Review paper

Cite as: Pacella G, Bruno M, Liguori L, Pascale A, Natella R, Zappia M: Microvascular flow imaging in musculoskeletal ultrasound: from technical innovation to clinical integration. J Ultrason 2026; 26: 6. doi: 10.15557/JoU.2026.0006.

Submitted:
19.11.2025
Accepted:
23.02.2026
Published:
31.03.2026

Microvascular flow imaging in musculoskeletal ultrasound: from technical innovation to clinical integration

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DOI: 10.15557/JoU.2026.0006

Keywords

musculoskeletal ultrasound; rheumatic diseases; Power Doppler; microvascular technologies; microvascular flow imaging

Abstract

Recent advances in Doppler ultrasound have led to the development of microvascular flow imaging, a technique designed to overcome the limitations of color and Power Doppler in detecting slow, small-vessel flow. This narrative review summarizes the technical foundations, clinical applications, and emerging perspectives of microvascular technologies in musculoskeletal ultrasound, emphasizing their role as a bridge between morphological and functional imaging. Microvascular flow imaging employs spatiotemporal clutter-suppression algorithms and high-frame-rate acquisition to visualize low-velocity blood flow within capillaries smaller than 100 μm, without the need for contrast agents. The method enhances detection of microvascularity in tendons, synovium, and peripheral nerves, providing early indicators of inflammatory or degenerative activity. Proprietary vendor implementations share the same physical principles but differ in algorithmic filtering and signal rendering. Clinically, microvascular flow imaging has demonstrated superior sensitivity compared with Power Doppler for detecting subclinical synovitis, assessing tendinopathies, and evaluating entrapment neuropathies, offering both quantitative and prognostic insights. Although microvascular flow imaging improves diagnostic sensitivity and supports dynamic, contrast-free assessment of tissue perfusion, its routine implementation remains limited by the absence of standardized acquisition protocols, validated quantitative metrics, and inter-vendor harmonization. Ongoing research into AI-based vascular quantification and portable point-of-care systems may enhance reproducibility, accessibility, and integration into everyday musculoskeletal imaging. Overall, microvascular flow imaging represents a pivotal step toward functional musculoskeletal ultrasound, with expanding diagnostic, prognostic, and theranostic potential.

Introduction

Doppler ultrasound has long been a cornerstone of musculoskeletal (MSK) imaging, allowing dynamic assessment of tissue perfusion and inflammatory activity. However, both color Doppler and Power Doppler (PD) remain limited in their ability to detect very slow or microvascular flow due to wall-filter suppression and motion artifacts. Microvascular flow imaging (MVFI) was developed to overcome these constraints, providing high-sensitivity, real-time visualization of capillary-level perfusion without the use of contrast agents. The following section describes the technical principles, optimization parameters, and clinical implications of this technology(1).

Technical principles of microvascular flow imaging

MVFI represents a major advancement in Doppler ultrasound technology, designed to overcome the inherent limitations of conventional color Doppler and PD in detecting very low-velocity blood flow. Traditional Doppler techniques rely on wall filters to suppress low-frequency motion artifacts ("clutter") generated by tissue movement. However, this process also inadvertently removes genuine microvascular signals arising from slow capillary perfusion. MVFI employs a fundamentally different approach based on spatiotemporal clutter-suppression algorithms that separate true blood flow signals from background tissue motion by comparing consecutive high-frame-rate images(2). This frame-to-frame subtraction technique isolates the dynamic signatures of red blood cell motion while retaining flow information even in vessels with diameters below 100 μm and velocities under 1 cm/s. The result is a highly sensitive, noncontrast method capable of depicting the microcirculatory network within tendons, synovium, and peripheral nerves. From a technical standpoint, MVFI requires careful optimization of acquisition parameters to achieve maximal sensitivity without sacrificing image stability. A low pulse repetition frequency (PRF), typically between 0.4 and 1.0 kHz, and a minimal wall filter are required to preserve slow-flow signals. High-frequency linear transducers (10–18 MHz for musculoskeletal applications, and up to 24–30 MHz for superficial structures) provide the axial resolution necessary to delineate fine vascular channels while maintaining frame rates exceeding 40 frames per second, which helps prevent motion-related noise. Transducer pressure should be minimal, as capillary compression can easily eliminate detectable flow. A stable region of interest (ROI) with a recording time of at least three seconds is recommended to ensure consistent perfusion assessment. These adjustments collectively enhance the signal-to-noise ratio and permit reliable visualization of physiologic microvascular flow(3).

