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Position Paper

Ultrasound use in clinical decision-making for spasticity and contracture management in neurological rehabilitation

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Abstract

Ultrasound is increasingly used in neurological rehabilitation, most visibly to improve the accuracy and safety of botulinum toxin (BoNT) and phenol administration for spasticity. However, it remains underused in its potential to guide wider clinical decision-making such as differentiating neural hyperexcitability from structural muscle–tendon unit (MTU) changes underpinning stiffness and contracture. Stroke and other acquired brain injuries trigger a cascade of MTU adaptations, including atrophy, altered architecture, fibrosis, and fatty infiltration, which contribute to passive and active functional limitations and elevate contracture risk. This position paper argues that ultrasound should be conceptualized not only as a procedural adjunct, but as a decision-making tool with emerging frameworks for ultrasound-informed spasticity management. We synthesize current evidence supporting muscle ultrasound for tissue characterization and intervention guidance, outline barriers to implementation, and propose a pragmatic governance and competency framework that distinguishes multiple scopes of ultrasound practice (e.g. ultrasound-guided injection of botulinum toxin or phenol, nerve blocks or muscle tissue evaluation) in spasticity and contracture management. The modified Heckmatt scale is presented as one feasible method for tissue characterization within this broader ultrasound toolkit. Greater integration of ultrasound into routine pathways may enable earlier identification of structural change, more appropriate selection and timing of interventions (including BoNT, cryoneurolysis, phenol, orthoses, casting, and surgery), along with improved outcomes related to both passive (ease of care) and active function.

Keywords: Spasticity; Contracture; Ultrasound

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1. Introduction

Paresis following stroke or other acquired brain injury results in substantial neurological and musculoskeletal impairments that affect both motor control and muscle structure [1,2]. Neural disruption reduces voluntary activation and contributes to disuse of muscle, triggering structural and functional changes within the muscle–tendon unit (MTU) [3,4]. Muscle atrophy occurs as a consequence of inactivity and impaired neural drive, while progressive alterations in the extracellular matrix contribute to fibrosis and reduced tissue elasticity [5,6]. In parallel, fatty infiltration may replace contractile tissue and further impair muscle quality [7]. Post-stroke adaptations in muscle architecture, including shortened fascicles, reduced pennation angle, and decreased muscle thickness, have also been documented [8,9]. Collectively, these MTU changes compromise both passive and active function, contributing to limitations including positioning, hygiene, mobility, self-care, and rehabilitation outcomes [10,11].

These changes contribute to the risk and can be causative of contractures [12]. Contractures are defined as a limitation in passive joint range of movement [13], are common in moderate to severe stroke and linked with poorer outcomes. Reported incidence of contractures varies widely from 43% [14] to 100% [15], with around half of all adults admitted to hospital with stroke developing at least one contracture [2]. The sequence of events in contracture development remains unclear [16], with onset reported as early as two weeks post-stroke and stabilization typically by 32 weeks [17], although incidence data beyond this time is limited. Stroke survivors in the Care of the Arm after STroke (CAST) study [18] reported experiencing increasing muscle stiffness around one-year post-stroke, suggesting that the functional impact of emerging contractures may become more apparent at this stage. As such, it is also likely that contracture development happens over time in the community post-stroke population. The development of contractures is complex and multi-factorial, involving joint capsules, ligaments, muscles, and tendons [19], and is influenced by factors such as the severity of motor impairment, mobility, communication ability, and the way care is delivered. While spasticity and contracture are not synonymous, their coexistence is thought to influence contracture formation [20–22]. It is important to better understand the development of contractures in order to inform targeted treatment for prevention and management in the stroke care pathway [19,23].

Moreover, the financial burden of contractures is also substantial. Individuals with contractures following severe stroke who receive specialized inpatient rehabilitation may remain in hospital substantially longer, on average 31 days, incurring an additional mean cost of £25,588 [24]. Despite this clinical and economic impact, guidance on prevention and management remains limited, and while national guidelines recommend preventative measures, supporting evidence remains limited [25].

