



Relationship between early infant motor repertoire and neurodevelopment on the hammersmith infant neurological examination in a developmentally vulnerable First Nations cohort

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ABSTRACT

Aim: To implement a culturally-adapted screening program aimed to determine the ability of infant motor repertoire to predict early neurodevelopment on the Hammersmith Infant Neurological Examination (HINE) and improve Australian First Nations families' engagement with neonatal screening.

Methods: A prospective cohort of 156 infants (55 % male, mean (standard deviation [SD]) gestational age 33.8 (4.6) weeks) with early life risk factors for adverse neurodevelopmental outcomes (ad-NDO) participated in a culturally-adapted screening program. Infant motor repertoire was assessed using Motor Optimality Score-revised (MOS-R), captured over two videos, 11–13⁺ weeks (V1; <14 weeks) and 14–18 weeks (V2; ≥14 weeks) corrected age (CA). At 4–9 months CA neurodevelopment was assessed on the HINE and classified according to age-specific cut-off and optimality scores as; developmentally 'on track' or high chance of either adverse neurodevelopmental outcome (ad-NDO) or cerebral palsy (CP).

Results: Families were highly engaged, 139/148 (94 %) eligible infants completing MOS-R, 136/150 (91 %), HINE and 123 (83 %) both. Lower MOS-R at V2 was associated with reduced HINE scores ($\beta = 1.73$, 95 % confidence interval [CI] = 1.03–2.42) and high chance of CP (OR = 2.63, 95%CI = 1.21–5.69) or ad-NDO (OR = 1.38, 95%CI = 1.10–1.74). The MOS-R sub-category 'observed movement patterns' best predicted HINE, infants who score '4' had mean HINE 19.4 points higher than score '1' (95%CI = 12.0–26.9). Receiver-operator curve analyses determined a MOS-R cut-off of <23 was best for identifying mild to severely reduced HINE scores, with diagnostic accuracy 0.69 (sensitivity 0.86, 95%CI 0.76–0.94 and specificity 0.40, 95 % CI 0.25–0.57). A trajectory of improvement on MOS-R (≥2 point increase in MOS-R from 1st to 2nd video) significantly increased odds of scoring optimally on HINE (OR = 5.91, 95%CI 1.16–29.89) and may be a key biomarker of 'on track' development.

Interpretation: Implementation of a culturally-adapted program using evidence-based assessments demonstrates high retention. Infant motor repertoire is associated with HINE scores and the early neurodevelopmental status of developmentally vulnerable First Nations infants.

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1. Introduction

Infants born preterm, low birth weight or who require neonatal support experience an increased risk of adverse neurodevelopmental outcomes (ad-NDO) including cerebral palsy (CP) [1]. Developmental vulnerability is experienced at higher rates among First Nations children and those living in low-resource settings, impacting lifelong health and development [2]. Identifying infants who require extra support to move, learn and play in the first 1000 days, provides an opportunity to optimise neuroplasticity, positively influencing long-term health, well-being and participation [3]. While screening programs support the early identification of ad-NDOs, First Nations Australians demonstrate low retention (~50 %) in neonatal follow-up programs and experience inequities in access to specialised services and culturally responsive healthcare [4]. Re-thinking models of care to overcome the structural, geographical and cultural barriers are a priority for improving engagement and access to culturally responsive health services for First Nations families [5].

Early screening aims to identify an infant's risk status for a range of ad-NDOs [6]. Appropriate tools should be predictive, valid, reliable and feasible for use across multiple settings, promoting equity in healthcare [7]. Strong evidence supports the use of Prechtl's General Movements Assessment (GMA) and the Hammersmith Infant Neurological Examination (HINE) [8,9] to identify CP, non-CP ad-NDOs [10] and developmental delays [11–13]. The HINE demonstrates strong predictive accuracy for diagnostic outcomes, with age-specific cut-off scores differentiating infants developing 'on track' from those with a 'high chance' of CP [14] and/or significant delays [11,15]. Additionally, HINE global scores are a prognostic indicator of CP severity [14], topography [16] and gross motor abilities [17], however diagnostic accuracy on the HINE improves with age, with global scores from 6 months corrected age (CA) demonstrating stronger associations with non-CP outcomes at 2 years [11,15]. Absent fidgety movements (FMs) are the strongest predictor of CP [8] with good predictive accuracy for severe motor and cognitive delays [12], however are less sensitive to detect milder delays [13,18] and/or non-CP ad-NDOs [10,19]. Additionally, the quality and temporal organisation of FMs does not provide prognostic information regarding the functional severity of CP.

Recent research has focused on the predictive relationship between infant motor repertoire and neurodevelopmental outcomes. The Motor Optimality Score-revised (MOS-R) assesses the quality of an infant's movements and postures in addition to FMs [20] and may be an early biomarker for non-CP ad-NDOs [21]. Reduced MOS-R scores have been associated with motor, cognition and communication delays in preterm and low birthweight populations, despite the presence of normal FMs [22], providing early markers for CP subtype, topography and functional outcome [20,21].

While studies have investigated the diagnostic accuracy of MOS-R [21] and infant developmental trajectories on FMs and HINE to predict NDOs [23,24], to date no studies have explored the predictive relationship between MOS-R and the HINE. The primary aim of this study was to evaluate the accuracy of tools used for CP early detection (FMs and MOS-R) to predict neurodevelopmental status on HINE at 4–9 months corrected age (CA) to earlier identify developmental vulnerability in a cohort of First Nations infants. We aimed to determine whether accuracy of prediction was impacted by the timing of MOS-R assessment (<14 weeks vs ≥14 weeks) and/or improved with the use of infant MOS-R trajectories (2 videos) to guide recommendations for clinical implementation. Our secondary aim was to evaluate whether implementing a culturally-adapted screening program improved the engagement of First Nations families with neonatal follow-up services.

2. Methods

2.1. Study design and participants

This prospective cohort study invited families of First Nations infants to participate in a culturally-adapted early screening program (Learning through Everyday Activities with Parents; LEAP-CP), as per the published protocol [4]. Infants who experienced increased developmental vulnerability due birth (i.e. born preterm (<37 weeks), low birthweight (<2500 g), Hypoxic Ischemic Encephalopathy; HIE, admission to a neonatal unit), post-neonatal (i.e.: head injury, stroke, infection, non-accidental injury) or maternal (i.e.: medical conditions, pregnancy complications, antenatal substance use) risk factors met eligibility for study inclusion.

