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Spinal Surveillance, Spine Surgery, and Perioperative Physiotherapy in Children with Spinal Muscular Atrophy: An Interprofessional Modified Delphi Study

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Abstract

Disease-modifying therapies have altered the course of spinal muscular atrophy (SMA), creating new challenges in spinal surveillance and perioperative management. This three-round modified Delphi study used 91 question blocks to establish consensus between paediatric spine surgeons and physiotherapists. Twenty-nine experts participated in Round 1, 28 in Round 2, and 10 surgeons in Round 3. Consensus required at least 80% agreement within each eligible professional group. Forty statements achieved interprofessional consensus, supporting multidisciplinary care, function-based assessment, radiographic evaluation, tailored physiotherapy, respiratory management, and early postoperative mobilisation. Physiotherapists reached additional consensus on 14 items concerning surgical referral in the presence of functional loss, pain, or respiratory deterioration; use of the scoliometer; three-dimensional postural correction and active autocorrection; preoperative education; cautious postoperative stretching; and early postoperative positioning and family education. In Round 3, surgeons supported function-based surgical planning, preoperative bone mineral density assessment, non-invasive ventilation for respiratory impairment, and more frequent radiography for rapid curve progression. Consensus was not achieved for halo-gravity traction, growth-friendly surgery, or preservation of distal lumbar motion segments. These findings provide an interprofessional framework for spinal care in children with SMA and identify priorities for further research.

Keywords: Spinal Muscular Atrophy; Scoliosis; Perioperative Care; Physiotherapy; Delphi Method.

1. Introduction

The clinical landscape of spinal muscular atrophy (SMA) has changed substantially following the introduction of disease-modifying therapies (DMTs) and newborn screening programmes. Earlier diagnosis and treatment have improved survival and enabled many children to achieve or retain motor abilities that would have been uncommon in the untreated natural history of the disease [1,2]. Consequently, the traditional classification based on age at onset and the highest acquired motor milestone no longer adequately describes the functional trajectories of all treated patients. Contemporary clinical decision-making increasingly relies on current functional status, commonly distinguishing between non-sitters, sitters, and walkers [3].

Despite these therapeutic advances, spinal deformity remains one of the most prevalent and clinically relevant musculoskeletal complications of SMA. Scoliosis may develop early, particularly in non-sitters and sitters, and is frequently accompanied by pelvic obliquity, impaired trunk control, progressive difficulty with sitting and positioning, pain, and restrictive thoracic deformity. DMTs have therefore not eliminated the need for spinal surveillance, conservative management, or surgery. Instead, the emergence of new and less predictable phenotypes has altered the population at risk and created uncertainty regarding the timing and frequency of radiographic monitoring, indications for surgical referral, selection of operative strategy, and organisation of perioperative care [4–6].

Existing recommendations provide an essential framework for managing musculoskeletal complications in SMA, but important limitations remain. The international standards of care were developed at the beginning of the disease-modifying therapy era [3]. A subsequent orthopaedic Delphi consensus addressed spinal deformity, hip instability, contractures, and operative strategy in children receiving contemporary therapies, but its panel consisted predominantly of orthopaedic surgeons, while physical and occupational therapy were deferred to a separate working group [5]. More recent reviews have described current surgical techniques and general rehabilitation strategies without establishing detailed consensus-based protocols for spinal surveillance or physiotherapy before and after scoliosis surgery [6–8]. A French–Belgian Delphi study subsequently expanded the available guidance by addressing respiratory monitoring, trunk orthoses, surgical approaches, and perioperative care [9]. However, its panel consisted exclusively of physicians and did not include practising physiotherapists as a distinct professional group. Detailed aspects of physiotherapy—including functional assessment, prehabilitation, positioning, transfers, postural correction,

respiratory interventions, standing, and postoperative mobilisation—therefore remain insufficiently standardised, with the available evidence derived mainly from narrative reviews, professional competency statements, and individual case reports [7,8,10,11].

This gap is clinically important because the management of spinal deformity in SMA extends beyond the decision to operate. Surveillance, preparation for surgery, postoperative mobilisation, and restoration of function require close cooperation between spine surgeons and physiotherapists. Differences in professional perspective may influence the perceived value of clinical screening tools, thresholds for intervention, preoperative priorities, and postoperative rehabilitation. Recommendations developed without examining these perspectives separately may conceal clinically relevant disagreement behind apparent overall consensus.

The primary aim of this study was to establish interprofessional consensus between paediatric spine surgeons and physiotherapists on spinal surveillance and perioperative management of children with SMA. Particular emphasis was placed on function-specific monitoring, indications for surgical referral, operative strategy, preoperative preparation and physiotherapeutic interventions. A secondary aim was to identify areas in which consensus could not be achieved and to characterise clinically relevant differences between the two professional groups.

2. Methods

2.1. Study design

A three-round modified Delphi study was conducted between 2025 and 2026 to establish interprofessional consensus on spinal surveillance and perioperative management of spinal deformity in children with spinal muscular atrophy (SMA). The Delphi method was selected because high-quality comparative evidence was limited and clinical practice remained variable. It provides a structured approach to organising expert judgement through an expert panel, anonymous questionnaires conducted over successive rounds, controlled feedback, and statistical aggregation of responses [12,13]. Because definitions of consensus vary across Delphi studies, the consensus threshold and criteria for retaining, modifying, or rejecting statements were established a priori and reported transparently [13,14]. This approach enabled areas of interprofessional agreement to be identified while allowing responses from orthopaedic surgeons and physiotherapists to be analysed separately. The study was designed and reported in accordance with the Guidance on Conducting and Reporting Delphi Studies (CREDES) [13].

After providing contact details for survey distribution, participants received access to a secure online platform that enabled anonymous and independent responses. Non-responders received several reminders during the four-week response period in Round 1 and the six-week period in Round 2. In successive rounds, statements were refined, structured feedback from the preceding round was provided, and items that had not reached consensus were reassessed.

The study consisted solely of surveys completed by healthcare professionals. It did not involve patients or the use of patient-level clinical data.

All participants provided informed consent. The study protocol was reviewed and approved by the Institutional Review Board at Poznan University of Medical Sciences, Poland (approval No. 1035/19). The protocol submitted for ethical review explicitly described the project as an international, multicentre Delphi study. Thus, the Ethics Committee was informed of the research's international and multicentre nature as part of the original approval process. All procedures were conducted in accordance with the Declaration of Helsinki and relevant institutional guidelines.

2.2. Expert panel

The international expert panel included participants from Poland, Portugal, Canada, Germany and Estonia. Experts were selected based on their relevant clinical experience. Eligibility required participants to be professionally active paediatric orthopaedic and spine surgeons, and physiotherapists and to have direct clinical experience in at least one of the following areas: multidisciplinary care of individuals with SMA, assessment or treatment of neuromuscular spinal deformity, spinal surveillance, surgical management of SMA-related scoliosis, or conservative and perioperative physiotherapy of children undergoing scoliosis surgery. Participants were required to be actively involved in clinical care or decision-making within their respective professions.

No fixed minimum number of years in practice or annual number of treated patients was used as an absolute eligibility threshold. This approach was chosen to include experts with different durations of clinical practice while ensuring that all participants had direct and current experience relevant to the study. Professional background, years of experience in caring for patients with SMA, experience in managing neuromuscular scoliosis, participation in multidisciplinary SMA care, and—among orthopaedic surgeons—the annual number of surgically treated patients with SMA-related scoliosis were collected in Round 1 and used to characterise the panel.