Ultrasound is increasingly accessible in rehabilitation and is already embedded in clinical practice for some purposes, particularly as point-of-care ultrasound (PoCUS) to guide injections for spasticity management. However, ultrasound is not widely used as a tool to inform clinical decisions about the mechanisms of stiffness (neural versus structural), the presence and progression of MTU degeneration, or the optimal selection and timing of interventions [26]. This position paper argues that ultrasound should be integrated into spasticity and contracture pathways as a decision-support framework, extending beyond procedural guidance toward tissue-informed reasoning. The modified Heckmatt (mHeckmatt) scale (see Table 1) is used as an exemplar tool within the decision-support framework, alongside other ultrasound approaches including visual qualitative assessment, quantitative echogenicity analysis, and elastography [27,28].

2. Ultrasound in spasticity and contracture management: from procedural guidance to clinical reasoning

Muscle ultrasound is increasingly recognized as a valid and reliable approach to assess muscle structure in neuromuscular and neurological populations, and it can provide clinically meaningful information about MTU composition and architecture at the bedside [27,29]. In practice, ultrasound can contribute to decision-making in at least three ways: (1) identifying muscle targets and avoiding risk structures during interventions, (2) evaluating structural muscle changes relevant to stiffness/contracture to inform treatment approach, and (3) monitoring response to interventions over time. While the first is now well embedded in spasticity services, the latter two are less consistently integrated into clinical reasoning pathways.

Assessment of muscle echogenicity is particularly relevant when clinical stiffness is dominated by structural change, such as fibrosis or fatty infiltration. Echogenicity refers to the brightness of muscle tissue on ultrasound images, reflecting the degree of sound wave reflection and often associated with structural changes such as fibrosis or fatty infiltration. In clinical practice, resistance to passive movement is often interpreted as spasticity; however, stiffness may also arise from structural alterations within the MTU. Distinguishing between these mechanisms is important because they have different implications for treatment selection and expected responsiveness to interventions. The mHeckmatt scale provides a feasible and clinically pragmatic method for grading muscle echogenicity in individuals with spasticity, bridging solely qualitative visual assessment and more technically demanding quantitative grayscale analysis. The mHeckmatt scale offers a semi-quantitative, real-time evaluation using a four-point ordinal scale ranging from Grade 1 (normal muscle architecture) to Grade 4 (severe degeneration with a hyperechoic appearance) [30,31] (Table 1). The modified scale improves discrimination between intermediate grades, particularly Grades 2 and 3, by considering the proportion of muscle exhibiting increased echogenicity. By integrating expert visual grading with image-based markers of muscle degeneration, the scale has demonstrated good validity when compared with quantitative grayscale analysis [32] (Figure 1).

Ultrasound therefore offers advantages over purely clinical assessment by providing insight into the mechanisms underlying resistance to movement. Common clinical measures of spasticity, such as the Modified Ashworth Scale, quantify resistance but do not discriminate between neural hyperexcitability and passive structural change. In contrast, ultrasound allows visualization of muscle echogenicity, muscle architecture and, where available, mechanical properties, thereby providing mechanistic information. For example, shear wave elastography—an ultrasound technique that estimates tissue stiffness by measuring the speed at which mechanically induced shear waves propagate through muscle—has been used to quantify changes in muscle mechanical properties. Studies in post-stroke upper limb muscles have shown that stiffness metrics derived with elastography can be measured reliably and are related to clinical spasticity and functional performance [33]. A systematic review of elastography in post-stroke spasticity similarly concluded that quantitative stiffness measures provide useful information about spastic muscle mechanical properties, although further methodological standardization is required before widespread clinical adoption [34]. Importantly, Campanella et al. demonstrated that elastography can detect changes associated with spastic dystonia and responsiveness to botulinum toxin, supporting a role for ultrasound not only in guiding injections but also in evaluating treatment effects [35]. In the same study, muscle hyperechogenicity, graded using the mHeckmatt scale, was positively associated with elastography-derived stiffness in shortened muscles, indicating that echogenicity-based and elastography-based approaches may provide complementary information [35].