Technically, MVFI signals are derived from amplitude modulation rather than frequency shift, enabling visual representation of very low-velocity flow regardless of insonation angle. Because the algorithm operates without exogenous contrast and with real-time motion suppression, MVFI combines the sensitivity of contrast-enhanced ultrasound with the convenience of routine Doppler acquisition. The technology thus allows detection of capillary-level neovascularization associated with early synovitis, low-grade inflammation in tendinopathy, and intraneural hyperemia in compressive neuropathies – all of which may remain occult on PD imaging(4). However, as sensitivity increases, establishing standardized reference values for normal perfusion and achieving inter-vendor harmonization of acquisition settings have become new technical priorities for multicenter reproducibility.

Clinical impact and optimization strategies in musculoskeletal applications

Doppler ultrasound (US) plays a critical role in many facets of MSK imaging, including the diagnosis and monitoring of inflammatory arthropathies, and the assessment of neoplasms, tendinopathies, pulley lesions, and neuropathies(5), and relying on the capability and ease of use of real-time evaluation in blood flow differences, also in the rapid comparison between pathological findings and the healthy control(6). The clinical relevance of MVFI in musculoskeletal ultrasound lies in its ability to bridge the sensitivity gap between conventional PD and contrast-enhanced techniques. By revealing submillimeter vascular networks in real time, MVFI enables earlier and more precise characterization of inflammatory, degenerative, and compressive disorders in which tissue perfusion serves as a biomarker of activity(7).

In inflammatory arthropathies, MVFI demonstrates superior sensitivity for detecting synovial hyperemia and capillary proliferation compared with PD, allowing discrimination between active pannus and fibrotic inactive synovium. Quantitative or semiquantitative scoring of microvascular signal intensity may correlate with serum inflammatory markers, thereby assisting in disease monitoring and assessment of treatment response(8). In tendinopathies, visualization of intratendinous neovessels offers a direct marker of disease chronicity and pain severity, supporting tailored management strategies such as biologic injection or load modulation. Similarly, in entrapment neuropathies, the ability to depict intraneural or perineural hypervascularity precedes morphologic nerve enlargement, providing an earlier diagnostic window and complementary information to nerve conduction studies. For optimal results, acquisition parameters should be adapted to the anatomic region and the pathology under evaluation. Superficial tendons, pulleys, and small joints benefit from high-frequency probes (≥14–18 MHz) and minimal wall filters, whereas deeper structures such as the shoulder capsule or hip entheses require lower frequencies (7–12 MHz) with an appropriate balance between penetration and spatial resolution. The PRF must be kept as low as possible to capture slow perfusion signals without inducing aliasing, and the dynamic range should be sufficiently wide to preserve gradations of vascular intensity. For quantitative analysis, the vascular index (VI%) = (number of color pixels / total ROI pixels) × 100 can be calculated using the mean of three acquisitions obtained at peak perfusion. Gain, PRF, and wall filter settings should be kept identical between baseline and follow-up examinations to ensure comparability. To minimize false-positive signals, mechanical stabilization of the probe and gentle coupling are crucial, particularly when scanning highly compliant structures such as synovium or nerve sheaths. When consistently applied, these technical strategies allow MVFI to serve not only as a qualitative imaging tool but also as a quantitative biomarker of microvascular remodeling, potentially integrating into composite scoring systems for disease activity in rheumatology and sports medicine(9,10). A comprehensive guide to suggested optimization parameters is provided in Tab. 1.

Several proprietary MVFI methods have been developed by different manufacturers; thus, similar techniques may be encountered in the literature under various names(11). All systems share the same core principle of adaptive clutter reduction, very low PRF, minimal wall filtering, and high-frequency imaging for superficial tissues:

- Canon Medical Systems (superb microvascular imaging, SMI)
- Samsung Medison (MV-Flow™)
- Philips Healthcare (microflow imaging, MFI)
- Mindray (MvFlow)
- GE (Slow Flow / SMI – prototype)
- Hitachi Aloka (advanced microvascular imaging, AMI)
- Esaote (XFlow / MicroV)

Clinical applications

Rheumatic diseases

Arthritis encompasses a heterogeneous group of rheumatic disorders characterized by joint inflammation, pain, stiffness, and progressive limitation of motion. The most prevalent entities include osteoarthritis(12), rheumatoid arthritis (RA), psoriatic arthritis, and crystal-induced arthropathies such as gout and calcium pyrophosphate deposition, each with distinct pathophysiologic mechanisms, clinical manifestations, and imaging features. Osteoarthritis is primarily a degenerative joint disease, marked by articular cartilage degradation, osteophyte formation, and subchondral bone sclerosis, typically affecting weight-bearing joints and exhibiting a predominantly non-inflammatory profile(13). In contrast, rheumatoid arthritis is a systemic autoimmune disease characterized by chronic