The panel was established to represent the two professional groups directly involved in spinal surveillance, surgical decision-making, preparation for surgery, and postoperative functional recovery. The initial panel consisted of 29 participants: 12 orthopaedic surgeons and 17 physiotherapists. Twenty-eight experts participated in Round 2, including 11 orthopaedic surgeons and 17 physiotherapists. Round 3 focused on unresolved surgical and radiographic surveillance items and was completed by 10 orthopaedic surgeons.

2.3. Questionnaire development

The initial questionnaire was developed on the basis of published standards of care for SMA, contemporary literature concerning spinal deformity in the era of DMTs, and the clinical experience of the study steering group. The questionnaire covered the following domains: multidisciplinary care, clinical and radiographic surveillance, conservative management, indications and timing of surgical referral, surgical strategy, preoperative preparation, perioperative respiratory management, physiotherapeutic assessment, prehabilitation, postoperative physiotherapy, and the potential influence of DMTs on spinal management.

Questions were stratified according to current functional status—non-sitters, sitters, and walkers—where differences in surveillance or management were considered clinically relevant. The questionnaire included Likert-scale statements, single- and multiple-choice questions, ranking questions, and free-text fields. Agreement with each Likert-scale statement was rated using five response options: “strongly disagree”, “disagree”, “neither agree nor disagree”, “agree”, and “strongly agree”. Free-text responses allowed participants to justify their ratings, identify ambiguities, and propose revisions or additional response options. For reporting questionnaire structure, a question block was defined as either a stand-alone question or a matrix of items sharing a common stem. Repeated or reformulated question blocks were counted separately in each Delphi round.

2.4. Delphi rounds

Round 1 comprised 55 substantive question blocks administered to both professional groups. It was designed to identify areas of agreement, variation in clinical practice, and topics requiring further clarification. Participants evaluated questions concerning spinal surveillance, radiographic assessment, indications for conservative and surgical treatment, operative strategy, respiratory preparation, and physiotherapy before and after surgery. Responses to open-ended questions and comments were reviewed by the steering group and used to refine the subsequent questionnaire.

Round 2 comprised 27 distinct question blocks. Nine were administered to both professional groups, nine were specific to orthopaedic surgeons, and nine were specific to physiotherapists; therefore, participants in each professional group completed 18 question blocks. Statements that had not reached the predefined consensus threshold, required clarification, or emerged from participants’ comments were reformulated and resubmitted. Several questions were further stratified by functional status. Participants rated their agreement on a five-point Likert scale, selected one or more predefined responses, or ranked proposed management priorities. Results from Round 1 were summarised and provided as structured feedback before reassessment.

Round 3 comprised nine question blocks and was restricted to the orthopaedic subgroup. Three addressed unresolved radiographic surveillance issues: factors requiring more frequent radiographic assessment, the age at which routine spinal radiography should commence

according to functional status, and criteria for discontinuing structured radiographic surveillance. Six additional questions addressed surgical and perioperative management, including the role of functional status in surgical planning, bone mineral density assessment, halo-gravity traction, preoperative non-invasive ventilation (NIV), growth-friendly surgery, and preservation of distal lumbar motion segments in ambulant patients.

Across all three rounds, the questionnaires comprised 91 substantive question blocks: 64 administered to both professional groups, 18 administered only to orthopaedic surgeons, and nine administered only to physiotherapists. Consequently, the orthopaedic pathway comprised 82 question blocks and the physiotherapy pathway 73.

2.5. Definition of consensus

The consensus criterion was established a priori at 80%. For positively worded Likert-scale statements, consensus in favour of a recommendation was defined as at least 80% of respondents selecting “agree” or “strongly agree”. Consensus against a statement was defined as at least 80% selecting “disagree” or “strongly disagree”.

For single-choice questions, consensus was considered achieved when at least 80% of respondents selected the same response option. For multiple-choice questions, each response option was analysed separately and was retained as a consensus-supported component when selected by at least 80% of eligible respondents.

Items with less than 80% agreement were classified as not having reached consensus. Results between 60% and 79.9% were reported descriptively as majority preferences but were not interpreted as recommendations. Where the combined panel appeared to reach consensus, responses were additionally examined by professional subgroups to determine whether the overall result concealed disagreement between orthopaedic surgeons and physiotherapists. For consensus analysis, each Likert statement and each response option within multiple-choice or matrix questions was analysed as a separate item. Accordingly, the total of 91 question blocks describes the structure of the questionnaires and was not used as the denominator for calculating the proportion of items that reached consensus.

2.6. Statistical analysis

The analysis was descriptive. Participant characteristics and categorical survey responses were summarised using frequencies and percentages. Years of experience with patients with SMA and the annual number of patients assessed were collected using predefined response categories and were therefore analysed as categorical rather than continuous variables. The steering group reviewed free-text responses to identify ambiguities, suggest additional response options, and inform the development of subsequent Delphi rounds; no formal qualitative analysis was performed.

Analyses were performed for the complete panel and separately for orthopaedic surgeons and physiotherapists. Percentages were calculated using the number of eligible respondents who answered a given item as the denominator. Missing responses were not imputed. For each item, the number of eligible respondents, response distribution, percentage agreement, professional subgroup, consensus status, and the round in which the final decision was reached were recorded. Interprofessional consensus was considered to have been achieved only when the predefined 80% threshold was reached separately in both professional groups. No statistical tests comparing the two professional groups were performed, as the analysis focused on whether the predefined consensus threshold was reached.

A large language model (ChatGPT, OpenAI) was used solely for language editing and refinement of the manuscript structure. All scientific content, analyses, and conclusions were reviewed and approved by the authors.

3. Results

3.1. Panel Characteristics and Participant Flow

The initial panel comprised 29 experts: 12 paediatric orthopaedic or spine surgeons and 17 physiotherapists. All were professionally active and had relevant clinical experience. Their experience in SMA care, neuromuscular scoliosis, multidisciplinary practice, and surgical volume is summarised in Table 1.