2.2. Procedure and data collection

Participants were recruited prior to 9 months CA across three health services, in Queensland, Australia (birth years 2020–2022) and completed screening at two timepoints. At Screening timepoint 1 (S1; 11–18.0 weeks CA) infants completed GMA, aiming for two videos, two weeks apart between 12- and 16 weeks CA, at clinic appointments or on caregiver's phone via the Baby Moves App [25]. Advanced GMA-trained assessors masked to perinatal history assessed the MOS-R from videos captured at, 11 to 13⁺6 (V1; <14 weeks) and 14 to 18 (V2; ≥14 weeks) weeks CA. At Screening Timepoint 2 (S2; 4–9 months CA) infants completed the HINE, administered and scored by locally trained clinicians, and two multi-domain developmental screening tools (Fig. 1).

2.3. Culturally-adapted screening program

To promote engagement and participation in early screening programs we considered the cultural barriers and enablers to accessing current neonatal follow-up services. Both culturally-specific (use of language, resources, cultural engagement) and clinically-specific (workforce, environment, tools) changes to current health service models were required to create a novel, culturally responsive model of care for early screening (Table SIII). First Nations families' engagement with the program was measured using percentage retention at each screening timepoint.

2.4. Screening timepoint 1 (S1): 11–18 weeks CA: Fidgety movements and Motor Optimality Score-Revised

Firstly, we assessed the quality of FMs, then the infant's concurrent motor repertoire on MOS-R across five sub-categories, FMs, observed movement patterns, age-adequate movement repertoire, observed postural patterns and movement character, each scored separately and combined to gain a total optimality score (range 5–28), with higher scores indicating greater optimality. For analyses, MOS-R scores were further classified according to optimality category [20,26] and MOS-R trajectory (Fig. 1). Additional analyses were performed to understand the predictive relationship between the additional MOS-R sub-categories and neurodevelopmental status above FMs alone.

2.5. Screening timepoint 2 (S2): 4–9 months CA: Hammersmith Infant Neurological Examination

The HINE assesses 26 items of infant neuromotor function across five scoreable domains, cranial nerve function, posture, movements, tone, reflexes and reactions. Individual items are scored (range 0–3) with higher scores representing a more optimal response [27]. Item scores are summed to determine a global optimality score, with a maximum possible score of 78. Global scores were compared to age-specific optimality and cut-off scores to determine the risk of ad-NDOs and/or CP [11,14,27] and classify neurodevelopmental status as; developing 'on

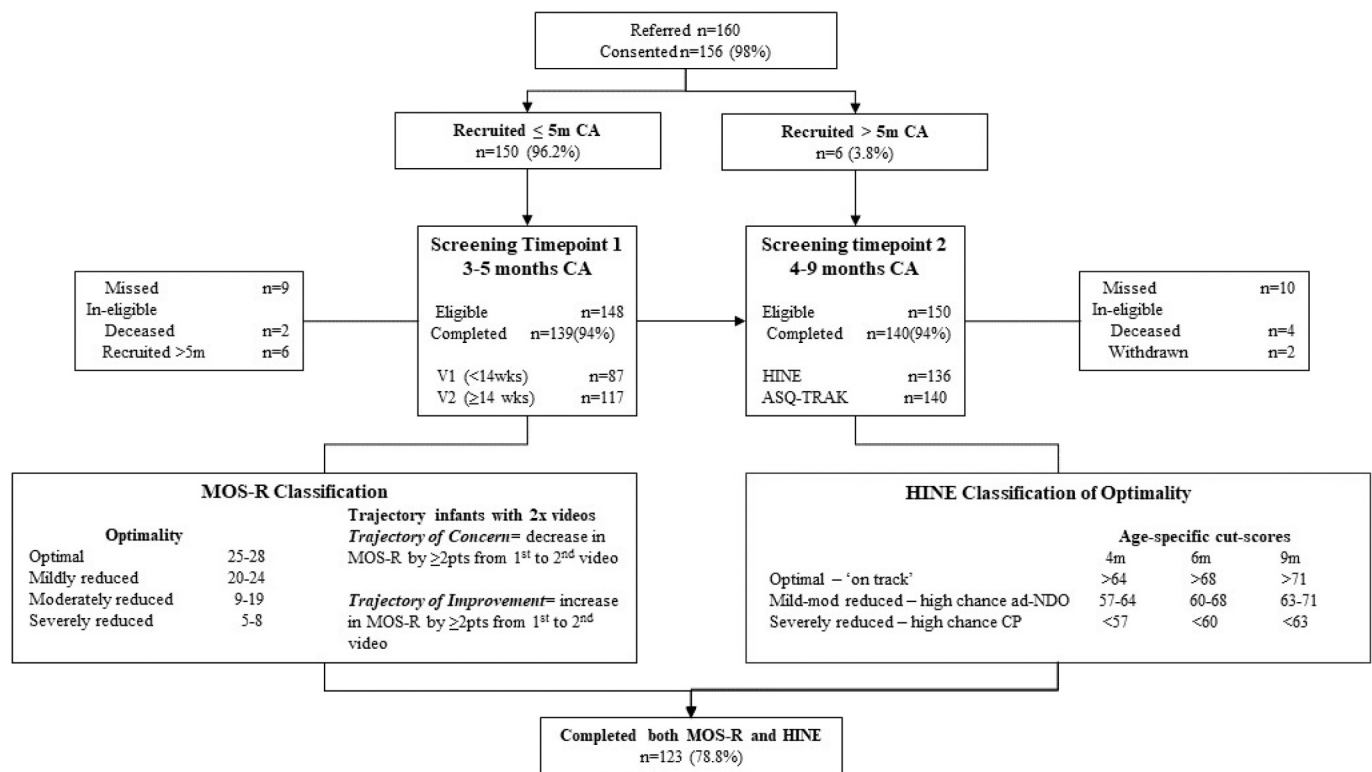


Fig. 1. Flow of study. Abbreviations: ad-NDO = adverse neurodevelopmental outcome, ASQ-TRAK = Ages and Stages Questionnaire- Talking about Raising Aboriginal Kids, CA = corrected age, CP=Cerebral Palsy, HINE = Hammersmith Infant Neurological Examination, m = months, MOS-R = Motor Optimality Score-revised, n = number, V1 = Video 1, V2 = Video 2, wks = weeks.

track’, ‘high chance of ad-NDO’ or ‘high chance of CP’ (Fig. 1). Differences observed in item responses between the left and right sides were recorded as asymmetries. For sub-analyses of CP severity and topography, HINE scores <40 were used to indicate severe CP [14], with ≥ 5 asymmetries on HINE used for high chance of unilateral CP [16].

