concluded that both radial and ulnar collateral ligaments are primary stabilizers of the MCP joint in all modes of displacement. The accessory collateral ligaments primarily contribute to abduction-adduction rotational stability but offer little in stabilizing dorsopalmar dislocation or axial rotations. The study also noted that the palmar plate prevents dorsal dislocation only at full extension, while the dorsal capsule moderately contributes to stability.

Minami et al. (1984)

Using gross examination and biplanar radiographic techniques on human cadaver specimens, this study discovered that the dorsal and volar portions of the collateral ligament provide constraint at both flexed and extended positions of

Table 1 Main characteristics of included studies.

Author(s)	Year	Title	Type of study	Methods	Outcome
Sun et al. [9]	2017	*In vivo metacarpo-phalangeal joint collateral ligament length changes during flexion*	Observational study	Computed tomography scans of fingers from six healthy adult volunteers	Dorsal and middle portions of radial and ulnar collateral ligaments lengthened during flexion, reaching maximum at 90° flexion. Volar portion increased from 0° to 30° then decreased, reaching minimum at 90° flexion
Schultz et al. [5]	1987	*Metacarpophalangeal joint motion and the role of the collateral ligaments*	Observational study	Triaxial spatial goniometer, computer model, anatomical study	Metacarpophalangeal joint has an instant axis with two degrees of freedom; collateral ligament is taut in all positions, supporting joint motion and stability
Werner et al. [13]	2003	*The Biomechanical Properties of the Finger Metacarpo-phalangeal Joints to Varus and Valgus Stress*	Observational study	Testing of MCP joints from 9 cadaver hands	Index and long fingers showed significant decrease in collateral ligament laxity between 0° and 90°. No significant change in collateral ligament stiffness across MCP joint flexion except in late radial collateral ligament stiffness of the long finger between 0° and 60°
Minami et al. [14]	1985	*Ligament stability of the metacarpo-phalangeal joint: A biomechanical study*	Observational study	Load-displacement tests on joints of 15 human cadavers	Both radial and ulnar collateral ligaments play primary roles in stabilizing the metacarpophalangeal joint in all modes of displacement. The accessory collateral ligaments contribute primarily to abduction-adduction rotational stability but little to stabilizing dorsopalmar dislocation or axial rotations. The palmar plate prevents dorsal dislocation only at full extension, and the dorsal capsule moderately contributes to stability

Table 1 (*Continued*)

Author(s)	Year	Title	Type of study	Methods	Outcome
Minami et al. [15]	1984	*Ligamentous Structures of the Metacarpophalangeal Joint: A Quantitative Anatomic Study*	Observational study	Gross examination and biplanar radiographic techniques on human cadaver specimens	The study found that the dorsal and volar portions of the collateral ligament provide constraint at the flexed and extended positions of the MCP joint. The collateral ligament is separable into two layers and changes length in different portions when the joint is moved from hyperextension to flexion. Specifically, the dorsal portions of the radial and ulnar collateral ligaments lengthen during flexion, while the middle portions elongate slightly, and the volar portions shorten. The study has clinical relevance in understanding extension contracture at the MCP joint and designing prosthetics
Kataoka et al. [4]	2011	*Changes in Shape and Length of the Collateral and Accessory Collateral Ligaments of the Metacarpophalangeal Joint During Flexion*	Observational study	Examination of 12 fingers from three cadavers using microcomputed tomography, creating three-dimensional models, and calculating changes in ligament shape and length during flexion	Contact region of each collateral ligament with the metacarpal increased during flexion; dorsal and middle portions of each collateral ligament became taut in flexion; volar portion of each accessory collateral ligament became taut only in extension

DC: dorsal capsule, MCP: metacarpophalangeal, MTS: material testing system, RCL: radial collateral ligament, VCL: ulnar (volar) collateral ligament.

the MCP joint. The study highlighted that the collateral ligament can be separated into two layers and changes in length at different portions as the joint moves from hyperextension to flexion.

Kataoka et al. (2011)

By examining 12 fingers from three cadavers using micro-computed tomography and creating three-dimensional models, this study found that the contact region of each collateral ligament with the metacarpal increased during flexion. It also observed that the dorsal and middle portions of each collateral ligament became taut in flexion, while the volar portion of each accessory collateral ligament became taut only in extension.