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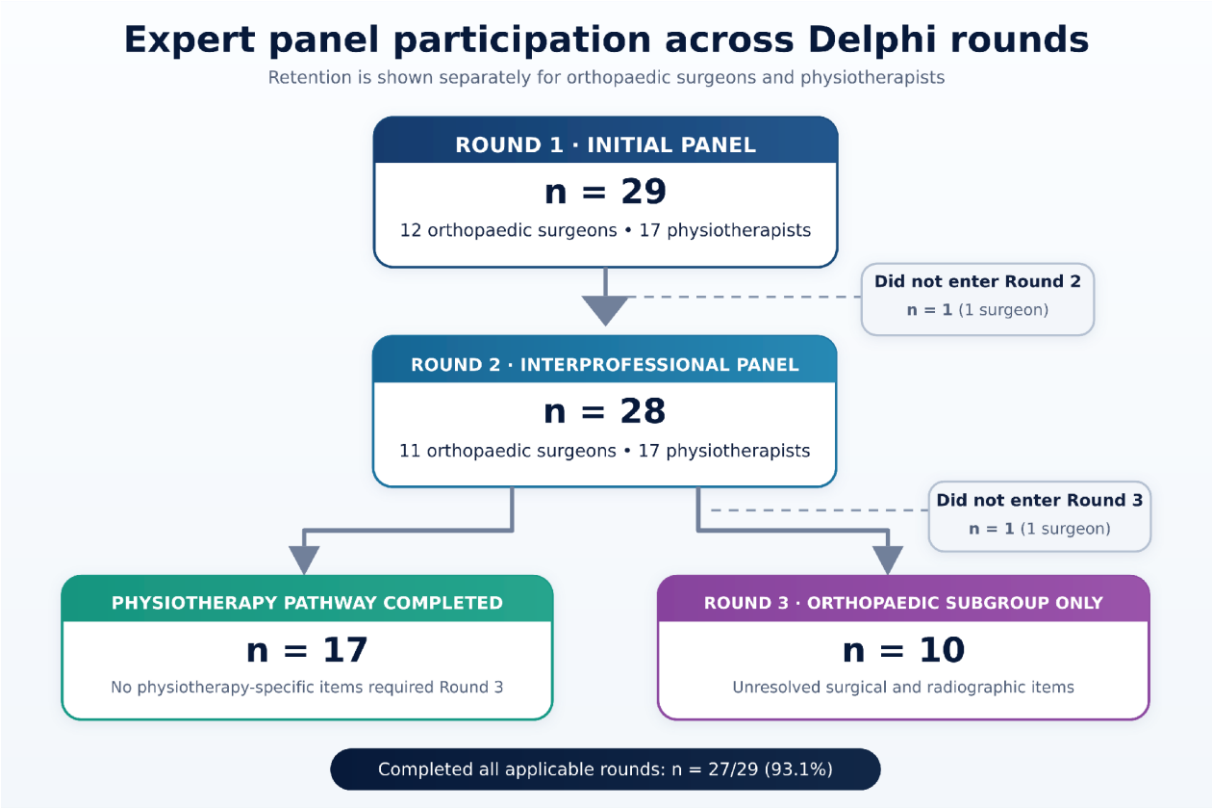
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286 Table 1. Characteristics of the expert panel participating in Round 1

Characteristic	Whole panel (n=29)	Orthopaedic surgeons (n=12)	Physiotherapists (n=17)
Professional group, n (%)			
Orthopaedic surgeons	12 (41.4%)	12 (100%)	—
Physiotherapists	17 (58.6%)	—	17 (100%)
Experience in the management of patients with SMA, n (%)			
<3 years	3 (10.3%)	1 (8.3%)	2 (11.8%)
3–5 years	5 (17.2%)	3 (25.0%)	2 (11.8%)
6–10 years	9 (31.0%)	2 (16.7%)	7 (41.2%)
11–20 years	10 (34.5%)	5 (41.7%)	5 (29.4%)
>20 years	2 (6.9%)	1 (8.3%)	1 (5.9%)
Number of children with SMA personally assessed per year, n (%)			
<5	8 (27.6%)	5 (41.7%)	3 (17.6%)
5–9	3 (10.3%)	2 (16.7%)	1 (5.9%)
10–30	8 (27.6%)	2 (16.7%)	6 (35.3%)
>30	10 (34.5%)	3 (25.0%)	7 (41.2%)
Annual number of surgically treated patients with SMA scoliosis, n (%)	—		Not applicable
No previous SMA scoliosis surgery	—	2 (16.7%)	—
1–4 cases annually	—	4 (33.3%)	—
5–10 cases annually	—	3 (25.0%)	—
>10 cases annually	—	3 (25.0%)	—

Twenty-eight experts completed Round 2 (11 surgeons and 17 physiotherapists; retention rate, 96.6%). The physiotherapy pathway ended after Round 2 because no physiotherapy-specific items required reassessment. Round 3 was restricted to unresolved surgical and radiographic items and was completed by 10 surgeons. Overall, 27 of the initial 29 participants completed all rounds applicable to their subgroup (93.1%; Fig. 1).

Figure 1. Expert panel participation across the modified Delphi process. Round 3 was restricted to the orthopaedic subgroup because the remaining unresolved items concerned surgical management and radiographic surveillance. Overall, 27 of the 29 initial participants (93.1%) completed all rounds applicable to their professional subgroup.

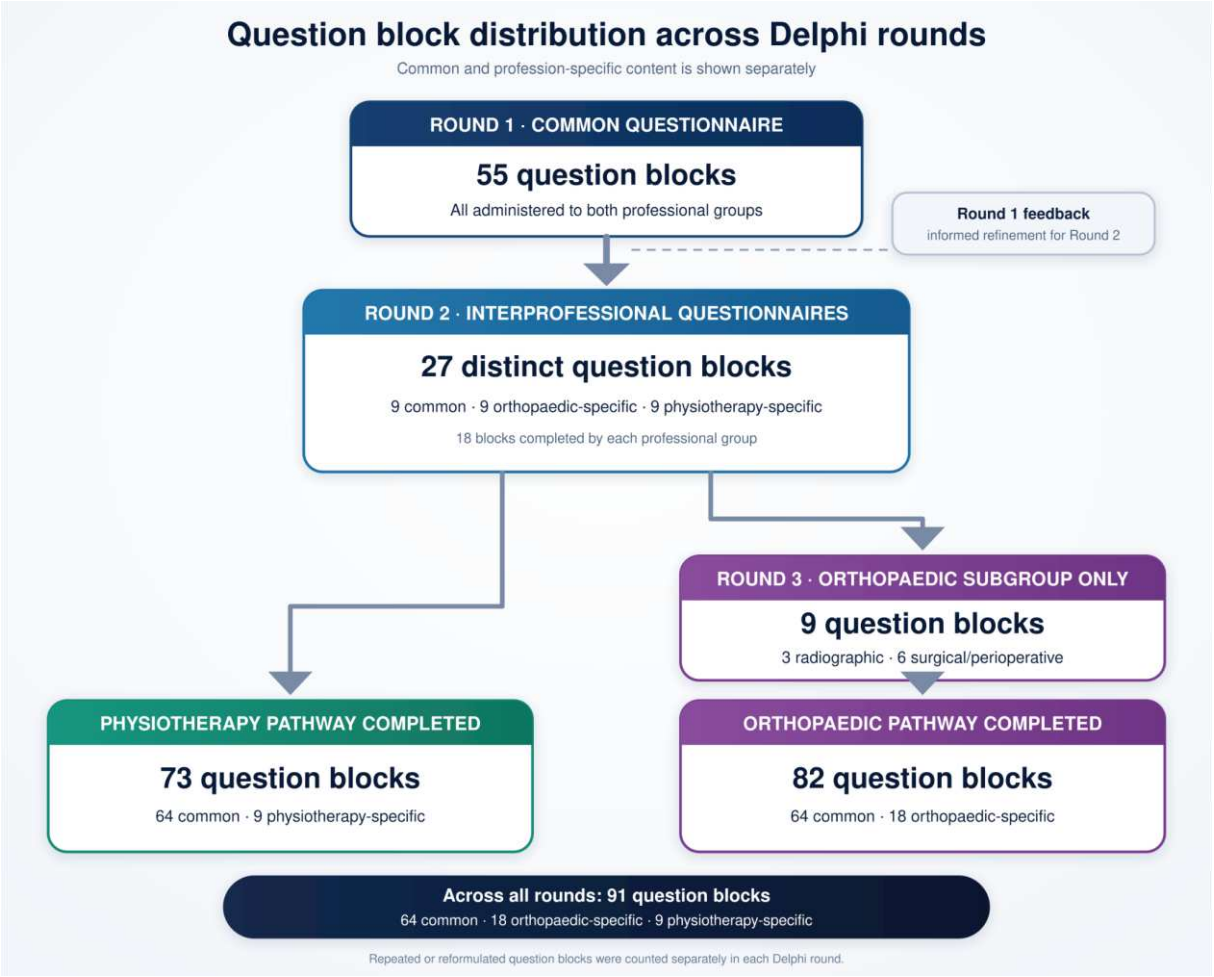


3.2. Questionnaire structure across Delphi rounds

The three Delphi rounds comprised 55, 27, and 9 substantive question blocks, respectively (Fig. 2). All 55 blocks in Round 1 were administered to both professional groups. Round 2 comprised 27 distinct blocks: nine common, nine orthopaedic-specific, and nine physiotherapy-specific; therefore, each professional group received 18 blocks. All nine Round

3 blocks were administered only to orthopaedic surgeons and included three radiographic surveillance blocks and six surgical or perioperative blocks. Across the study, the questionnaires comprised 91 round-specific question blocks: 64 common, 18 orthopaedic-specific, and 9 physiotherapy-specific. Consequently, the orthopaedic pathway comprised 82 blocks and the physiotherapy pathway 73.