Table 1. Comparison of the Heckmatt and mHeckmatt Scales

Grade	Original Heckmatt Scale	Modified Heckmatt Scale
1	Normal	Normal echogenicity in more than 90% of the muscle that is distinct from bone echogenicity
2	Increased muscle echogenicity intensity with distinct bone echogenicity	Increased muscle echogenicity in 10-50% of tissue with reduced distinction of bone echogenicity from muscle
3	Marked increased in muscle echogenicity with a reduced bone echogenicity	Marked increased in muscle echogenicity between 50% and 90% of tissue with a reduced distinction of bone echogenicity from muscle
4	Very strong muscle echogenicity and complete loss of bone echogenicity	Very strong muscle echogenicity with near complete loss of distinct bone echogenicity from muscle in >90% of tissue

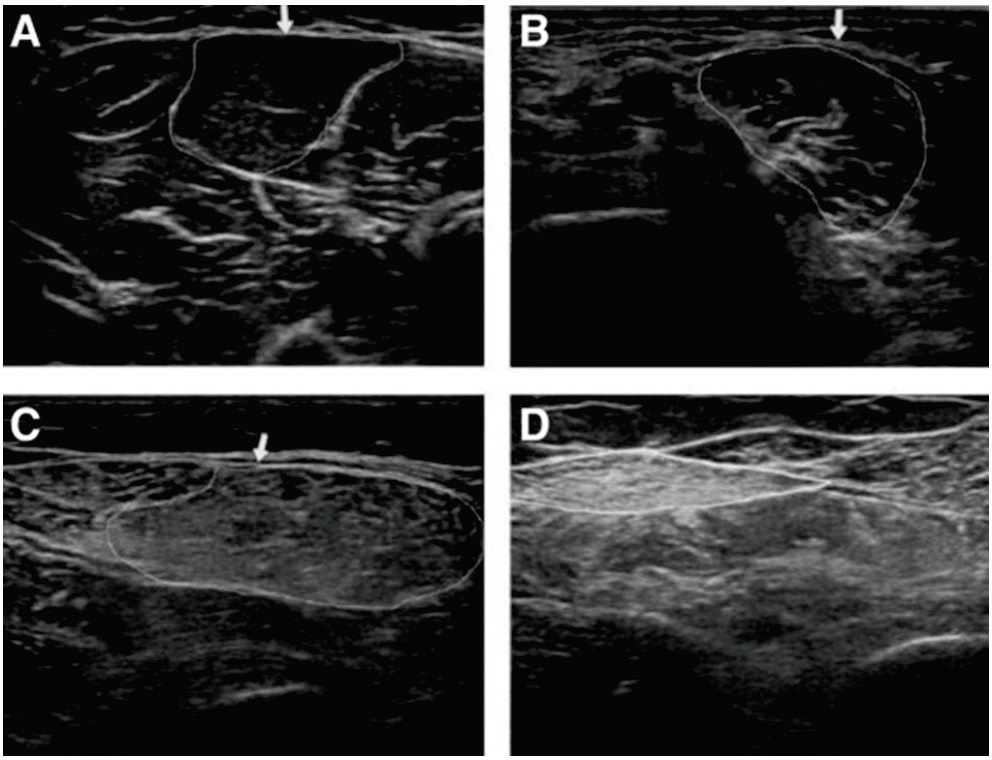


Figure 1. Traced muscles demonstrating the Modified Heckmatt grades. (A) Grade 1: normal echogenicity in more than 90% of the muscle that is distinct from bone echo. (B) Grade 2: increased muscle echogenicity in 10% to 50% of tissue, but with distinct bone echo and some areas of normal muscle echo. (C) Grade 3: marked increase in muscle echogenicity between 50% and 90% of tissue with reduced distinction of bone echo from muscle. (D) Grade 4: very strong muscle echogenicity, with near complete loss of distinct bone echo from muscle in more than 90% of tissue. Moreta, Fleet, Reebye, McKernan, Berger, Farag, Munin. Reliability and Validity of the Modified Heckmatt Scale in Evaluating Muscle Changes With Ultrasound in Spasticity, Archives of Rehabilitation Research and Clinical Translation 2020, 2, 4 [32]. Reproduced under a Creative Commons license. Reproduced under a Creative Commons license.

Moreta et al. demonstrated good inter- and intra-rater reliability and a strong relationship between mHeckmatt and quantitative grayscale measures, supporting its use as a clinically feasible tissue-characterization tool [32]. Broader overviews of muscle ultrasound in neuromuscular assessment highlight that such grading approaches can be applied at the point-of-care to support assessment and monitoring where full quantitative pipelines are unrealistic [31,36].

A central position of this paper is that ultrasound should be conceptualized not only as a procedural adjunct but also as a decision-support modality embedded in structured clinical reasoning. Ashford and colleagues explicitly argue that ultrasound should inform diagnosis, goal-setting and treatment selection rather than being confined to injection accuracy alone [26]. This is especially pertinent when a patient's resistance to movement reflects both neural components (e.g. reflex-mediated hypertonia) and structural MTU change, because these mechanisms suggest different treatment priorities and expected responsiveness.