Tab. 1. Practical optimization parameters for microvascular flow imaging (MVFI) in musculoskeletal ultrasound

Parameter	**Proposed setting**	**Rationale / Notes**
Probe type	Linear high-frequency transducer	High spatial resolution of superficial structures
Recommended frequency	• 14–18 MHz: superficial tendons and small joints • 8–12 MHz: medium-sized joints and shoulder • 6–9 MHz: deep bursae or hip region	Balance between resolution and penetration according to depth
Pulse repetition frequency (PRF)	0.4–1.0 kHz	Maximizes sensitivity to very-low-velocity flow; avoid aliasing by slight upward adjustment if necessary
Wall filter[11]	Minimal or "low"	Preserves slow-flow signals otherwise eliminated by clutter suppression
Gain	Increased gradually until noise just appears, then reduced by 2–3 dB	Ensures optimal signal-to-noise ratio without blooming artifacts
Frame rate	≥40 frames/s	Allows stable motion subtraction and high temporal resolution
Dynamic range	Wide (60–70 dB)	Preserves subtle gradations in microvascular signal intensity
Persistence/compounding	Low to moderate	Prevents temporal blurring of fast microflow variations
Transducer pressure	Minimal, avoid tissue compression	Excessive pressure collapses capillaries and suppresses flow
Region of interest (ROI)	Fixed field (≈ 1 cm^2 for small joints, 5 × 5 mm for intratendinous assessment); acquisition ≥3 s	Enables reproducible quantification and averaging of perfusion
Patient positioning	Relaxed, muscles at rest, avoid tendon tension	Reduces motion artifacts and physiologic compression
Documentation	Save ≥3 cine loops and static frames per site with parameters displayed	Facilitates reproducibility and quantitative vascular index computation

synovial inflammation, which, if untreated, may lead to progressive joint destruction and deformity(14). Psoriatic arthritis, commonly associated with cutaneous psoriasis, typically exhibits a mixed pattern of axial and peripheral joint involvement, accompanied by enthesitis and dactylitis (Fig. 1)(15). Gout, a metabolic arthropathy, results from intra-articular deposition of monosodium urate crystals and classically presents as acute monoarthritis(16).

In psoriatic disease, ultrasound assessment of the nail unit can quantify nailfold microvascular changes and correlates with videocapillaroscopy findings, underscoring the role of microvascular imaging as a biomarker(17). Musculoskeletal ultrasound (MSK-US) has become an indispensable imaging modality for evaluating arthritis. It is non-invasive, cost-effective, and enables real-time dynamic assessment of articular and periarticular structures. Ultrasound is particularly sensitive in detecting synovial hypertrophy, joint effusions, and erosions, even at early stages of disease(18). When complemented by Doppler techniques, it allows visualization of synovial vascularization, which correlates closely with inflammatory activity(19). In rheumatoid arthritis, Doppler ultrasound plays a crucial role in evaluating disease activity and therapeutic response. In psoriatic arthritis, it facilitates differentiation between synovial and entheseal involvement. In gout, it identifies pathognomonic findings, such as the double-contour sign and intra-articular tophi. In osteoarthritis, ultrasound aids in the detection of osteophytes and may assist image-guided intra-articular procedures. The integration of grayscale