Figure 2. Distribution of question blocks across the three Delphi rounds. Question matrices sharing a common stem were counted as single question blocks. Repeated or reformulated blocks were counted separately in each round.



3.3. Consensus reporting across professional groups

Responses to shared questions were analysed for the whole panel and separately by a professional group. Interprofessional consensus required the predefined 80% threshold to be reached in both groups; items meeting this threshold in only one group were reported as profession-specific. Profession-specific questions were analysed only within the relevant subgroup.

Consensus achieved across both professional groups

A total of 40 statements reached the predefined consensus threshold in both professional groups. Of these, 37 reached interprofessional consensus in Round 1 and three in Round 2. No additional shared statements were assessed in Round 3, which was restricted to the orthopaedic subgroup. Consensus shared by orthopaedic surgeons and physiotherapists was achieved primarily for the general principles of spinal deformity management in children with SMA. Both professional groups agreed that decisions concerning spinal surveillance and treatment should be made within a multidisciplinary SMA team. They also supported the use of the patient's current functional status—non-sitter, sitter, or walker—as an important framework for planning surveillance, conservative management, and perioperative care.

Both groups agreed that clinical examination alone is insufficient for a complete assessment of spinal deformity and that radiographic evaluation is required for an objective assessment of spinal alignment. When radiographs are obtained, they should be performed in the most gravity-dependent position that the patient can safely maintain, with standing preferred to sitting and sitting preferred to supine positioning. Radiographic assessment was also considered necessary whenever clinical examination raised concern regarding the presence or progression of spinal deformity, regardless of the patient's age or functional status.

Shared consensus was also achieved for selected elements of perioperative care. Orthopaedic surgeons and physiotherapists recognised the importance of respiratory management and agreed that non-invasive ventilation may reduce the risk of postoperative respiratory complications in appropriately selected patients. Both groups agreed that physiotherapy should be tailored to the child's current functional status as a non-sitter, sitter, or walker.

Detailed results for statements reaching consensus in both professional groups are presented in Tables 2a–c.

Table 2a. Consensus statements: general principles, clinical consequences of scoliosis, spinal surveillance and conservative management.

Domain	Consensus statement	Round	Whole panel, n/N (%)	Orthopaedic surgeons, n/N (%)	Physiotherapists, n/N (%)
General principles	A multidisciplinary SMA team is crucial when planning treatment	1	29/29 (100%)	12/12 (100%)	17/17 (100%)
	Functional classification as non-sitters, sitters, and walkers is more useful for spinal assessment than traditional SMA subtype classification	1	26/29 (89.7%)	10/12 (83.3%)	16/17 (94.1%)
Clinical consequences	Scoliosis affects motor function in children with SMA	1	27/29 (93.1%)	11/12 (91.7%)	16/17 (94.1%)
	Scoliosis affects pulmonary function in children with SMA	1	27/29 (93.1%)	11/12 (91.7%)	16/17 (94.1%)
Spinal surveillance	The child's age should be considered when determining the frequency of spinal assessment	1	27/29 (93.1%)	12/12 (100%)	15/17 (88.2%)
	Clinical examination alone is insufficient for a complete assessment of spinal alignment	1	24/29 (82.8%)	10/12 (83.3%)	14/17 (82.4%)
	Radiographic examination is required for an objective assessment of spinal alignment	1	29/29 (100%)	12/12 (100%)	17/17 (100%)
	Radiographs should be obtained in the most gravity-dependent position that the patient can safely maintain	1	28/29 (96.6%)	12/12 (100%)	16/17 (94.1%)
	Radiography should be performed whenever clinical examination raises concern, irrespective of SMA subtype	1	28/29 (96.6%)	12/12 (100%)	16/17 (94.1%)
	Radiography should be performed whenever clinical examination raises concern, irrespective of the patient's age	1	28/29 (96.6%)	12/12 (100%)	16/17 (94.1%)
	Radiography should be performed whenever clinical examination raises concern, irrespective of functional status	1	29/29 (100%)	12/12 (100%)	17/17 (100%)
Conservative management	Specific physiotherapy should be introduced when the Cobb angle exceeds 10°	1	25/29 (86.2%)	10/12 (83.3%)	15/17 (88.2%)
	Bracing combined with specific physiotherapy should be introduced at a Cobb angle of 15–25°	1	26/29 (89.7%)	11/12 (91.7%)	15/17 (88.2%)

Table 2b. Consensus statements: physiotherapeutic assessment and function-based physiotherapy.

Domain	Consensus statement	Round	Whole panel, n/N (%)	Orthopaedic surgeons, n/N (%)	Physiotherapists, n/N (%)
	Physiotherapeutic assessment should include measurement of elbow range of motion	1	24/29 (82.8%)	10/12 (83.3%)	14/17 (82.4%)
	Physiotherapeutic assessment should include measurement of hip range of motion	1	27/29 (93.1%)	11/12 (91.7%)	16/17 (94.1%)
	Physiotherapeutic assessment should include measurement of knee range of motion	1	24/29 (82.8%)	10/12 (83.3%)	14/17 (82.4%)
	Physiotherapeutic assessment should include motor function scales	1	28/29 (96.6%)	12/12 (100%)	16/17 (94.1%)
	Physiotherapeutic assessment should include independent changes of body position	1	28/29 (96.6%)	12/12 (100%)	16/17 (94.1%)
	Physiotherapeutic assessment should include pain assessment	1	27/29 (93.1%)	11/12 (91.7%)	16/17 (94.1%)
	Physiotherapeutic assessment should include ranges of motion	1	28/29 (96.6%)	12/12 (100%)	16/17 (94.1%)
	Physiotherapeutic assessment should include the ability to maintain body positions	1	28/29 (96.6%)	12/12 (100%)	16/17 (94.1%)
	Physiotherapeutic assessment should include walking or other forms of mobility	1	28/29 (96.6%)	12/12 (100%)	16/17 (94.1%)
	Physiotherapeutic assessment should include muscle strength	1	27/29 (93.1%)	11/12 (91.7%)	16/17 (94.1%)
	Physiotherapeutic assessment should include examination of the spine	1	27/29 (93.1%)	11/12 (91.7%)	16/17 (94.1%)
	Physiotherapeutic assessment should include examination of the chest	1	27/29 (93.1%)	11/12 (91.7%)	16/17 (94.1%)
	Physiotherapeutic assessment should include examination of the pelvis	1	27/29 (93.1%)	11/12 (91.7%)	16/17 (94.1%)
Function-based physiotherapy	Physiotherapy should be tailored to the child's current functional status as a non-sitter, sitter, or walker	1	29/29 (100%)	12/12 (100%)	17/17 (100%)

Table 2c. Consensus statements: perioperative management.