2.6. Data and statistical analysis

Summary statistics are presented as mean; standard deviation (SD) for continuous variables and frequency (percentage) for categorical variables. The association between continuous variables and neurodevelopmental status were evaluated using Kruskal-Wallis test, and between categorical variables and neurodevelopmental status using Fisher’s exact test. The relationships between total MOS-R, subcategory scores and neurodevelopmental status were determined using linear regression models for HINE global score and multinomial logistic regression for infant neurodevelopmental status. First univariable analyses were conducted for MOS-R and FMs (absent). Two multivariable models were constructed: model one included MOS-R and FMs (absent) as predictors, to determine the predictive relationship between the additional MOS-R sub-categories and neurodevelopmental status when controlled for FMs. Model two included MOS-R, gestational age, male sex, presence of significant brain injury (i.e. hypoxic ischemic encephalopathy, Intraventricular haemorrhage Grade III-IV or periventricular leukomalacia). Three covariables known to be associated with increased ad-NDO. All analyses were performed including infants assessed at one and/or both MOS-R timepoints. Receiver operator curve (ROC) analysis and diagnostic statistics (sensitivity, specificity, positive and negative predictive values) were calculated to determine accuracy of MOS-R to predict neurodevelopmental status. Additional sub-analyses were undertaken to determine the predictive relationship between severely reduced MOS-R (<9) and severity of CP (HINE <40) [14] and asymmetry of finger postures on MOS-R and high chance of unilateral CP (HINE ≥ 5

asymmetries) [16]. First Nations engagement with the program was measured using percentage retention compared to historical data. Significance was $p < 0.05$, with analyses performed using STATA, version 17 [28].

3. Results

A total 156 of 160 (97 %) eligible First Nations infants consented to participate in the LEAP-CP screening program. Families demonstrated high engagement with 139/148 (94 %) eligible infants completing assessments at S1 (FMs, MOS-R) and 140/150 (93 %) at S2 (HINE, ASQ-TRAK). Of these, 123 infants (51 % male, mean (SD) gestational age 33.3 (4.5) weeks) completed both MOS-R and HINE assessments (Fig. 1). Infant characteristics are outlined in Table 1.

Of the 123 infants, 48 (39 %) were classified as developmentally ‘on track’, 46 (37 %) high chance of ad-NDO and 29 (24 %) high chance of CP (Table 1). HINE scores differed significantly between neurodevelopmental groups, infants who were developing ‘on track’ (mean (SD) 71.3 (2.9)) demonstrated higher HINE scores than those with high chance of ad-NDO (64.1 (2.8)) or CP (48.9 (11.5)), regardless of age at assessment ($p < 0.0001$, Table 1). More infants completed MOS-R at V2 (≥ 14 wks, $n = 107$) than V1(<14wks, $n = 96$), with 82 (67 %) completing MOS-R at both timepoints (Table 1). The relationship between total MOS-R, sub-categories and neurodevelopmental status on HINE are detailed in Table 2. MOS-R demonstrated a significant positive association with HINE global score at both V1 and V2 (Fig. 2). Infants with high chance of CP demonstrated significantly lower MOS-R at V1 (mean (SD), 16.4 (6.5)) and V2 (14.0 (6.5)) than those at high chance of ad-NDO (V1; 21.3 (2.5), V2; 20.9 (2.7)) or on-track developmentally (V1; 22.0 (4.1), V2; 22.1 (2.9)). Infants developing ‘on track’ had significantly higher MOS-R at V2 than those high chance of ad-NDO ($p = 0.032$, Fig. 3).

The uni- and multivariable relationships between FMs, MOS-R and

Table 1
Infant characteristics, early life risk factors and outcomes, $n = 156$ infants.

	Infants with MOS-R and HINE $n = 123$	Infants with incomplete data $n = 33$	Missing $n(\%)$
Gestational age (weeks), mean (SD)	33.3 (4.5)	35.4 (4.4)	
VPT (<32 weeks) $n(\%)$	42 (34.2)	6 (18.2)	
Birthweight (g), mean (SD)	2075.3 (959.4)	2593.2(955.0)	
HIE, $n(\%)$	5(4.1 %)	2 (6.1)	
Therapeutic cooling	3(2.4 %)	1 (3.0)	
Seizures	10(8.1 %)	3 (9.1)	
Bronchopulmonary dysplasia	24(19.5)	3(9.0)	1(3.0)
Multiple birth	33(26.8)	6(18.2)	
Neonatal surgery	16(13.0)	3(9.0)	5(15.2)
Post-neonatal injury	5(4.1)	3 (9.0)	
Sex			
Male	63(51.2)	23 (69.7)	
Cultural identity			
Aboriginal	62(50.4)	26(78.8)	
Torres Strait Islander	13(10.6)	2(6.1)	
Both	48(39.0)	5(15.1)	
Neuroimaging			
CUS	71(58.2)	8 (25.8)	2(6.5)
MRI	23(18.7)	6 (18.2)	
Both	17(13.8)	3(9.1)	
IVH	13(10.6)	1(3.0)	
PVL	3(2.4)	0(0.0)	
Stroke	0(0.0)	0(0.0)	
Other brain abnormalities	3(2.4)	1 (0.0)	
Screening Timepoint 1 (3–5 months), $n = 139$			
<14 weeks, $n(\%)$	87 (70.7)	9 (27.3)	
Corrected age at assessment (weeks), mean (SD)	12.3 (0.7)	12.2 (0.6)	
Absent/abnormal FMs, $n(\%)$	14 (16.1)	1 (11.1)	
MOS-R median (IQR)	21 (20–23)	21 (20–23)	
≥14 weeks, $n(\%)$	107 (80.5)	10 (30.3)	
Corrected age at assessment (weeks), mean (SD)	14.9 (1.0)	15.3 (1.6)	
Absent/abnormal FMs, $n(\%)$	17 (15.9)	1 (9.1)	
MOS-R median (IQR)	21 (20–22)	21.5 (20–23)	
Screening Timepoint 2 (4–9 months), $n = 140$	123(100.0)	13 (39.4)	
Corrected age at HINE (months), mean (SD)	6.1 (1.3)	6.4 (1.5)	
Global HINE score, mean (SD)	63.3 (10.5)	65.4 (8.7)	
Optimal (on-track), $n = 48$, mean (SD)	71.3 (2.9)	6 (46.1)	
Mild-mod red. (high chance ad-NDO), $n = 46$, mean(SD)	64.1 (2.8)	5 (38.5)	
Severely reduced (high chance CP), $n = 29$, mean(SD)	48.9 (11.5)	2 (15.4)	
Asymmetries ≥5 $n(\%)$	27 (22.0)	2 (15.4)	