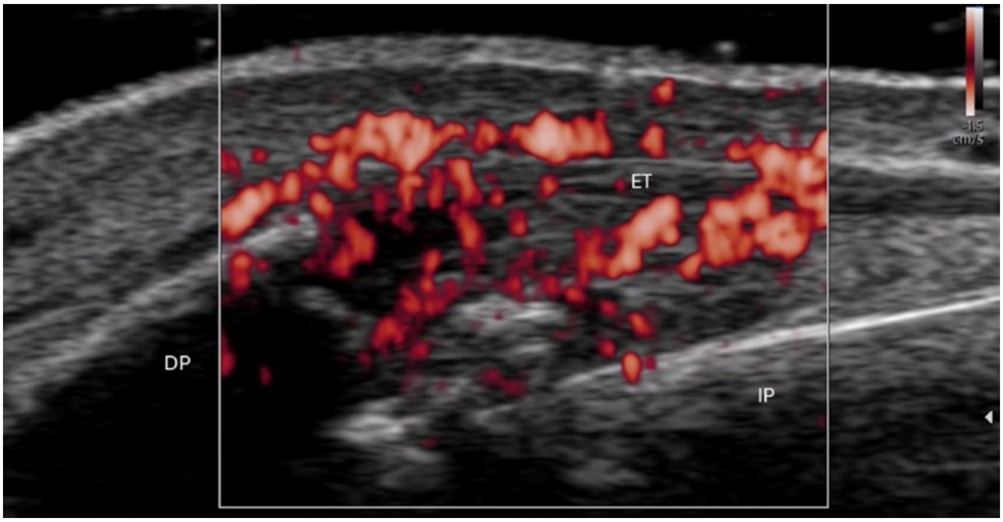

Fig. 1. *Long-axis US scan of distal interphalangeal joint with microvascular flow (MVFI). MVFI image shows diffuse vascularization of the synovial membrane, extensor enthesis, and subcutis. IP – intermediate phalanx; DP – distal phalanx; ET – extensor tendon*

and Doppler ultrasound into rheumatologic workflows has markedly enhanced diagnostic accuracy, enabled earlier intervention, and improved disease monitoring. More recently, microvascular technologies (MVTs) have significantly expanded this diagnostic landscape by increasing sensitivity for subclinical synovial inflammation. Evidence regarding the acromioclavicular joint is limited but supportive: in a prospective series of 134 symptomatic joints – including two acromioclavicular joints – MVFI detected vascularity in 30% of joints that were PD-negative. When both modalities were positive, the vascular signal was more conspicuous with MVFI, indicating superior sensitivity for low-grade synovitis(20). According to Lim et al.(21), superb microvascular imaging(22) revealed synovial flow undetected by PD in over 30% of examined joints, yielding significantly higher vascular-visibility scores. A systematic review by Oo et al.(10) corroborated the value of SMI for early detection of arthritis and monitoring of therapeutic response. In a separate study, Lee et al.(9) reported that MVFI exhibits superior sensitivity for detecting synovial inflammation under routine clinical conditions. Importantly, MVFI identified persistent synovitis in at least one joint even among patients in clinical remission, underscoring its potential to detect subclinical disease activity(23,24). Wang et al.(25) further explored MVFI in the assessment of the synovial sheath of extensor tendons, demonstrating its value in the early diagnosis of seronegative RA and tenosynovitis, as well as in evaluating disease activity, remission status, and therapeutic efficacy. Zhong et al.(26) investigated the use of MVFI in differentiating rheumatoid arthritis from pigmented villonodular synovitis (PVNS), reporting that joint effusion occurred more frequently in PVNS, whereas synovial hyperplasia predominated in RA. Finally, Alis et al.(27) demonstrated the superiority of SMI over PD in visualizing blood flow within hypertrophied synovial tissue of the knee in patients with clinically active juvenile idiopathic arthritis, emphasizing its enhanced diagnostic performance in pediatric rheumatology. Beyond inflammatory arthritis, MVFI has also shown promise in osteoarthritis, where assessment of subchondral and capsular microvasculature may aid in stratifying disease severity. Recent studies have highlighted a significant correlation between vascular patterns detected by MVFI and clinical indices of pain and functional disability, suggesting that microvascular activity may serve as an imaging biomarker of symptomatic osteoarthritis progression(28).

Regarding the follow-up of patients with inflammatory arthritis in clinical remission, consecutive and complementary studies by Kurtulus et al.(29,30) demonstrated that SMI(22) not only detects significantly more synovial vascular signals than Doppler ultrasound, but also correlates strongly with disease activity in rheumatoid arthritis. These findings suggest superior sensitivity for subclinical synovitis and support the potential role of SMI as a reliable imaging biomarker of disease activity. A comprehensive review of typical MVFI findings is provided in Tab. 2.

Tendinopathies(31)

Tendinopathies, especially lateral epicondylitis, patellar tendinopathy, and Achilles tendinopathy, are among the most common musculoskeletal disorders, frequently resulting from overuse, repetitive microtrauma, and degenerative alterations. Although traditionally regarded as non-inflammatory conditions, recent evidence highlights the pivotal role of neovascularization and accompanying sensory nerve ingrowth, underscoring their contribution to the pathogenesis of chronic tendon pain(32). Microvascular technolo-