Domain	Consensus statement	Round	Whole panel, n/N (%)	Orthopaedic surgeons, n/N (%)	Physiotherapists, n/N (%)
Preoperative physiotherapy	Preoperative physiotherapy should include positioning	1	26/29 (89.7%)	10/12 (83.3%)	16/17 (94.1%)
	Preoperative physiotherapy should include strengthening exercises	1	27/29 (93.1%)	11/12 (91.7%)	16/17 (94.1%)
	Preoperative physiotherapy should include chest physiotherapy and breathing exercises	1	28/29 (96.6%)	12/12 (100%)	16/17 (94.1%)
Surgical decision-making	Curve progression greater than 10° within 6 months should influence the decision regarding surgical treatment	2	24/28 (85.7%)	9/11 (81.8%)	15/17 (88.2%)
Respiratory management	Non-invasive ventilation may reduce the risk of postoperative respiratory complications	1	25/29 (86.2%)	11/12 (91.7%)	14/17 (82.4%)
Postoperative physiotherapy	Specific physiotherapy is necessary after scoliosis surgery	1	27/29 (93.1%)	10/12 (83.3%)	17/17 (100%)
	Postoperative physiotherapy may be initiated when the child is in a stable general clinical condition	1	26/29 (89.7%)	11/12 (91.7%)	15/17 (88.2%)
	Postoperative physiotherapy should include changing basic body positions	1	24/29 (82.8%)	10/12 (83.3%)	14/17 (82.4%)
	Postoperative physiotherapy should include transfer training	1	26/29 (89.7%)	11/12 (91.7%)	15/17 (88.2%)
	Postoperative physiotherapy should include mobility activities such as rolling, crawling, or walking, according to functional ability	1	25/29 (86.2%)	10/12 (83.3%)	15/17 (88.2%)
	Postoperative physiotherapy should include chest physiotherapy and breathing exercises	1	27/29 (93.1%)	11/12 (91.7%)	16/17 (94.1%)
	Physiotherapy should begin within the first 3 postoperative days, provided that the patient is clinically stable	2	27/28 (96.4%)	10/11 (90.9%)	17/17 (100%)
Postoperative standing	Standing may be considered after spinal surgery provided that the patient does not experience significant pain while standing	2	25/28 (89.3%)	9/11 (81.8%)	16/17 (94.1%)

3.4. Consensus specific to orthopaedic surgeons

Beyond the statements supported by both professional groups, nine additional statements reached the predefined consensus threshold within the orthopaedic subgroup: four in Round 1, one in Round 2, and four in Round 3. These findings concerned surgical indications, operative strategy, preoperative preparation, respiratory optimisation, bone health, and radiographic surveillance (Table 3).

In Round 1, orthopaedic surgeons agreed that a Cobb angle of 20° alone, irrespective of motor function, should not be considered the primary indication for surgery. Progressive spinal deformity accompanied by declining pulmonary function was considered an important indication for surgical treatment, whereas neurological symptoms alone were not regarded as an appropriate primary indication.

Consensus was also reached regarding selected aspects of operative planning. The upper thoracic spine, between T2 and T4, was identified as the preferred location of the upper instrumented vertebra. In Round 2, optimisation of respiratory function was ranked as the most important component of preoperative preparation.

In Round 3, orthopaedic surgeons reached consensus on three additional surgical and perioperative statements. Current functional status—non-sitter, sitter, or walker—should be considered when selecting the surgical management strategy (9/10, 90.0%). Routine preoperative assessment of bone mineral density by dual-energy X-ray absorptiometry (DXA) should be incorporated into surgical planning (9/10, 90.0%). Surgeons also agreed that, in patients with preoperative respiratory impairment, non-invasive ventilation initiated before surgery should be considered to optimise respiratory status (8/10, 80.0%).

Radiographic surveillance remained an area of greater uncertainty. Curve progression exceeding 10° within 6 months was consistently identified as an indication for more frequent radiographic assessment and was confirmed by all 10 participating surgeons in Round 3. However, the panel did not reach the predefined 80% threshold regarding the age at which routine radiographic surveillance should begin in non-sitters, sitters, or walkers. No consensus was reached on uniform criteria for discontinuing structured radiographic surveillance. These unresolved questions are presented together with the remaining non-consensus findings in a subsequent section.

Table 3. Statements reaching consensus within the orthopaedic subgroup

Domain	Consensus statement	Round	Orthopaedic surgeons, n/N (%)
Surgical indications	A Cobb angle of 20° alone, irrespective of motor function, should not be considered the primary indication for surgery	1	10/12 (83.3%)
Surgical indications	Progressive spinal deformity accompanied by declining pulmonary function should be considered an important indication for surgery	1	11/12 (91.7%)
Surgical indications	Neurological symptoms alone should not be considered the primary indication for surgery	1	10/12 (83.3%)
Surgical strategy	The preferred upper instrumented vertebra is located in the upper thoracic spine, between T2 and T4	1	11/12 (91.7%)
Preoperative preparation	Optimisation of respiratory function is the highest-ranked component of preoperative preparation	2	10/11 (90.9%)
Surgical strategy	The patient's current functional status—non-sitter, sitter, or walker—should be considered when selecting the surgical management strategy for spinal deformity	3	9/10 (90.0%)
Preoperative assessment	Preoperative assessment of bone mineral density by DXA should be routinely incorporated into surgical planning for patients with SMA undergoing spinal surgery	3	9/10 (90.0%)
Preoperative respiratory management	In patients with preoperative respiratory impairment, non-invasive ventilation initiated before surgery should be considered to optimise respiratory status	3	8/10 (80.0%)
Radiographic surveillance	Curve progression exceeding 10° within 6 months should prompt more frequent radiographic assessment	3	10/10 (100%)

3.5. Physiotherapist-specific findings

Beyond the statements supported by both professional groups, physiotherapists reached consensus on 14 additional items in Round 2. These findings concerned clinical factors influencing surgical referral, the use of the scoliometer, specific preoperative physiotherapy interventions, preoperative education, and the content of early postoperative physiotherapy (Table 4).

In addition to curve progression, which was supported by both professional groups, physiotherapists identified loss of motor function, significant pain, and worsening respiratory function as important non-Cobb factors influencing referral for surgical assessment. Pelvic obliquity did not reach the predefined consensus threshold. Measurement of cervical spine rotation range of motion did not reach the predefined consensus threshold but was supported by a majority of respondents.

Physiotherapists supported the use of the scoliometer for the assessment of the angle of trunk rotation and thoracic deformity.

Specific preoperative physiotherapy was considered to include three-dimensional correction of spinal and pelvic alignment and active autocorrection. Physiotherapists also unanimously agreed that preoperative education should address changing body position, transfers, positioning in sitting and standing, and adjustment of assistive devices such as wheelchairs and standing frames.

Regarding postoperative care, consensus was reached that stretching should be performed with particular caution in the cervical spine, hips, and shoulders. Early postoperative physiotherapy should also include positioning and education of the patient and family. Breathing exercises and changing basic body positions also received strong support from physiotherapists, but these components had already reached consensus in both professional groups and are therefore reported in Tables 2a–c rather than repeated among profession-specific findings.

No consensus was reached on the precise weekly frequency of individual physiotherapy interventions before or after surgery.