Abbreviations: ad-NDO = adverse neurodevelopmental outcome, CP = cerebral palsy, CUS = cranial ultrasound, g = grams, FMs = Fidgety Movements, HIE = Hypoxic Ischemic Encephalopathy, HINE = Hammersmith Infant Neurological Examination, IQR = inter-quartile range, IVH = intraventricular haemorrhage, MOS-R = Motor Optimality Score-revised, mild-mod red. = mild-moderately reduced, MRI = magnetic resonance imaging, n = number of participants, on-track = typically developing, PVL = periventricular leukomalacia, SD = standard deviation, VPT = very preterm birth (<32 weeks), % = percentage.

HINE are reported in Table 3. MOS-R explained a higher proportion of variance than FMs alone for HINE global score and neurodevelopmental status. Relationships improved when corrected for absent FMs (model 1), with MOS-R at V2 differentiating between neurodevelopmental outcomes. FMs were not associated with ad-NDO at either V1 or V2. Relationships remained strong for predicting high chance of CP and HINE global scores when adjusted for perinatal variables (model 2). When the total cohort was included, MOS-R differentiated infants with high chance ad-NDO from those ‘on track’ in all models. Model 2 demonstrated the highest proportion of variance, for each 1-point MOS-

R decrease the odds of high chance ad-NDO (OR = 1.32, 95%CI 1.05–1.64) and CP (OR = 3.04, 1.46–6.32) increased compared to ‘on track’.

The MOS-R sub-category ‘observed movement patterns’ best predicted HINE score, with ‘age-adequate movement repertoire’ the least predictive (Table 3). At V2, infants who score ‘2’ (typical = atypical) or ‘4’ (typical > atypical) for ‘observed movement patterns’ have HINE scores on average 19.1 or 19.4 points higher, respectively, than those who score ‘1’ ($p < 0.001$). Detailed analysis of observed movements, postures and movement character by neurodevelopmental status (Table SI) found infants high chance of CP demonstrated more atypical movements, postures and a stiff movement character. Infants high chance of ad-NDO demonstrated monotonous movements, while infants ‘on track’ were more likely to demonstrate smiles, hand-to-hand contact, body symmetry and variability of finger postures.

Receiver-operator curve analyses determined a MOS-R cut-off of <23 best predicted high chance of ad-NDO/CP on HINE with cut-off <20 for high chance of CP. MOS-R < 23 demonstrated greater predictive accuracy for high chance of ad-NDO/CP than FMs alone (Table 4). Diagnostic accuracy was strongest at V2, 69 % accuracy (Sensitivity [Se] = 0.86, Specificity [Sp] = 0.40) compared to V1, 63 % accuracy (Se = 0.71, Sp = 0.51). A MOS-R < 20 demonstrated similar accuracy as absent FMs for predicting CP, with overall lower sensitivity (V1 = 0.43, V2 = 0.52) but higher specificity (0.95) compared to prediction of ad-NDO/CP. For the 82 infants with two MOS-R videos, a consistently low MOS-R (<23) or trajectory of concern (≥ 2 point decrease in MOS-R from 1st to 2nd video) were 72 % accurate (Se = 0.88, Sp = 0.44) for high chance of ad-NDO/CP on HINE. In contrast, a trajectory of improvement (≥ 2 point increase in MOS-R from 1st to 2nd video) increased odds of developing ‘on track’ compared to high chance of ad-NDO (OR = 5.91) and CP (OR = 9.50, Table 3).

Sub-analyses for severity and topography of CP (Table SII), revealed significant associations between severely reduced MOS-R (<9) and HINE (<40), demonstrating high predictive accuracy at both V1 and V2 (Se = 1.00, Sp = 0.99–1.00). Early asymmetry of finger postures on MOS-R was associated with increased odds of ≥ 5 asymmetries on HINE (Table SII).

4. Discussion

This study demonstrated a strong predictive relationship between MOS-R and early neurodevelopmental status in a cohort of developmentally vulnerable Australian First Nations infants. Families demonstrated high participation in the culturally-adapted screening program, with improved retention at 9 months CA compared to previously offered neonatal follow-up (93 % vs ~50 %). Higher MOS-R scores at both video timepoints (V1:<14wks and V2:≥14wks) were strongly associated with higher HINE global scores and ‘on track’ development. When controlled for absent FMs, MOS-R at V2 differentiated infants developing ‘on track’ from those at high chance CP and ad-NDO. The sub-category ‘observed movement patterns’ best predicted HINE global score and neurodevelopmental status, with absent FMs a strong predictor of lower HINE scores and high chance of CP. Early identification of infants with a higher chance of ad-NDOs promotes timely access to targeted support services. This is the first study to implement evidence-based CP early detection tools to predict CP and/or ad-NDOs in an Australian First Nations cohort.

The MOS-R is a key early biomarker for later infant neurodevelopmental outcomes and, as it is scored concurrently with FMs, it is a cost-effective, accessible, transdiagnostic tool. Earlier identification of infants with high chance of ad-NDO/CP is imperative for linking families with appropriate services to optimise infant outcomes. In our cohort, the MOS-R demonstrated promising predictive ability for HINE global score and early neurodevelopmental status. Compared to FMs alone, MOS-R demonstrated substantially higher predictive accuracy for mild to severely reduced HINE global score (ad-NDO/CP), with similar

Table 2

Total Motor Optimality Score-revised and subcategory frequency, by video (V1 vs V2) and outcome, n = 123 infants.