Tab. 2. MVFI findings in rheumatic diseases

Condition	MVFI	Relevance
Rheumatoid arthritis (RA)	• Synovial microvascular signal within hypertrophic pannus, extending to the bone–cartilage interface • Increased vascular density even when Power Doppler is negative • Residual microvascular flow in clinically remitted joints	Indicates active synovitis and neoangiogenesis; predicts erosive progression and relapse; enables detection of subclinical inflammation and monitoring of therapeutic response
Seronegative RA / Early tenosynovitis	• Peritendinous microvascular flow along extensor tendon sheaths • Fine perisynovial capillary network	Reflects early inflammatory tenosynovitis and supports the diagnosis of seronegative or early RA before erosive damage
Psoriatic arthritis (PsA)	• Hypervascularity at enthesis and adjacent bone cortex • Combined synovial and perientheseal microflow signals	Reflects enthesitis and mixed axial–peripheral inflammation; differentiates PsA from RA; useful for biologic therapy monitoring
Juvenile idiopathic arthritis (JIA)	• Prominent synovial microvascular flow, especially in the knees • Higher vascular density compared with Power Doppler	Improves sensitivity for active disease detection and therapy adjustment in pediatric rheumatology
Pigmented villonodular synovitis (PVNS)	• Coarse, heterogeneous vascular pattern • Effusion more frequent; synovial hyperplasia less pronounced than in RA	Helps differentiate PVNS from RA; effusion predominance favors PVNS, while dense synovial vascularity favors RA
Gout	• Absent or minimal intratophus flow; possible mild peripheral flow during acute flare	Differentiates crystal deposition from inflammatory pannus; confirms the non-neovascular nature of gouty tophi
Osteoarthritis (13)	• Mild to moderate microvascular flow in capsular or perimeniscal tissues • Focal subchondral hyperemia adjacent to osteophytes	Reflects low-grade synovial or capsular inflammation; vascularity correlates with pain and functional disability
Clinical remission	• SMI detects more joints with synovial flow and higher semiquantitative vascularity scores compared with Power Doppler • Correlates moderately with DAS-28 and strongly with Power Doppler across baseline and follow-up	Confirms superior sensitivity of SMI for subclinical synovitis and its validity as a quantitative imaging biomarker of disease activity and remission

gies, which represent advanced Doppler-based techniques, enable detection of low-velocity, small-caliber blood flow within soft tissues. Compared with conventional PD, MVFI provides higher flow sensitivity and spatial resolution without the need for contrast administration, making it particularly well suited for identifying subtle vascular alterations in tendinopathies(1–3). In lateral epicondylitis, MVFI has shown superior capability in depicting neovessels at the common extensor tendon origin, often correlating with clinical symptom severity. Tanaka et al.(33) demonstrated that superb microvascular imaging(22) not only enhanced visualization of intratendinous vascularity compared with PD, but also provided quantitative parameters correlating with clinical scores, thereby supporting its role in disease staging and treatment monitoring. Similarly, Pang et al.(34) observed that changes in vascular signal intensity after platelet-rich plasma (PRP) injection could be objectively tracked using MVFI, underscoring its value in monitoring regenerative and interventional therapies.

Research on PRP has been conducted in both acute and chronic wound healing, demonstrating its capacity to act as both a promoter and a suppressor of the healing process, particularly regarding vascularization. In acute musculoskeletal injuries, PRP may expedite healing by promoting early revascularization(35–38). The release of growth factors, including platelet-derived growth factor, plays a crucial role, as these factors support cell proliferation, vascularization, and tissue regeneration(39). In chronic conditions, however, sustained hypervascularization, characterized by excessive development of new blood vessels, may signify pathology rather than healing if it persists beyond 12–24 weeks(40–43). Unfortunately, the correlation between PRP injection therapy and MVFI-based monitoring lacks robust data in the literature and requires future studies for a clear definition. In patellar tendinopathy (jumper's knee), MVFI has proven valuable for evaluating symptomatic athletes involved in jumping sports. Zordo et al.(44) reported that SMI enabled early detection of intratendinous microvascular flow, even in cases where B-mode ultrasound showed no structural abnormalities. The presence and degree of neovascularization, as detected by SMI, were significantly associated with pain intensity and functional limitation, suggesting that MVFI may serve as a biologic marker of disease activity and help guide therapeutic decision-making. Achilles tendinopathy represents another area in which MVTs demonstrate substantial clinical utility. Klauser et al.(45) showed that SMI provided sharper delineation of neovessels in the mid-portion of the Achilles tendon compared with PD, improving diagnostic confidence and longitudinal monitoring (Fig. 2). Moreover, MVFI enabled differentiation between active tendinopathy, characterized by pronounced vascularity, and chronic degenerative forms, which typically lacked detectable flow.