3. Ultrasound-guided intervention as core to clinical interventions

Ultrasound guidance for BoNT injection has the clearest evidence base and strongest clinical uptake. The rationale is straightforward: if the intended muscle is not accurately targeted, efficacy may be reduced and unintended weakness may compromise function. Multiple studies have demonstrated that ultrasound guidance improves localization accuracy compared with landmark-based approaches, particularly in smaller or deeper muscles and in anatomically complex regions. For example, Ko et al. reported markedly higher injection accuracy with ultrasound guidance compared with non-guided techniques, with particularly large differences in more challenging muscle groups [37]. Earlier work on forearm muscles also concluded that ultrasound improves localization and helps avoid injection near vascular or nerve structures [38]. More recent evidence continues to support improved accuracy with ultrasound guidance even with relatively limited training exposure [39].

Beyond accuracy, there is evidence that ultrasound guidance can translate into improved clinical outcomes in post-stroke spasticity. Santamato et al. recommended that ultrasound-guided BoNT injections could improve clinical outcome measures compared with anatomically guided needle placement in post-stroke patients [40]. A clinical discussion paper also argues that the accumulating evidence base makes routine ultrasound guidance increasingly defensible in spasticity services, particularly when targeting muscles where landmark accuracy is low [38,40]. These studies align with the practical reality that spasticity injections occur in heterogeneous clinical environments: ultrasound increases consistency and reduces dependence on anatomical assumptions and localization techniques, which include ultrasound, improve outcomes [41,42].

Phenol neurolysis is less common than BoNT but remains important in focal spasticity management, especially when longer-lasting denervation effects are required or when BoNT response is limited. Ultrasound-guided phenol approaches have been evaluated in several contexts. Matsumoto et al. compared electrical stimulation alone versus electrical stimulation plus ultrasound guidance in phenol neurolysis of the musculocutaneous nerve for elbow flexor spasticity, demonstrating the clinical relevance of ultrasound to improve targeting and define nerve appearance in this population [43]. Phenol neurolysis under combined ultrasound and stimulation guidance has also been reported as feasible and safe in people with spinal cord injury [44]. Ultrasound has also effectively been applied in cryoneurolysis to target motor points in muscle as well as blocking motor nerves, with positive outcomes for pain and spasticity management [45–47]. Collectively, the evidence from these areas of practice supports ultrasound as a procedural tool for interventional targets where safety and accuracy are paramount.

Critically, while procedural guidance is becoming widely accepted, it does not automatically confer tissue-level diagnostic insight. Ultrasound-guided injection tells clinicians that the needle has entered the intended structure, but it does not necessarily indicate whether the muscle is structurally degenerated, fibrotic, or fatty-infiltrated, nor whether reduced passive range is likely to respond to spasticity management alone. This distinction is central to the argument advanced by Ashford et al. [26], namely that ultrasound can support broader treatment decisions across spasticity and contracture management rather than being limited to procedural accuracy.

4. Scope of practice, competency, and governance: aligning ultrasound use to clinical risk and purpose

As ultrasound becomes more portable and increasingly used by clinicians outside radiology, the scope of practice must be clearly defined to ensure safety, quality, and

appropriate interpretation. The term "ultrasound use" can encompass a range of activities, each associated with different levels of complexity, training requirements, and clinical risk. The point-of-care ultrasound (PoCUS) literature emphasizes that formal training, competency assessment, and appropriate governance structures are essential, as confidence without competence may lead to misinterpretation and inappropriate clinical decisions [49,50]. In response to these challenges, an internationally conducted Delphi study linked to the development of the UK National Framework for Ultrasound Practice has proposed a structured approach to defining ultrasound use within spasticity interventions [49], summarized in Table 2.

Table 1. Scope of practice statements within spasticity intervention agreed by consensus statements.