	V1 (<14 wks) n = 87				V2 (≥14 wks) n = 107			
	On-track n = 35 (40.3 %)	High chance ad-NDO n = 29 (33.3 %)	Cerebral Palsy n = 23 (26.4 %)	p-value*	On-track n = 40 (37.4 %)	High chance ad-NDO n = 42 (39.2 %)	Cerebral Palsy n = 25 (23.4 %)	p-value*
MOS-R mean (SD)	22.0 (4.1) ⁺⁺	21.3 (2.5) ⁺⁺	16.4 (6.5) ⁺		22.1 (2.9) ⁺	20.9 (2.7) ⁺	14.0 (6.5) ⁺	
Classification								
Optimal (25–28)	8 (22.9)	0 (0.0)	0 (0.0)	<0.001	8 (20.0)	2 (4.8)	0 (0.0)	<0.001
Mild reduced (20–24)	24 (68.6)	27 (93.1)	13 (56.6)		31 (77.5)	37 (88.1)	12 (48.0)	
Mod. reduced (9–19)	3 (8.5)	2 (6.9)	7 (30.4)		1 (2.5)	3 (7.1)	7 (28.0)	
Sev. reduced (5–8)	0 (0.0)	0 (0)	3 (13.0)		0 (0.0)	0 (0.0)	6 (24.0)	
Fidgety movements								
Normal	32 (91.4)	27 (93.2)	14 (60.9)	0.001	39 (97.5)	39 (92.9)	12 (48.0)	<0.001
Abnormal	1 (2.9)	1 (3.4)	0 (0.0)		0 (0.0)	3 (7.1)	0 (0.0)	
Absent	2 (5.7)	1 (3.4)	9 (39.1)		1 (2.5)	0 (0.0)	13 (52.0)	
Movement patterns								
Normal>atypical	35 (100.0)	29 (100.0)	19 (82.6)	0.004	40 (100.00) ⁺⁺	41 (97.6) ⁺⁺	19 (76.0) ⁺	<0.001
Normal = atypical	0 (0.0)	0 (0.0)	2 (8.7)		0 (0.0)	1 (2.4)	0 (0.0)	
Atypical>Normal	0 (0.0)	0 (0.0)	2 (8.7)		0 (0.0)	0 (0.0)	6 (24.0)	
Age-adequacy								
Present	16 (45.7)	10 (34.5)	5 (21.7)	0.259	10 (25.0)	3 (7.1)	1 (4.0)	0.05
Reduced	14 (40.0)	14 (48.3)	10 (43.5)		15 (37.5)	22 (52.4)	9 (36.0)	
Absent	5 (14.3)	5 (17.2)	8 (34.8)		15 (37.5)	17 (40.5)	15 (60.0)	
Postural patterns								
Normal>atypical	8 (22.9)	3 (10.3)	0 (0.0)	0.056	13 (32.5)	9 (21.4)	0 (0.0)	0.004
Normal = atypical	7 (20.0)	3 (10.3)	3 (13.0)		7 (17.5)	4 (9.5)	1 (4.0)	
Atypical>Normal	20 (57.1)	23 (79.4)	20 (87.0)		20 (50.0)	29 (69.1)	24 (96.0)	
Movement Character								
Smooth and Fluent	3 (8.6)	0 (0.0)	0 (0.0)	0.068	2 (5.0)	1 (2.4)	0 (0.0)	0.406
Abnormal not CS	32 (91.4)	29 (100.0)	22 (95.7)		38 (95.0)	41 (97.6)	24 (96.0)	
CS	0 (0.0)	0 (0.0)	1 (4.3)		0 (0.0)	0 (0.0)	1 (4.0)	

Abbreviations: ad-NDO = adverse neurodevelopmental outcome, CS = cramped-synchronised, mild reduced = mildly reduced, mod.reduced = moderately reduced, MOS-R = Motor Optimality Score-revised, n = number, SD = standard deviation, on-track = typically developing, Sev.reduced = severely reduced, V1 = video 1, V2 = video 2, wks = weeks, * = Fisher's exact, + = significant difference ($p \leq 0.05$), ++ = non-significant difference ($p > 0.05$).

predictive accuracy for high chance of CP as FMs. The relationship between MOS-R and HINE was strongest at V2 and improved when adjusted for absent FMs, indicating that the additional MOS-R sub-categories provide key predictive information for infant neurodevelopment above FMs alone.

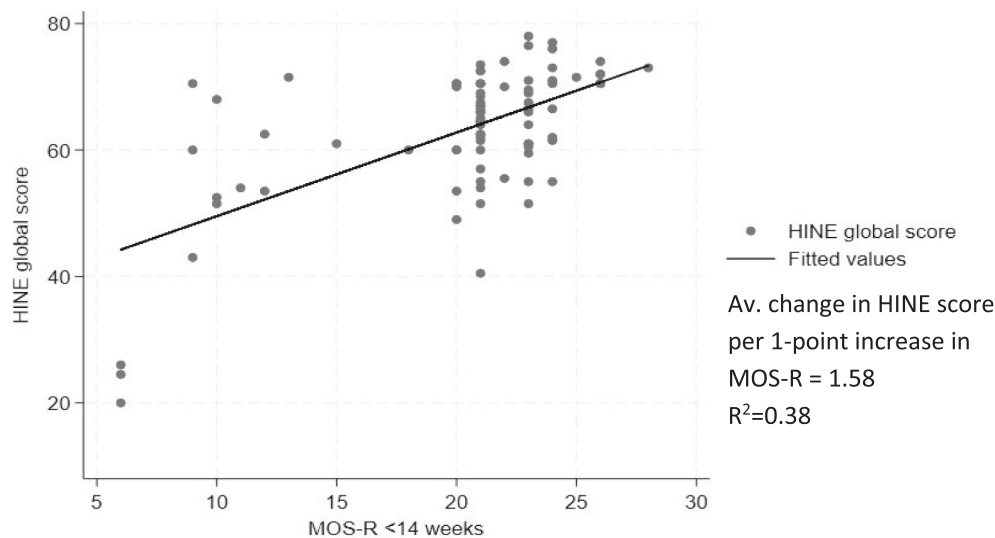
Our findings concur with previous studies reporting consistent associations between MOS-R and neurodevelopmental outcomes, including CP and/or cognitive and motor delays, at 2 years in very (VPT) [21,22,29] and extremely preterm (EPT) [25] populations, even with the exclusion of sub-category 'fidgety movements' from the total optimality score [18]. We now add to these studies that a MOS-R < 23 provided the best predictive accuracy for identifying infants with high chance of ad-NDO or CP. Using MOS-R cut-off at <23 substantially improved sensitivity and the negative predictive value (NPV) compared to FMs alone, decreasing the rate of false negatives. MOS-R < 23 however had a higher rate of false positives, reflecting a lower specificity. The trade-off for a lower specificity means that some infants may be fast-tracked to support services unnecessarily, however, it is less likely to miss infants with a higher chance of ad-NDO/CP who would benefit from intervention. This is supported by the relatively high positive predictive values associated with MOS-R < 23 which are promising for ensuring almost all infants with high chance of ad-NDO/CP are identified earlier. In the context of our reported high NPVs, when FMs are present or when MOS-R is >20 there is a relatively low chance of CP.