Table 4. Statements reaching consensus within the physiotherapist subgroup

Domain	Consensus statement	Round	Physiotherapists, n/N (%)
Surgical referral	Loss of motor function should influence referral for surgical treatment	2	16/17 (94.1%)
Surgical referral	Significant pain should influence referral for surgical treatment	2	17/17 (100%)
Surgical referral	Worsening respiratory function should influence referral for surgical treatment	2	16/17 (94.1%)
Clinical assessment	A scoliometer can be used to assess the angle of trunk rotation	2	17/17 (100%)
Clinical assessment	A scoliometer can be used to assess thoracic deformity	2	16/17 (94.1%)
Preoperative physiotherapy	Specific preoperative physiotherapy should include three-dimensional correction of spinal and pelvic alignment	2	17/17 (100%)
Preoperative physiotherapy	Specific preoperative physiotherapy should include active autocorrection of the spine	2	17/17 (100%)
Preoperative education	Preoperative education should include instruction on changing body position	2	17/17 (100%)
Preoperative education	Preoperative education should include instruction on transfers	2	17/17 (100%)
Preoperative education	Preoperative education should include positioning in sitting and standing	2	17/17 (100%)
Preoperative education	Preoperative education should include adjustment of assistive devices, including wheelchairs and standing frames	2	17/17 (100%)
Postoperative physiotherapy	Postoperative stretching should be performed with particular caution in the cervical spine, hips, and shoulders	2	14/17 (82.4%)
Early postoperative physiotherapy	Early postoperative physiotherapy should include positioning	2	17/17 (100%)
Early postoperative physiotherapy	Early postoperative physiotherapy should include education of the patient and family	2	17/17 (100%)

3.6. Areas without consensus and differences between professional groups

Non-consensus items concerned the influence of DMTs, Cobb-angle thresholds, the role of clinical examination, selected indications for surgery, radiographic monitoring, operative strategy, postoperative standing, and the frequency of physiotherapy interventions.

Neither professional group reached consensus on whether DMTs had reduced the need for spinal surgery. Agreement with this statement was reported by 2 of 11 orthopaedic surgeons (18.2%) and 4 of 17 physiotherapists (23.5%). Responses were also divided regarding whether disease-modifying therapies had fundamentally changed the goals of spinal surgery or had only modified them to a limited extent.

No uniform Cobb-angle threshold for surgical referral was identified in walkers, sitters, or non-sitters. For walkers, the most frequently selected threshold was 41–50° in both groups, chosen by 5 of 11 surgeons (45.5%) and 8 of 17 physiotherapists (47.1%). For sitters, surgeons most commonly selected 41–50° (6/11, 54.5%), whereas physiotherapists most commonly selected 51–60° (9/17, 52.9%). Responses were most dispersed for non-sitters: the most frequent surgical response was a Cobb angle above 60° (4/11, 36.4%), while physiotherapists most commonly indicated that factors other than the Cobb angle were more important (8/17, 47.1%). None of these response options reached the consensus threshold.

Differences between the professional groups were more apparent for non-Cobb factors influencing surgical decision-making. Curve progression exceeding 10° within 6 months reached consensus in both groups. However, loss of motor function was selected by 5 of 11 surgeons (45.5%) compared with 16 of 17 physiotherapists (94.1%). Significant pain was selected by 8 of 11 surgeons (72.7%) and all 17 physiotherapists (100%), while worsening respiratory function was selected by 8 of 11 surgeons (72.7%) and 16 of 17 physiotherapists (94.1%). Thus, these three factors reached consensus among physiotherapists but not among surgeons. Pelvic obliquity did not reach consensus in either group.

The perceived role of clinical examination also differed descriptively between the groups. Seven of 11 surgeons (63.6%) considered clinical examination an auxiliary tool and supported routine radiographic assessment regardless of the clinical findings. In contrast, 9 of 17 physiotherapists (52.9%) regarded clinical examination as the primary screening tool before radiography. Neither position reached the predefined threshold.

Radiographic surveillance remained unresolved after the third round. Among surgeons, the most frequently selected age for initiating routine surveillance was 5–6 years in non-sitters (6/10, 60.0%) and 2–4 years in sitters (7/10, 70.0%). For walkers, monitoring initiated when clinical suspicion arose was the most frequent response (6/10, 60.0%). No option reached 80%. Similarly, no consensus was obtained on when structured radiographic surveillance should be discontinued.

Three additional surgeon-specific statements assessed in Round 3 did not reach consensus. Preoperative halo-gravity traction as a potential treatment option was supported by 5 of 10 surgeons (50.0%). A growth-friendly technique was preferred over postponing surgery until definitive fusion in skeletally immature non-ambulant patients by 7 of 10 surgeons (70.0%). Similarly, prioritising preservation of distal lumbar motion segments in ambulant patients was supported by 7 of 10 surgeons (70.0%). The latter two findings represent majority preferences but do not meet the predefined consensus threshold.

Differences were also observed in the criteria for postoperative standing. Full hip extension was supported by 4 of 11 surgeons (36.4%) and 11 of 17 physiotherapists (64.7%). Flexion contractures not exceeding 10° were supported by 6 of 11 surgeons (54.5%) and 13 of 17 physiotherapists (76.5%). Neither criterion reached consensus in either group. In contrast, the absence of significant pain during standing reached consensus in both groups and is reported among the shared recommendations.

Finally, physiotherapists did not reach consensus on the exact frequency of individual interventions before or after surgery. Responses generally favoured physiotherapy three to seven times per week, but no single frequency category reached the predefined 80% threshold for most interventions. These findings indicate agreement on the content and early initiation of physiotherapy but continuing uncertainty regarding its optimal intensity and frequency. The most clinically relevant non-consensus findings and differences between professional groups are summarised in Table 5. No statistical comparisons between the professional groups were performed.

522 Table 5. Selected areas without consensus and clinically relevant differences in responses between orthopaedic surgeons and
523 physiotherapists.

Item	Orthopaedic surgeons	Physiotherapists	Interpretation
Loss of motor function should influence referral for surgical treatment	5/11 (45.5%)	16/17 (94.1%)	Consensus only among physiotherapists
Significant pain should influence referral for surgical treatment	8/11 (72.7%)	17/17 (100%)	Consensus only among physiotherapists
Worsening respiratory function should influence referral for surgical treatment	8/11 (72.7%)	16/17 (94.1%)	Consensus only among physiotherapists
Clinical examination as primary screening before radiography	1/11 (9.1%)	9/17 (52.9%)	No consensus; descriptive difference
Clinical examination as an auxiliary tool	7/11 (63.6%)	8/17 (47.1%)	No consensus
Full hip extension required for postoperative standing	4/11 (36.4%)	11/17 (64.7%)	No consensus
Flexion contracture ≤10° required for postoperative standing	6/11 (54.5%)	13/17 (76.5%)	Majority preference among physiotherapists, but no consensus
Preoperative halo-gravity traction may be considered as a treatment option in patients with SMA	5/10 (50.0%)	Not assessed	No consensus among orthopaedic surgeons
In skeletally immature non-ambulant patients with progressive spinal deformity meeting surgical indications, a growth-friendly technique should be preferred over postponing surgery until definitive fusion can be performed	7/10 (70.0%)	Not assessed	Majority preference among orthopaedic surgeons, but no consensus
In ambulant patients with SMA, preservation of distal lumbar motion segments should be prioritised when selecting the distal extent of spinal fusion	7/10 (70.0%)	Not assessed	Majority preference among orthopaedic surgeons, but no consensus

524 Data are presented as numbers and percentages. Consensus was defined as agreement of at least 80%.
525 Differences between the professional groups are presented descriptively.