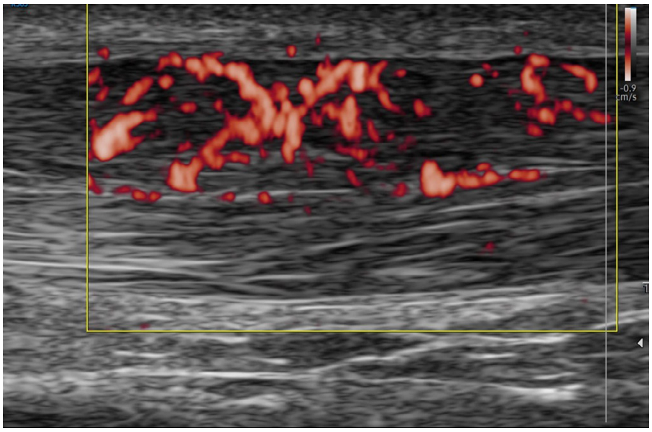

Fig. 2. *Achilles tendon – long-axis US scan. The MVFI demonstrates low-velocity intratendinous and peritendinous microvascularity consistent with neovascularization in symptomatic Achilles tendinopathy*

In trigger finger, Doppler ultrasound often reveals flow at the A1 pulley, indicating hypervascularity of the flexor sheath. Reported detection rates range from ~60% to 91%(46,47). Sato et al. aimed to determine whether hypervascularity of the A1 pulley detected on color Doppler correlates with clinical symptoms in trigger finger. They found that Doppler-detected hypervascularity was associated with patient-reported pain (Fig. 3)(48).

In our experience, MVFI is more sensitive than PD in this setting. Beyond trigger finger, microvascular techniques (e.g., SMI/MVFI) are also useful in other tendon disorders – such as De Quervain tenosynovitis – by depicting tiny intralesional vessels and very low-velocity flow that conventional PD may miss; an example of MVFI in De Quervain tenosynovitis is shown in Fig. 4(49).

Rotator cuff (RC) tendinopathy is a clinical syndrome characterized by pain, functional impairment, and reduced exercise tolerance of the shoulder with primarily degenerative rather than inflammatory tendon changes. The RC comprises the supraspinatus, infraspinatus, subscapularis, and teres minor muscles(50).

One of the underlying mechanisms of tendon degeneration is intratendinous hypovascularity(51), in contrast to peribursal hypervascularity, which indicates an inflammatory response

Advanced microvascular imaging techniques detect these subtle vascular changes with greater sensitivity than conventional Doppler(52).

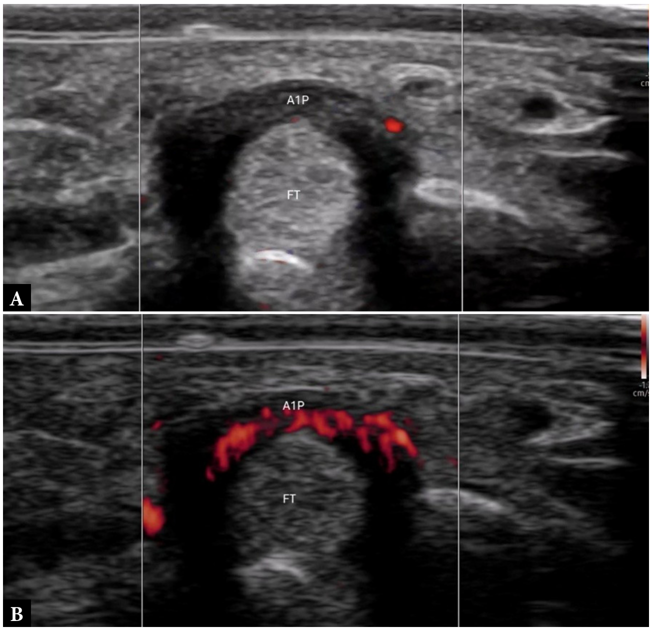

Fig. 3. *Trigger finger. Short-axis US scan of flexor tendons showing a single vascular spot on the Power Doppler image (***A***) and diffuse vascularity of the third finger A1 pulley on MVFI (***B***). FT – flexor tendons; A1P – A1 pulley*