Currently MOS-R < 21 is the recommended indicator for early

intervention [30], however, cut-off-scores for prediction of non-CP ad-NDOs vary, with reported MOS-R ranging from <21 to <24 [22,30,31]. This variability is likely due to population differences across studies, VPT [22], EPT [30], neonatal surgery [31], timing of follow-up (>2 years CA) and reported outcomes. Our cohort included infants with a broader range of risk factors with outcomes at a much earlier age (<9 months CA). The findings from our study may be useful to guide the timing of clinical follow-up and surveillance for infants with a range of early risk factors.

In line with previous studies [21,31], classification of MOS-R and specific sub-categories were more predictive of outcomes. In our multivariable model, 'observed movement patterns' demonstrated the strongest relationship to HINE, infants who scored optimally had significantly higher HINE than those who scored non-optimal at both timepoints. 'Observed postural patterns' and 'fidgety movements' were strong predictors of HINE, with significant associations for infants who scored optimally compared to those who scored atypical/absent. Interestingly, 'age-adequate repertoire' was not associated with neurodevelopmental status. Overall a low number of infants demonstrated optimal age-adequacy, decreasing from 38 % at V1 to 13 % at V2. This is consistent with recent cohorts [31] and suggests that an age-adequate movement repertoire is difficult to achieve, even for infants who are developing 'on track'. While associations between 'movement character' and HINE were not significant, likely due to the high number of infants (~95 %) who scored non-optimal, infant neurodevelopmental status

A. Motor Optimality Score-revised (MOS-R) <14 weeks, n=87



B. Motor Optimality Score-revised (MOS-R) ≥14 weeks, n=107

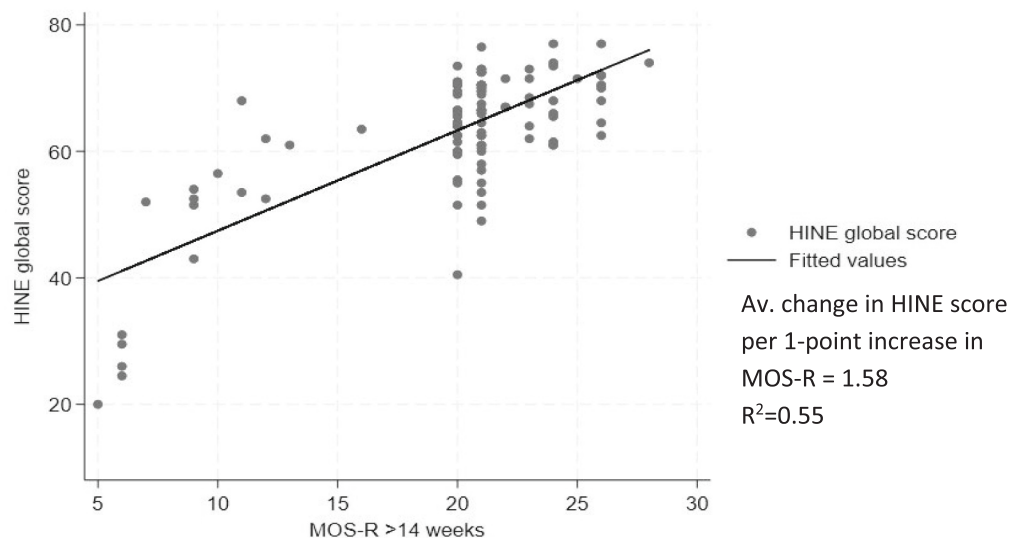


Fig. 2. Relationship between Hammersmith infant neurological examination (HINE) global score and Motor Optimality Score-revised, comparison of <14 weeks and ≥ 14 weeks n = 123 infants. Abbreviations: Av. = average, HINE = Hammersmith Infant Neurological Examination, MOS-R = Motor Optimality Score-revised, n = number.

was associated with specific movement characters. Movements of infants with high chance of ad-NDO were more monotonous, reflecting previous findings of autism, substance exposure, genetic conditions and cognitive delay cohorts [21]. Comparatively, infants with high chance of CP demonstrated stiffer movements, while movements of those developing ‘on track’ were characteristically jerky.

The association between MOS-R classification and neuro-developmental status was strongest when infant motor repertoire was clearly optimal or severely reduced. Of note, the majority of infants demonstrated a ‘mildly reduced’ (score 20–24) motor repertoire at V2, including 77 % of infants ‘on track’, suggesting that this classification has varied outcomes. Of those developing ‘on track’, 62 % scored MOS-R ≥ 23 compared to only 22 % of infants with high chance of ad-NDO or CP, further supporting the relevance of a cut-off score. Similar to

previous studies [20], MOS-R demonstrated excellent prognostic ability for severity of CP, with ‘severely reduced’ scores (MOS-R < 9), highly predictive of HINE scores <40, which are associated with severe CP (GMFCS IV-V) [14]. Only infants with ‘severely reduced’ MOS-R and HINE demonstrated circular arm movements, consistent with previous findings that these predict severe CP [20]. In our study 100 % of infants with ‘severely reduced’ MOS-R on both videos scored <40 on HINE, confirming the importance of infant trajectory as a predictor of later outcomes.

To our knowledge this is the first study to report on the predictive value of an infant’s MOS-R trajectory and whether a change in MOS-R score (±2 points) from first to second video is significant. A trajectory of improvement (+2 points) was significantly associated with higher HINE global scores and ‘on track’ development. Comparatively,