Scope of practice statements
1. Visualization and identification of target muscle and neighbouring tissues (including neurovascular structures). Visualization of needle passage and subsequent localization of botulinum toxin into target muscle; avoiding at risk structures.
The first scope is procedural guidance for BoNT injection: this requires image optimisation, accurate identification of muscle boundaries, real-time needle visualisation, and safety awareness around neurovascular structures.
2. Visualization and identification of target muscle or nerve; and neighbouring tissues. Visualization of needle passage and subsequent localization of injectate such as phenol (or cryoneurolysis)* into target tissue; avoiding at risk structures.
The second scope is procedural guidance for phenol neurolysis: in addition to needle guidance, clinicians must reliably identify nerves and understand target relationships, which may require additional training and governance
3. Evaluation of muscle structure, thickness, and composition to aid clinical assessment and decision making.
The third scope extends ultrasound beyond procedures into tissue characterisation and decision support—such as echogenicity grading (e.g., mHeckmatt), architectural assessment, and (where available) elastography—to inform whether stiffness is predominantly neural versus structural and to guide escalation pathways.

*An addition since the original publication of the statements

The three scopes described in Table 2 represent progressively broader applications of ultrasound within spasticity management. The first two relate primarily to procedural guidance for injection-based interventions. While both involve real-time visualization to improve accuracy and safety, the second scope requires additional expertise because it involves reliable identification of peripheral nerves and understanding their anatomical relationships with surrounding tissues. In this paper we also recognize the relevance of cryoneurolysis within this procedural category, reflecting developments in clinical practice since the original consensus publication.

The third scope extends ultrasound beyond procedural guidance into tissue characterization and decision support. Approaches such as echogenicity grading (e.g., the mHeckmatt scale), assessment of muscle architecture, and, where available, elastography may help clinicians interpret the mechanisms underlying resistance to movement. This scope is currently the least developed in routine clinical practice but arguably has the

greatest potential to influence clinical decision-making. A common challenge in rehabilitation is that two patients may present with similar resistance to passive movement, yet the underlying contributors differ: one may have predominantly neural hypertonia (such as spasticity or spastic dystonia), whereas another may have substantial structural muscle shortening or fibrosis. These mechanisms may require different treatment strategies and lead to different expectations regarding responsiveness to intervention. In practice, neural and structural components often coexist and can be difficult to distinguish using clinical examination alone, meaning that both may require targeted management (see Figure 2).

Figure 2. Clinical decision making for spasticity management using the mHeckmatt scale.

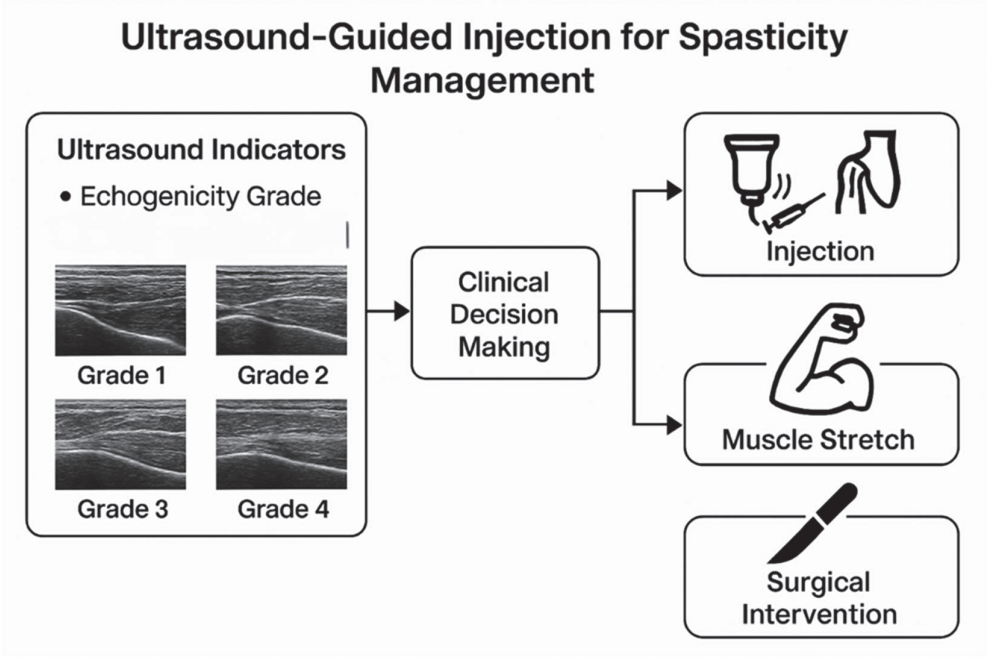


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Ultrasound can support this differentiation. For example, Moreta et al. showed that mHeckmatt provides a feasible way to evaluate pathologic muscle changes in spasticity and correlates with quantitative analysis [32]. Campanella et al. and Heckmatt et al. also demonstrate relationships between echogenicity and stiffness metrics, reinforcing the value of combining approaches when feasible [30,35].