Discussion

In this review, we have critically analyzed six studies to delineate the unique conformation of the metacarpophalangeal (MCP) joint, moving beyond traditional classifications of it being solely a glenoid or trochlear joint. Our analysis underscores the MCP joint's distinct anatomical features, notably the circular shape of its dorsal head and the bicondylar formation of its volar portion, which significantly differentiate it from other joint structures. This unique conformation facilitates enhanced mobility at the base of the first phalanx (P1) while concurrently acting as a movement restrictor in certain aspects. Schultz's [5] research, pivotal in this context, demonstrates a significant decrease in varus-valgus movement beyond 70° flexion of the MCP joint, thereby affirming its distinct joint conformation. The trapezoidal contour of the MCP head, observed in the transverse plane, plays a crucial role in elongating the collateral ligaments as they navigate the lateral aspects of the head. This feature is instrumental in the ligaments' tension dynamics, consistent across various positions of the MCP joint, as echoed by the consensus among the reviewed studies. The dynamics of the MCP joint's collateral ligaments mirror those observed in the proximal interphalangeal joint's ligaments, exhibiting position-dependent tension. Notably, the principal collateral ligament is under increased tension in its dorsal and intermediate portions during flexion, whereas the volar portion remains consistently taut. The accessory ligament exhibits a contrasting tension pattern, primarily in its volar and intermediate bundles during extension. However, the persistent tension across these ligament structures raises questions about the feasibility of varus-valgus movement during extension. The spherical configuration of the MCP head in its extended state potentially allows for greater articulation, counterbalancing the tension in the ligaments. In contrast, flexion, characterized by the bicondylar shape of the head and increased contact between the articular surfaces, appears to restrict abduction-adduction movement, a notion supported by Kataoka's 3D [4,16] reconstruction and reinforced by Pagowski's mathematical modeling.

In conclusion, the biomechanical properties of the MCP joint under varus and valgus stress are intricately linked to the functionality and integrity of the radial and ulnar collateral ligaments, along with other capsuloligamentous structures. These elements work cohesively to stabilize the MCP joint, ensuring its resilience and flexibility across various modes of displacement. This intricate interplay is essential for maintaining joint stability, allowing for a wide range of hand movements while preventing injury. The findings underscore the critical roles of these ligaments in joint biomechanics, offering insights into therapeutic strategies for joint stabilization and rehabilitation.

Limitations of the study

Scope of literature

The review's focus on only six papers may not fully encompass the breadth of existing knowledge on MCP joint mechanics.

Diversity of methodologies

The heterogeneous nature of study designs complicates the synthesis of findings.

Consensus in literature

The divergent perspectives in existing literature necessitate cautious interpretation of the findings.

Methodological constraints

The limitations inherent in the methodologies of the individual studies might impact the generalizability of our conclusions.

Temporal scope

The review's reliance on literature available only up to September 2021 might omit recent developments in the field.

Clinical translation

The direct applicability of our findings to clinical practice remains speculative, underlining the need for further research.

Strengths of the study

Literature search rigor

The comprehensive approach to literature search ensures a broad collection of relevant articles.

Inclusion of varied perspectives

The study benefits from the integration of diverse viewpoints.

Focus on ligament dynamics

A meticulous analysis of the MCP collateral ligaments' mechanics forms the crux of our review.

Evidence integration

The amalgamation of biomechanical experiments and 3D modeling techniques enriches the discussion.

Identification of knowledge gaps

The review effectively highlights areas needing further exploration, contributing to the advancement of the field.

Conclusions

In conclusion, our review delineates the intricate biomechanical responses of the metacarpophalangeal (MCP) joint to varus and valgus stresses, spotlighting the pivotal roles of the radial and ulnar collateral ligaments alongside other capsuloligamentous structures in stabilizing the joint. These findings underscore the ligaments' essential contribution to the joint's stability and range of motion, highlighting the need for further detailed exploration into their specific mechanics and interactions. Despite the broad understanding of the MCP joint's conformation and ligament tension's importance, this review identifies gaps in current knowledge, advocating for targeted research to unpack the nuanced dynamics of ligament function within MCP joint biomechanics. This focused inquiry is crucial for advancing our comprehension of joint stability mechanisms, potentially informing more effective treatment strategies for MCP joint-related pathologies.

Availability of supporting data

The protocol and the dataset analyzed during the current study is available from the corresponding author on reasonable request.

Disclosure of interest

The authors declare that they have no competing interest.

Funding

No external funding.

Author contributions

All authors read and approved the final version of the manuscript.

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