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4. Discussion

This modified Delphi study established interprofessional agreement on the general principles of spinal surveillance and perioperative management in children with SMA. Shared recommendations concerned multidisciplinary decision-making, assessment according to current functional status, complementary clinical and radiographic surveillance, respiratory risk reduction, and function-adapted physiotherapy. The panel did not establish a uniform radiographic schedule or a single Cobb angle threshold for surgical referral. Analysis by profession also revealed differences that might have been obscured by results from the combined panel. Together, these findings support a shared framework for care while leaving several decisions dependent on individual clinical assessment.

The agreement on using current functional status—non-sitter, sitter, or walker—reflects the changing phenotype of SMA in the era of DMTs. Some treated children achieve or retain motor abilities that would have been uncommon for their historical subtype [15,16]. Functional status may therefore be more useful than subtype alone when planning surveillance and perioperative care, consistent with contemporary recommendations [3,5,9]. In Round 3, nine of ten surgeons agreed that functional status should also inform the choice of surgical strategy. It remains one component of assessment alongside skeletal maturity, curve characteristics, respiratory reserve, bone health, treatment history, and the goals of the child and family.

The findings support clinical examination combined with radiographic assessment. Changes in trunk alignment, sitting balance, pelvic position, pain, and function may prompt imaging, while radiographs allow objective measurement of deformity and progression. When obtained, they should be performed in the most gravity-dependent position the child can safely maintain [3,5,9]. Risk-based surveillance pathways in cerebral palsy demonstrate how functional level and age can inform imaging and referral [17–19]. No comparable schedule was established for SMA in this study: the panel did not agree on a uniform starting age or fixed interval for routine radiography. Surveillance should consequently take account of functional status, previous imaging, clinical change, and anticipated progression.

Similarly, the absence of consensus on a single Cobb angle threshold does not negate the role of surgical assessment. Referral for an opinion and the decision to operate serve different purposes. Thresholds proposed in Duchenne muscular dystrophy and Rett syndrome relate to

decisions within those conditions, whereas a cerebral palsy protocol uses earlier radiographic findings to trigger referral [17,20,21]. They cannot be applied directly to SMA. Documented progression or deterioration in sitting, positioning, mobility, comfort, or respiratory management may justify consultation before a definitive operative threshold is reached. Early referral allows longitudinal assessment and preparation without implying immediate surgery.

The professional groups differed in their responses to some potential indications for surgical assessment. Physiotherapists more frequently supported referral in the presence of functional loss, pain, or respiratory deterioration, while surgeons more often remained below the consensus threshold for these factors. Physiotherapists may observe changes in everyday function during longitudinal care [3,22]; surgeons must also weigh radiographic progression, technical options, expected benefit, and perioperative risk [23]. These perspectives make communication between the groups particularly valuable when functional deterioration precedes clear radiographic progression. The differences were descriptive: the groups were small, and no statistical tests were performed to establish between-group differences.

Respiratory optimisation was the surgeons' leading preoperative priority. This accords with SMA standards of care, which address pulmonary assessment, cough effectiveness, airway clearance, and ventilatory support [24]. Planning for scoliosis surgery should include anticipated postoperative respiratory needs; when NIV is likely to be required, establishing its tolerance before surgery may aid postoperative care. Perioperative approaches combining ventilatory and cough-assistance strategies have been described [25], and respiratory preparation features in recent SMA consensus guidance [9]. The agreement reached here concerns management of respiratory risk. It should not be taken as evidence that scoliosis surgery itself improves pulmonary function, for which postoperative findings remain heterogeneous [26].

Round 3 identified consensus among surgeons on two further aspects of preoperative planning. Nine of ten supported routine assessment of bone mineral density by DXA. Bone health is relevant to operative risk in SMA, although DXA results require interpretation in the context of body size, skeletal maturity, deformity, previous fractures, and potential technical difficulties [3]. Eight of ten surgeons also supported considering NIV initiated before surgery in patients with respiratory impairment. This finding reinforces the broader emphasis on respiratory preparation while leaving the indication for NIV dependent on individual assessment [24,25].

Physiotherapy was examined across the surgical pathway because postoperative recovery involves more than correction of the spinal curve. Studies have reported reductions in motor performance after surgery, particularly among patients with higher preoperative function, as well as unmet needs for postoperative rehabilitation support [27,28]. Evidence for individual physiotherapy interventions remains limited: scoliosis-specific exercises have been reported in a case study, and a structured perioperative framework has been described by a single centre [11,29]. The panel agreed on adapting physiotherapy to functional status but did not establish a uniform schedule, content, or intensity for individual interventions. Joint planning by surgeons and physiotherapists is therefore needed, together with prospective evaluation of rehabilitation strategies.

Three additional operative strategy statements in Round 3 did not reach the 80% threshold. Perioperative halo-gravity traction has been used in patients with severe spinal deformity, including those with neuromuscular scoliosis. Watanabe et al. reported its use in 21 patients with curves of at least 100°, including 10 with neuromuscular scoliosis, with significant improvements in major-curve magnitude and space available for the lungs [30]. This supports the clinical relevance of evaluating halo-gravity traction as a potential treatment option in the Delphi process, although it does not establish its routine use in SMA. Five of ten surgeons supported considering preoperative halo-gravity traction in SMA. Seven of ten preferred a growth-friendly technique over postponing surgery until definitive fusion in skeletally immature non-ambulant patients with progressive deformity meeting surgical indications. Seven of ten also supported prioritising preservation of distal lumbar motion segments when selecting the extent of fusion in ambulant patients. These responses indicate majority preferences, not surgeon-specific consensus. The choice of strategy remains individualised.

Other unresolved questions concerned the start and frequency of routine radiography, indications for shorter imaging intervals, the duration of postoperative radiographic follow-up, and the progression of perioperative physiotherapy. An item falling below 80% indicates that the panel could not support a common recommendation; it does not establish that the proposed practice is inappropriate. Variation in scoliosis progression and surgical management in treated SMA further complicates fixed surveillance schedules [4–6,9]. Results from Round 3 must also be identified as surgeon-specific, since physiotherapists did not take part in that round.

Earlier SMA standards and orthopaedic consensus documents provide guidance on multidisciplinary care, surveillance, and surgery, but offer less detail on physiotherapy across the operative pathway [3,5]. More recent recommendations address perioperative care without analysing practising physiotherapists as a separate group [9]. The present study adds independently assessed surgical and physiotherapy perspectives and identifies both shared recommendations and areas where professional or individual judgement remains necessary. These findings may inform local care pathways, provided they are adapted to the child's function, deformity, respiratory status, and treatment history [4].

The study's main strength is its interprofessional and international design, which allowed agreement to be assessed within each group rather than inferred from the combined panel. Anonymous responses, successive rounds, and a predefined 80% threshold supported a transparent consensus process [13,14]. Retention was high across rounds. Nevertheless, purposive recruitment and a relatively small panel limit the generalisability of the findings [13,31]. Patients, caregivers, and several other members of the multidisciplinary team were not represented as separate groups. Some questions differed between professions or were refined between rounds, limiting direct comparisons. Free-text responses informed revisions but were not formally analysed as qualitative data. Round 3 included only surgeons, and observed differences between professional groups were not tested statistically. Finally, consensus establishes expert agreement under limited evidence; it does not demonstrate that a recommended practice improves outcomes [14,31]. The findings also reflect practices in well-resourced healthcare systems and may not be generalisable to regions with limited access to specialised SMA centres or disease-modifying therapies.