Ashford et al. provide an important precedent for embedding such evaluation into structured spasticity pathways by using algorithms for early identification and treatment planning [48]. The implication is that ultrasound information should feed into structured reasoning rather than existing as an isolated measurement. Governance can therefore include explicit documentation and reporting expectations, quality assurance processes, and agreement over which clinical decisions can be informed by ultrasound under each scope.

5. Barriers to implementation: why adoption remains uneven despite availability

Despite growth in device availability, implementation barriers persist across spasticity and neuro-rehabilitation services. In a Canadian survey of rehabilitation physicians, limited familiarity with PoCUS ultrasound and uncertainty about clinical value were identified as key obstacles to integrating ultrasound into spasticity management [51]. These barriers are not unique to ultrasound and align with broader evidence on practice development and guideline uptake in stroke rehabilitation. A systematic review of stroke rehabilitation guideline implementation found persistent organizational and clinician-level barriers including limited time, limited resources, knowledge/skills gaps, and skepticism about applying new tools in real-world contexts [52]. This combination is particularly relevant for ultrasound because implementation requires both equipment and sustained skill development.

Evidence from the implementation of PoCUS in clinical practice highlights several barriers to adoption. Clinicians commonly report insufficient education, limited opportunities for supervised practice, and a lack of clear credentialing pathways as key obstacles, even where ultrasound technology is readily available [50]. In medical education, ultrasound curricula show that skills can be taught, but national surveys highlight variable provision, inconsistent standards and limited faculty expertise in many settings [53]. These issues are magnified when services seek to expand ultrasound beyond injection guidance into interpretation of tissue state, which requires additional competence and governance.

A further barrier is perceived value. Ultrasound guidance for intervention has an intuitive link to safety and accuracy, with cost-savings related to more effective treatment, so its value is easier to justify. By contrast, ultrasound-based tissue characterization is less embedded in standard pathways and outcome reporting, but is also likely to result in cost saving with more timely clinical decision making and the most appropriate treatment provision. Even where tools like mHeckmatt show good measurement properties, clinicians may remain uncertain how results should influence treatment choice, timing or escalation [32]. This creates a feedback loop: limited use leads to limited local evidence of impact, which reinforces limited adoption

6. Overcoming barriers: strengthening pathways, training and quality systems

Implementation requires a multi-layered strategy combining pathway design, education, and governance. Structured protocols and documentation are repeatedly associated with improved ultrasound uptake in PoCUS settings. For instance, a study evaluating ultrasound competency and use in trainees reported sustained improvements in uptake after structured training and quality systems were introduced [54]. Translating this into spasticity services implies that ultrasound findings, whether procedural guidance confirmation, echogenicity grading, or muscle assessment, should be integrated into standard documentation templates and linked explicitly to clinical decisions.

Education and training must also be aligned with the defined scope of practice. There is a need to further develop PoCUS practice in the context of central neurological impairment to enhance clinicians' skills in both interventional procedures and muscle evaluation to support clinical decision-making and treatment planning. Evidence suggests that targeted ultrasound education can improve competence and sustain clinical use over time. For example, studies evaluating structured ultrasound training programmes have shown that clinicians continue to incorporate PoCUS into clinical practice several years after completing formal training, demonstrating the value of supervised learning and ongoing clinical exposure for maintaining competency [55]. Similarly, curriculum development studies in medical education indicate that longitudinal integration of ultrasound training,

rather than isolated short courses, supports skill retention and increases uptake in routine clinical practice [56]. Within spasticity management, Ashford et al. also highlight that structured training packages can improve clinician confidence and consistency in the assessment and treatment of spasticity [57]. A similar structured approach may therefore be required for ultrasound competency development, incorporating staged education, supervised clinical practice, and formal assessment of competency to ensure that clinicians can use ultrasound safely and effectively to inform treatment decisions.

Workplace culture matters as well. Implementation literature emphasizes the importance of local champions, workflow integration, and iterative quality improvement for sustaining new practices [58]. In ultrasound programs, formalized audit and quality review processes help maintain accuracy and standardization [59]. For spasticity services, this could include periodic review of ultrasound-guided injection accuracy practices, peer review of tissue-characterization reports, and linking ultrasound indicators (e.g. echogenicity grade or elastography metrics) to planned intervention pathways and outcomes.