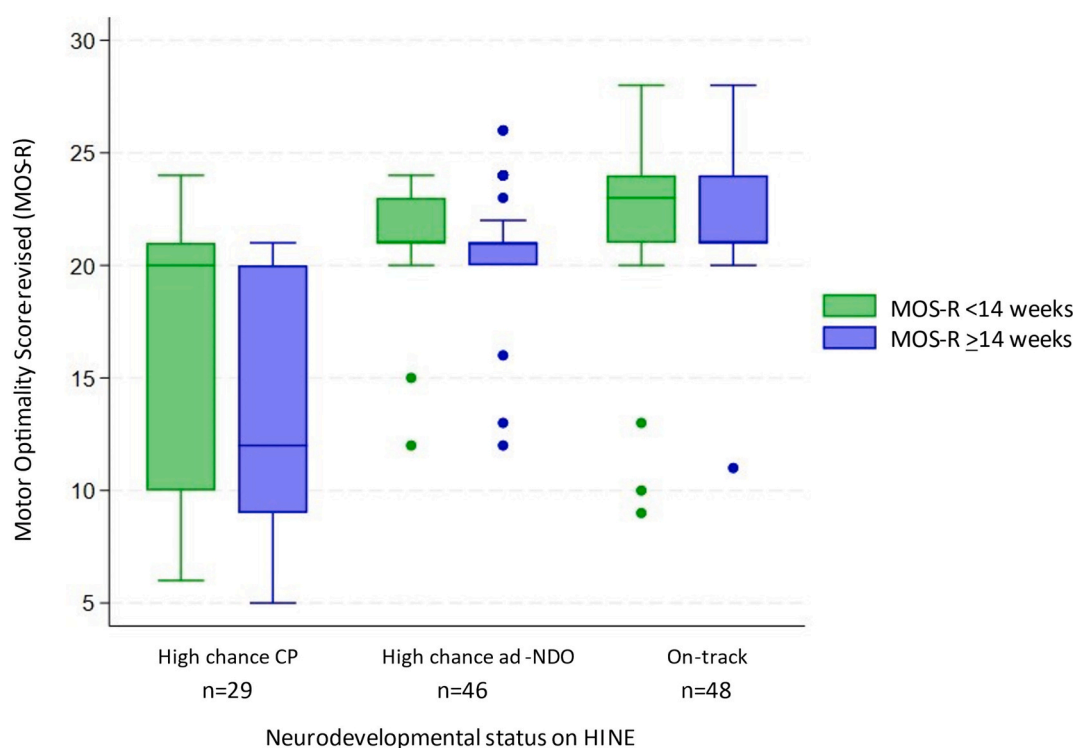


Fig. 3. Relationship between Motor Optimality Score-revised (MOS-R) and neurodevelopmental status, comparison of <14 weeks and ≥14 weeks $n = 123$ infants. Abbreviations: ad-NDO = adverse neurodevelopmental outcome, CP = cerebral palsy, MOS-R = Motor Optimality Score-revised, n = number, on-track = developing on track.

persistence of early asymmetry of finger postures on MOS-R increased odds of scoring ≥ 5 asymmetries on the HINE, which is linked with an increased risk of unilateral CP [16]. A consistently low MOS-R score (<23) and/or trajectory of concern (-2 points) across two videos demonstrated improved diagnostic accuracy compared to a single MOS-R (<23) at V1 or V2. The importance of a change in MOS-R scores across subsequent assessments needs to be explored in larger cohorts of infants with diagnostic and neurodevelopmental outcomes at later ages.

Earlier identification of infants developing 'on track' may streamline service models, decreasing low-value healthcare and improving clinical resource allocation. Our culturally-adapted program aimed to promote First Nations families' engagement with, and access to, existing health services by designing a program that utilised evidence-based tools, encompassed within a First Nations framework and embedded into current models of care. First Nations families, including 91 % living in regional, rural and remote locations, demonstrated high engagement in early screening. Our multi-site study utilised locally trained clinicians and health workers to complete HINE and capture MOS-R videos, which were scored centrally by advanced-trained clinicians. Families were offered flexibility in accessing the program through home visits and were empowered to be active participants in their child's developmental journey through use of tools that promoted caregiver participation (Baby Moves app). This model is feasible and can be utilised in low-resource, rural and/or remote settings with limited access to specialist services.

4.1. Strengths and limitations

No significant associations were found between total MOS-R and gestational age. This is promising when considering clinical implementation and the use of cut-off scores to determine which infants may require closer monitoring or referral to intervention services.

A limitation is our early follow-up time-point with outcomes based solely on HINE scores. We reported 24 % of infants as high chance of CP,

a potential overestimation, given almost 50 % demonstrated normal FMs. Diagnostic outcomes at a later age are required to confirm the predictive accuracy of the MOS-R in this cohort. All clinicians who administered and scored the HINE were masked to MOS-R scores, however, given this was a pragmatic real-world study, they were not always masked to infant perinatal information or local FM scores. To ensure accuracy in scoring, 10 % of HINEs from each site were scored by assessors masked to infant perinatal information and early screening outcomes, with 'excellent' inter-assessor reliability (intraclass correlation coefficient = 0.90, 95%CI = 0.69–0.97) between local and masked assessors.

5. Conclusion

The MOS-R was a strong predictor of early HINE scores with higher MOS-R associated with higher HINE global scores and increased odds of 'on track' development in Australian First Nations infants. The MOS-R at ≥ 14 weeks CA had a stronger association with HINE, however capturing two videos improved predictive accuracy, with a trajectory of improvement associated with optimal HINE scores. The MOS-R was a stronger predictor of ad-NDOs than FMs alone and could be implemented to guide the timing of high-risk infant follow-up and early referral to intervention services. Implementation of a culturally-adapted screening program improved First Nations families' engagement with early screening. Future research should focus on the significance of infant MOS-R trajectories and the predictive accuracy of MOS-R across broader risk cohorts.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.earlhumdev.2024.106004>.

CRediT authorship contribution statement

Carly Luke: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration,

Table 3

Relationship between Motor Optimality Score-revised and Hammersmith Infant Neurological Examination, n = 123 infants.

	Model	Neurodevelopmental status		High chance CP	p-value	R ²
		High chance ad-NDO				
		OR (95 % CI)	p-value	OR (95 % CI)	p-value	R ²
Reference group: on-track						
V1 < 14 wks (n = 87)						
MOS-R (lower)	univariable	1.06 (0.92–1.23)	0.426	1.19 (1.05–1.35)	0.005	0.09
FMs (absent)	univariable	0.59 (0.05–6.91)	0.677	10.29 (1.96–53.94)	0.006	0.08
	multivariable ¹	1.32 (0.99–1.76)*	0.056	1.71 (1.15–2.55)*	0.008	0.13
	multivariable ²	1.32 (1.01–1.87)*	0.042	1.84 (1.18–2.86)*	0.007	0.16
V2 ≥ 14 wks (n = 107)						
MOS-R (lower)	univariable	1.19 (0.98–1.44)	0.065	1.57 (1.27–1.94)	<0.001	0.19
FMs(absent)	univariable	1.02 (0.01–40.0)	0.269	42.25 (4.99–356.7)	0.001	0.19
	multivariable ¹	1.26 (1.00–1.60)*	0.050	2.63 (1.21–5.69)*	0.014	0.25
	multivariable ²	1.25 (0.98–1.59)*	0.064	2.69 (1.20–6.05)	0.017	0.28
Total cohort (n = 123) [#]						
MOS-R (lower)	univariable	1.27 (1.05–1.52)	0.011	1.61 (1.31–2.00)	<0.001	0.19
	multivariable ¹	1.33 (1.06–1.66)*	0.012	2.92 (1.48–5.75)*	0.002	0.24
	multivariable ²	1.32 (1.05–1.64)*	0.016	3.04 (1.46–6.32)*	0.003	0.26
Trajectory						
Improve (no)	univariable	5.91 (1.16–29.89)	0.032	9.5 (1.12–81.20)	0.039	0.05
Concern (yes)	univariable	1.19 (0.36–3.94)	0.775	1.05 (0.28–3.86)	0.941	0.05