Prospective studies should test whether function-based surveillance identifies progressive deformity in time while limiting unnecessary imaging. They should also evaluate perioperative physiotherapy and operative strategies using outcomes meaningful to children with SMA, including function, pain, respiratory complications, recovery of sitting and transfers, and burden on families. Children and caregivers should contribute to the selection of these outcomes. As treatment changes the functional trajectories of SMA, the recommendations will require reassessment against emerging clinical evidence [3,5,9].

This Delphi study established interprofessional consensus on spinal surveillance and perioperative care in children with SMA, integrating radiographic assessment, spine surgery,

655 respiratory management, and physiotherapy. The findings offer a framework for
656 individualised care but require prospective validation as treated phenotypes evolve.
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Competing interests

The author(s) declare no competing interests.

Data availability

The anonymised data supporting the findings of this study and the questionnaires used in all three Delphi rounds are available from the corresponding author upon request.

References:

1. Crawford, T. O. et al. Continued benefit of nusinersen initiated in the presymptomatic stage of spinal muscular atrophy: 5-year update of the NURTURE study. *Muscle Nerve* **68**, 157–170 (2023).

2. Dangouloff, T., Vrščaj, E., Servais, L. & Osredkar, D.; SMA NBS World Study Group. Newborn screening programs for spinal muscular atrophy worldwide: where we stand and where to go. *Neuromuscul. Disord.* **31**, 574–582 (2021).

3. Mercuri, E. et al. Diagnosis and management of spinal muscular atrophy: part 1: recommendations for diagnosis, rehabilitation, orthopedic and nutritional care. *Neuromuscul. Disord.* **28**, 103–115 (2018).

4. Gnazzo, M. et al. Scoliosis in spinal muscular atrophy in the era of disease-modifying therapy: a scoping review. *Neurol. Sci.* **46**, 3431–3442 (2025).

5. Vitale, M. et al. Best practices for the orthopaedic care of children with spinal muscular atrophy: a consensus statement from the European Neuromuscular Centre Standard of Care Orthopaedic Working Group. *J. Pediatr. Orthop. Soc. North Am.* **4**, 296 (2022).

6. Ruythooren, F. & Moens, P. Spinal muscular atrophy scoliosis in the era of background therapies—a review of the literature. *J. Clin. Med.* **13**, 3467 (2024).

7. Shin, H. I. Rehabilitation strategies for patients with spinal muscular atrophy in the era of disease-modifying therapy. *Ann. Rehabil. Med.* **48**, 229–238 (2024).

8. Cammarano, S. et al. Physical and respiratory rehabilitation in spinal muscular atrophy: a critical narrative review. *Appl. Sci.* **15**, 4398 (2025).

9. Gaume, M. et al. French-Belgian consensus statement to managing spinal deformities in children with spinal muscular atrophy treated with SMN restoring therapies. *Arch. Pediatr.* **32**, 538–546 (2025).

10. Timmerberg, J. F. et al. Essential competencies for physical therapist managing individuals with spinal muscular atrophy: a Delphi study. *PLoS ONE* **16**, e0249279 (2021).

11. Kanner, C. H., Rodriguez-Torres, R., Wallach, R., Bakarania, P. & Montes, J. Therapeutic scoliosis-specific exercises for a child with spinal muscular atrophy: a case report. *Pediatr. Phys. Ther.* **37**, 282–287 (2025).

12. Nasa, P., Jain, R. & Juneja, D. Delphi methodology in healthcare research: how to decide its appropriateness. *World J. Methodol.* **11**, 116–129 (2021).

13. Jünger, S., Payne, S. A., Brine, J., Radbruch, L. & Brearley, S. G. Guidance on Conducting and REporting DElphi Studies (CREDES) in palliative care: recommendations based on a methodological systematic review. *Palliat. Med.* **31**, 684–706 (2017).

14. Diamond, I. R. et al. Defining consensus: a systematic review recommends methodologic criteria for reporting of Delphi studies. *J. Clin. Epidemiol.* **67**, 401–409 (2014).

15. Schroth, M. K. et al. Spinal muscular atrophy update in best practices: recommendations for diagnosis considerations. *Neurol. Clin. Pract.* **14**, e200310 (2024).

16. Pane, M. et al. Type I SMA 'new natural history': long-term data in nusinersen-treated patients. *Ann. Clin. Transl. Neurol.* **8**, 548–557 (2021).

17. Latalski, M. et al. The traffic light protocol: preventing the 90° 'point of no return' through risk-stratified spinal surveillance in children with cerebral palsy. *J. Clin. Med.* **15**, 3205 (2026).

18. Hägglund, G., Pettersson, K., Czuba, T., Persson-Bunke, M. & Rodby-Bousquet, E. Incidence of scoliosis in cerebral palsy. *Acta Orthop.* **89**, 443–447 (2018).

19. Vinje, S., Terjesen, T. & Kibsgård, T. Scoliosis in children with severe cerebral palsy: a population-based study of 206 children at GMFCS levels III–V. *Eur. Spine J.* **32**, 4030–4036 (2023).

20. Birnkrant, D. J. et al. Diagnosis and management of Duchenne muscular dystrophy, part 2: respiratory, cardiac, bone health, and orthopaedic management. *Lancet Neurol.* **17**, 347–361 (2018).

21. Downs, J. et al. Guidelines for management of scoliosis in Rett syndrome patients based on expert consensus and clinical evidence. *Spine (Phila. Pa. 1976)* **34**, E607–E617 (2009).

22. de Lemus, M. et al. Identification of the most relevant aspects of spinal muscular atrophy with impact on the quality of life of patients and their caregivers: the PROfuture project, a qualitative study. *J. Patient Rep. Outcomes* **8**, 78 (2024).

765 23. Loughenbury, P. R. & Tsirikos, A. I. Current concepts in the treatment of neuromuscular
766 scoliosis: clinical assessment, treatment options, and surgical outcomes. *Bone Jt. Open* **3**, 85–
767 92 (2022).

768 24. Finkel, R. S. et al. Diagnosis and management of spinal muscular atrophy: part 2:
769 pulmonary and acute care; medications, supplements and immunizations; other organ
770 systems; and ethics. *Neuromuscul. Disord.* **28**, 197–207 (2018).

771 25. Halanski, M. A. et al. Peri-operative management of children with spinal muscular
772 atrophy. *Indian J. Anaesth.* **64**, 931–936 (2020).

773 26. Alhammoud, A., Othman, Y., El-Hawary, R., Mackenzie, W. G. & Howard, J. J. The
774 impact of scoliosis surgery on pulmonary function in spinal muscular atrophy: a systematic
775 review. *Spine Deform.* **9**, 913–921 (2021).

776 27. Dunaway Young, S. et al. Scoliosis surgery significantly impacts motor abilities in higher-
777 functioning individuals with spinal muscular atrophy. *J. Neuromuscul. Dis.* **7**, 183–192
778 (2020).

779 28. Brusa, C. et al. Secondary outcomes of scoliosis surgery in disease-modifying treatment-
780 naïve patients with spinal muscular atrophy type 2 and nonambulant type 3. *Muscle Nerve* **70**,
781 1000–1009 (2024).

782 29. Hu, A. et al. Perioperative management for patients with spinal muscular atrophy
783 undergoing scoliosis surgery: a single-center retrospective study. *Orthop. Surg.* **18**, 1328–
784 1341 (2026).

785 30. Watanabe, K. et al. Efficacy of perioperative halo-gravity traction for treatment of severe
786 scoliosis (≥100°). *J. Orthop. Sci.* **15**, 720–730 (2010).

787 31. Niederberger, M. & Spranger, J. Delphi technique in health sciences: a map. *Front. Public
788 Health* **8**, 457 (2020).

789