Finally, emerging technologies may lower barriers. AI-supported ultrasound tools aim to improve image acquisition and support interpretation consistency, potentially reducing operator variability [60]. While these tools are not a substitute for clinical reasoning and governance, they may help scale muscle ultrasound into settings where training time is limited, particularly for basic acquisition tasks.

7. Summary and Position Statement

To date, the primary clinical contribution of ultrasound in spasticity management has been procedural—improving targeting and safety of BoNT, phenol and cryoneurolysis interventions. However, evidence increasingly supports an expanded role in tissue evaluation and mechanism-based decision-making, including assessment of echogenicity [32], muscle stiffness [33,34], and changes following intervention [35]. Consistent with Ashford et al. [26], this paper argues ultrasound should be embedded within structured clinical reasoning frameworks and care pathways, with defined scopes of practice, competency standards, and governance systems. Tools such as the modified Heckmatt scale should be conceptualized as one component of a broader ultrasound toolkit to support differentiation of neural versus structural contributors to stiffness, inform appropriate timing of spasticity management, and guide escalation to interventions addressing MTU length and structure (e.g. orthoses, serial casting, surgery).

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence

BoNT	Botulinum Toxin
CAST	Care of the Arm after STroke
mHeckmatt	Modified Heckmatt Scale
MTU	Muscle-Tendon Unit
PoCUS	Point-of-Care Ultrasound
NHS	National Health Service

References

1. Bernhardt, J.; Hayward, K.S.; Kwakkel, G.; Ward, N.S.; Wolf, S.L.; Borschmann, K.; Krakauer, J.W.; Boyd, L.A.; Carmichael, S.T.; Corbett, D.; et al. Agreed definitions and a shared vision for new standards in stroke recovery research. Int. J. Stroke 2017.
2. Kwah, L.K.; Harvey, L.A.; Diong, J.; Herbert, R.D. Half of the adults who present to hospital with stroke develop at least one contracture within six months: An observational study. J. Physiother. 2012.
3. Lieber, R.L. Skeletal muscle structure, function, and plasticity. Phys. Ther. 2010.
4. Ward, S.R.; et al. Mechanisms of muscle adaptation after neurological injury. 2020.
5. Gillies, A.R.; Lieber, R.L. Structure and function of the skeletal muscle extracellular matrix. Muscle Nerve 2011.
6. Duncan, P.W.; et al. Muscle stiffness and fibrosis post-stroke. 2011.
7. Reimers, K.; et al. Skeletal muscle sonography: A correlative study of echogenicity and morphology. J. Ultrasound Med. 1993.
8. Barber, L.; Barrett, R.; Lichtwark, G. Passive muscle mechanical properties in stroke. J. Biomech. 2016.
9. Gao, F.; Zhang, L.Q. Altered muscle architecture in stroke survivors. Clin. Biomech. 2008.
10. Ada, L.; Dorsch, S.; Canning, C.G. Strengthening interventions increase strength and improve activity after stroke. Aust. J. Physiother. 2006.
11. Langhorne, P.; Bernhardt, J.; Kwakkel, G. Stroke rehabilitation. Lancet 2011.
12. Gracies, J.M. Pathophysiology of spastic paresis. Lancet Neurol. 2005.
13. Halar, E.M.; Bell, K.R. Contractures and other deformities. Arch. Phys. Med. Rehabil. 1988.
14. Sackley, C.; et al. Prevalence of joint contractures in stroke patients. 2008.
15. Malhotra, S.; et al. Spasticity, contractures and pain after stroke. Disabil. Rehabil. 2011.
16. Harvey, L.A. Contracture management following neurological conditions. Phys. Ther. 2011.
17. Pandyan, A.D.; et al. Spasticity: Clinical perceptions and measurement. Clin. Rehabil. 2003.
18. Allison, R.; et al. Care of the Arm after Stroke (CAST) study. 2018.
19. Farmer, S.E.; James, M. Contractures in neurological conditions. 2001.
20. Yip, B.; et al. Relationship between spasticity and contracture. 1996.
21. Tariq, M.; et al. Spasticity and contracture interaction. 2023.
22. Turner-Stokes, L.; et al. Spasticity management frameworks. 2021.
23. Souren, L.; et al. Contracture prevention in stroke. 1995.
24. Ashford, S.A.; et al. Cost implications of contractures post-stroke. 2022.