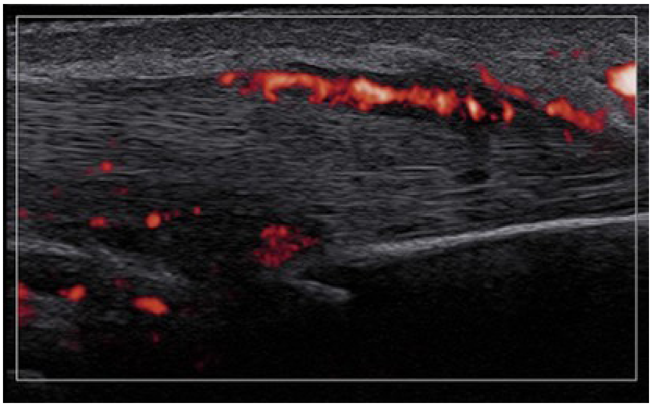

Fig. 4. *De Quervain tenosynovitis – long-axis US scan. MVFI demonstrates low-velocity hypervascularity consistent with active inflammation*

This distinction is clinically crucial when selecting between conservative and interventional management strategies(53). Recent clinical evidence(54) further supports the diagnostic and interventional value of microvascular technologies in tendinopathies. US-MV-Flow can detect intratendinous and periligamentous hyperemia that remains occult on conventional Doppler, thereby improving diagnostic grading and enabling targeted image-guided therapies such as PRP and percutaneous tenotomy. MV-Flow could also become a potential tool for objective follow-up and assessment of treatment response in regenerative and rehabilitation settings.

Adhesive capsulitis

Adhesive capsulitis, commonly referred to as *frozen shoulder*, is a chronic condition characterized by progressive pain, stiffness, and marked restriction of both active and passive glenohumeral motion. The disease typically progresses through three clinical stages: the painful or "freezing" phase, the stiff or "frozen" phase, and the recovery or "thawing" phase, which collectively span several months. The underlying pathology involves a cascade of chronic inflammation, synovial proliferation, and capsular fibrosis, primarily affecting the rotator interval, coracohumeral ligament, and anterior joint capsule(55,56).

Although adhesive capsulitis remains primarily a clinical diagnosis, often recognized by the characteristic loss of external rotation, imaging is essential to exclude secondary causes of stiffness and to assess disease stage. Only MRI is able to demonstrate synovial thickening but is limited in accessibility and dynamic evaluation. High-resolution MSK-US has therefore emerged as a non-invasive, real-time alternative capable of delineating soft-tissue changes, including capsular and coracohumeral ligament thickening, hypoechogenicity of the rotator interval, and synovial hypertrophy(57,58).

More recently, microvascular Doppler techniques – particularly SMI(22) – have enhanced the diagnostic yield of ultrasound by enabling visualization of low-velocity vascular flow within the rotator interval and anterior capsule. These findings reflect active inflammatory neovascularization during the early or "freezing" phase of the disease(59). Quantitative assessment of microvascularity has been shown to correlate with both pain intensity and range-of-motion(60) limitation, suggesting that vascular signal intensity may serve as a biologic marker of disease activity(61). This association further strengthens the role of microvascular ultrasound not only in early diagnosis but also in monitoring therapeutic response, as vascular activity typically diminishes during the resolution phase. A comprehensive overview of MVFI findings in adhesive capsulitis is provided in Tab. 3.

Nerves

Carpal tunnel syndrome is the most prevalent entrapment neuropathy, caused by compression of the median nerve within the carpal tunnel at the wrist. Clinically, it presents with numbness, tingling, pain, and weakness in the distribution of the median nerve, often worsening at night or with repetitive wrist movements(62). Early and accurate diagnosis is critical to prevent irreversible axonal injury and long-term functional impairment(63). The usefulness of US-MV-Flow in other entrapment neuropathies remains underexplored, and solid published data are still limited. Although nerve conduction studies remain the reference standard for diagnosing carpal tunnel syndrome, high-resolution ultrasound has emerged as a valuable non-invasive and dynamic alternative. US enables direct visualization of the median nerve and surrounding structures, allowing precise evaluation of nerve morphology, cross-sectional area (CSA), echotexture, and mobility(64). Characteristic findings include nerve swelling proximal to the tunnel, flattening at the level of the flexor retinaculum, thickening of the retinaculum itself, and occasionally bowing of the flexor retinaculum – features that reflect mechanical entrapment(65). The ratio between proximal and distal CSA (swelling ratio) has also been shown to correlate with electrodiagnostic severity. Doppler-based techniques, particularly PD and more recently microvascular technologies, have further expanded the diagnostic scope of ultrasound by detecting microvascular flow alterations in and around the compressed nerve. These include increased intraneural and perineural vascularity, reflecting ischemic

Tab. 3. Evolution of microvascular ultrasound findings in adhesive capsulitis

Phase	MVFI findings	Capsular morphology	Clinical features
Freezing (Painful / Inflammatory)	Dense, arborizing microvascular signals within the rotator interval and capsule. High vascular index on SMI	Capsule thickened and hypoechoic with mild effusion	Severe pain, progressive range-of-motion (ROM) loss (especially external rotation)
Frozen (Fibrotic / Stiff)	Focal or discontinuous low-grade flow; declining vascular index	Capsule thick, echogenic, reduced distensibility	Stiffness > pain; limited abduction and rotation
Thawing (Recovery)	No detectable microvascular flow	Fibrotic capsule thinning; reappearance of normal fascial planes	Gradual ROM improvement, minimal pain

and inflammatory changes secondary to compression(66). Such vascular signals are more frequently detected with SMI(22) or MVFI than with conventional Doppler, due to their superior sensitivity to slow-flow capillary perfusion. The identification of hypervascularity, especially when combined with morphometric parameters (e.g., CSA >10 mm²) and dynamic findings (reduced nerve gliding), may therefore serve as a composite indicator of disease severity and activity, assisting in diagnosis as well as in postoperative or post-injection follow-up. Postoperative evaluation of carpal tunnel syndrome using MVFI appears promising, providing insights into vascular changes within the median nerve after surgical decompression. Assessment of nerve microcirculation could potentially correlate with clinical performance and recovery outcomes(67–71).

Current challenges and future perspectives

MVTs represent an advanced, non-invasive ultrasound innovation that enables real-time visualization of microcirculatory blood flow without the need for contrast agents. By achieving exceptional sensitivity to low-velocity and small-vessel flow, MVFI enhances early detection of subtle inflammatory and ischemic changes across a wide range of musculoskeletal disorders(61,72). In addition to improving diagnostic accuracy, growing evidence suggests that MVTs may also have a prognostic role, enabling clinicians to monitor disease progression and therapeutic response over time(73).

Despite these promising advantages, several technical and methodological challenges currently limit the widespread adoption of MVTs. Foremost among these is the lack of standardized acquisition protocols and calibration parameters, resulting in considerable inter-vendor and inter-system variability in signal sensitivity and image rendering(74,75). Differences in hardware configuration (transducer frequency range, PRF, and wall filter settings) as well as proprietary software algorithms (adaptive clutter suppression and frame compounding) contribute to inconsistencies in image quality and vascular signal quantification. At present, there is no consensus on reference standards or validated cutoffs for quantitative indices such as the Vascularity Index, which limits reproducibility across studies and institutions. Despite collaborative initiatives from professional societies to develop harmonization frameworks for Doppler and MVFI techniques, universal guidelines are still lacking. From a clinical standpoint, limited availability in low-resource or peripheral settings remains a barrier to accessibility(76). Furthermore, the absence of validated quantitative scoring systems and outcome-linked benchmarks hinders integration into structured reporting and routine clinical decision-making(77,78). Future longitudinal, multicenter studies – particularly in rheumatologic and inflammatory conditions – will be critical to confirm the prognostic value and inter-vendor reproducibility of MVT findings(73).

The future direction of MVFI is nonetheless highly promising. Automated vascular quantification algorithms, based on deep-learning segmentation and texture analysis, are currently under development to standardize the calculation of perfusion indices and minimize operator dependency(79). Integration with artificial intelligence (AI) could further enable automated detection of pathological vascular patterns and assist in disease classification, thereby improving both accuracy and workflow efficiency. Technological miniaturization could also lead to the development of portable or point-of-care MVT systems, broadening accessibility and enhancing clinical utility(80). At the same time, early preclinical studies have suggested that combining MVTs with low-intensity focused ultrasound may hold theranostic potential, enabling simultaneous imaging and modulation of tissue perfusion. However, these findings remain experimental and require rigorous validation before clinical implementation(81).

In summary, microvascular imaging technologies represent a major step forward in MSK-US. They offer a contrast-free, dynamic assessment of microvascular architecture with expanding diagnostic, prognostic, and possibly theranostic implications. To realize their full potential, future research should prioritize technical standardization, quantitative validation, and cross-vendor harmonization, supported by multicenter studies that integrate AI-driven vascular analysis and multimodal imaging approaches, such as MRI perfusion and contrast-enhanced ultrasound. These efforts will be essential to validate MVFI as a reproducible imaging biomarker and to establish its role within evidence-based musculoskeletal imaging workflows.

Disclosure statement

The authors declare that they have no conflict of interest.

Author contributions

Original concept of study: MZ. Writing of manuscript: MZ, RN. Analysis and interpretation of data: GP. Final acceptation of manuscript: MZ, RN. Collection, recording and/or compilation of data: MB, LL, AP. Critical review of manuscript: RN.

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