25. College of Occupational Therapists; Association of Chartered Physiotherapists in Neurology. Guidelines for Stroke Rehabilitation; London, UK, 2015.
26. Ashford, S.A.; et al. Ultrasound in spasticity management. 2020.
27. Pillen, S.; van Alfen, N. Skeletal muscle ultrasound. Neurol. Res. 2011.
28. Nightingale, K.; et al. Elastography principles and applications. 2021.
29. Pillen, S.; et al. Muscle ultrasound in neuromuscular disorders. 2009.
30. Heckmatt, J.Z.; et al. Ultrasound imaging in muscle disease. J. Pediatr. 1982.
31. van Alfen, N.; Pillen, S. Muscle ultrasound interpretation. 2011.
32. Moreta, M.C.; Fleet, A.; Reebye, R.; McKernan, G.; Berger, M.; Farag, A.; Munin, M.C. Reliability and validity of the modified Heckmatt scale. Arch. Rehabil. Res. Clin. Transl. 2020.
33. Wu, C.H.; et al. Muscle stiffness in post-stroke patients using elastography. 2017.
34. Lehoux, M.C.; et al. Elastography in post-stroke spasticity: A systematic review. 2020.
35. Campanella, M.; et al. Relationship between echogenicity and stiffness in spastic muscle. 2022.
36. Boissonnault, J.S.; et al. Clinical applications of muscle ultrasound. 2024.
37. Ko, S.Y.; et al. Accuracy of ultrasound-guided injections. 2020.
38. Henzel, M.K.; et al. Ultrasound guidance in forearm injections. 2010.
39. Heslot, C.; et al. Ultrasound training and injection accuracy. 2024.
40. Santamato, A.; et al. Ultrasound-guided botulinum toxin injections. 2014.
41. Esquenazi, A.; Zorowitz, R.D.; Ashford, S.A.; Beneteau, M.; Maisonobe, P.; Hannes, C.; Jacinto, J. Longitudinal goal attainment with repeat injections. Arch. Phys. Med. Rehabil. 2025.
42. Fheodoroff, K.; Jacinto, J.; Ashford, S.A.; Danchenko, N.; Grandoulier, A.-S.; Pietri, G.; Bourhis, Y.; Spurden, D.; Turner-Stokes, L. Predictors of real-world response. J. Int. Soc. Phys. Rehabil. Med. 2024.
43. Matsumoto, H.; et al. Ultrasound-guided phenol neurolysis. 2018.
44. Korupolu, R.; et al. Phenol neurolysis in spinal cord injury. 2022.
45. Guynn, C.C. Cryoneurolysis for spasticity. Arch. Rehabil. Res. Clin. Transl. 2025.
46. Pick, A.; Dye, R.; Fleming, M.K. Cryoneurolysis case series. Adv. Rehabil. Sci. Pract. 2025.
47. Hashemi, M.; et al. Cryoneurolysis outcomes in spasticity. 2025.
48. Ashford, S.A.; et al. Ultrasound clinical decision-making framework. 2018.
49. Ashford, S.A.; Morris, G.; Smith, M.J. Ultrasound scope of practice Delphi study. Arch. Rehabil. Res. Clin. Transl. 2023.

50. Moore, C.L.; Copel, J.A. Point-of-care ultrasonography. N. Engl. J. Med. 2011. 421

51. Harnie, J.; et al. Barriers to ultrasound adoption in rehabilitation. 2020. 422

52. Jolliffe, L.; et al. Implementation of stroke rehabilitation guidelines. 2021. 423

53. Bahner, D.P.; et al. Ultrasound education in medical training. 2012. 424

54. Amini, R.; et al. Ultrasound competency and training impact. 2016. 425

55. Lewiss, R.E.; et al. Long-term retention of ultrasound skills. 2013. 426

56. Hoppmann, R.; et al. Longitudinal ultrasound curriculum. 2011. 427

57. Ashford, S.A.; et al. Training in spasticity management. 2015. 428

58. Damschroder, L.J.; et al. Implementation science framework. 2009. 429

59. Adhikari, S.; Amini, R. Quality assurance in ultrasound programs. 2014. 430

60. van Sloun, R.J.G.; Demi, L. AI in ultrasound imaging. 2020. 431

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