	Model	Total HINE score		V2 ≥ 14 wks	p-value	R ²
		V1 < 14 wks				
		estimate (95 % CI)	p-value	estimate (95 % CI)	p-value	R ²
MOS-R	univariable	1.32 (0.96–1.69)	<0.001	1.59 (1.31–1.87)	<0.001	0.55
FMs (absent)	univariable	–16.56	<0.001	–22.01	<0.001	0.46
		(–22.25– -10.86)		(–26.57– -17.45)		
	multivariable ¹	2.13 (1.2–3.06)*	<0.001	1.73 (1.03–2.42)*	<0.001	0.56
	multivariable ²	2.0 (1.11–2.89)	<0.001	1.47 (0.79–2.13)	<0.001	0.61
**MOS-R subcategories: Reference score 1						
Fidgety movements						
Score 12		7.09 (1.74–12.45)	0.010	11.77 (6.91–16.62)	<0.001	0.64
Score 4		7.73 (–3.68–19.15)	0.181	6.91 (–3.44–17.26)	0.189	
Movement patterns						
Score 4		33.77 (22.15–45.39)	<0.001	19.44 (11.99–26.91)	<0.001	
Score 2		30.65 (12.16–49.15)	0.001	19.14 (1.15–37.14)	0.037	
Age-adequacy						
Score 4		1.99 (–2.91–6.89)	0.421	3.85 (–0.55–8.24)	0.085	
Score 2		0.44 (–4.29–5.18)	0.852	1.72 (–1.03–4.48)	0.218	
Postural patterns						
Score 4		5.10 (0.24–9.96)	0.040	4.42 (0.23–8.61)	0.039	
Score 2		2.99 (–1.54–7.53)	0.193	2.69 (–1.07–6.45)	0.159	
Movement character						
Score 4		30.76 (7.76–53.77)	0.009	12.26 (–1.89–26.40)	0.089	
Score 2		26.90 (5.77–48.03)	0.013	13.56 (–2.71–29.83)	0.101	

Abbreviations: ad-NDO = adverse neurodevelopmental outcome, CP=Cerebral Palsy, estimate = average change in HINE score for every 1-pt increase in MOS-R and/or occurrence of categorical predictor, FMs = fidgety movements, HINE = Hammersmith Infant Neurological Examination, MOS-R = Motor Optimality Score-revised, multivariable¹ = MOS-R adjusted for fidgety movements, multivariable² = MOS-R adjusted for sex, gestational age, brain injury (HIE, PVL, IVH), multivariable³ = adjusted MOS-R subcategories, on-track = typically developing, OR = odds ratio, Trajectory improve ≥ 2 pt. increase 1st -2nd MOS-R, Trajectory concern ≥ 2 pt. decrease 1st -2nd MOS-R, V1 = video 1, V2 = video 2, wks = weeks, 95%CI = 95 % confidence intervals, * = adjusted MOS-R, ** = multivariable model includes all MOS-R subcategories as predictors, [#] = 2nd MOS-R score was used for all infants with 2 videos.

Bold = statistically significant (p<0.05).

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Conceptualization. **Anya Gordon:** Writing – review & editing, Project administration, Data curation. **Hailey Williams:** Writing – review & editing, Resources, Project administration, Data curation. **Chloe Taifalos:** Resources, Project administration, Data curation. **Maria Smith:** Project administration, Data curation. **Shaneen Leishman:** Software, Resources, Project administration, Data curation. **Ellena Oakes:** Project administration, Data curation. **Megan Kentish:** Writing – review & editing, Resources, Project administration. **Lynda McNamara:**

Table 4

Diagnostic accuracy of General Movements Assessment and Motor Optimality Score-revised for high chance of adverse neurodevelopmental outcome and/or cerebral palsy at 4–9 months corrected age, n = 123 infants.

	Sensitivity (95 % CI)	Specificity (95 % CI)	PPV (95 % CI)	NPV (95 % CI)	Accuracy (95%CI)
High chance ad-NDO/CP					
V1 (<14 wks)					
FMs (absent)	0.19 (0.10–0.33)	0.94 (0.81–0.99)	0.83 (0.54–0.96)	0.44 (0.40–0.48)	0.49 (0.39–0.60)
MOS-R (<23)	0.71 (0.57–0.83)	0.51 (0.34–0.69)	0.69 (0.60–0.76)	0.54 (0.41–0.67)	0.63 (0.52–0.73)
V2 (≥14 wks)					
FMs (absent)	0.19 (0.11–0.31)	0.98 (0.87–1.00)	0.93 (0.64–0.99)	0.42 (0.39–0.45)	0.48 (0.39–0.58)
MOS-R (<23)	0.86 (0.76–0.94)	0.40 (0.25–0.57)	0.71 (0.65–0.76)	0.64 (0.46–0.78)	0.69 (0.59–0.78)
Trajectory					
GMA (absent)	0.16 (0.07–0.29)	0.97 (0.84–1.00)	0.89 (0.51–0.98)	0.42 (0.39–0.46)	0.48 (0.36–0.59)
MOS-R(<23 and/or TC)	0.88 (0.76–0.95)	0.44 (0.26–0.62)	0.71 (0.64–0.77)	0.71 (0.50–0.84)	0.72 (0.60–0.80)
High chance CP					
V1 (<14 wks)					
FMs (absent)	0.39 (0.20–0.61)	0.95 (0.87–0.99)	0.75 (0.47–0.91)	0.81 (0.76–0.86)	0.80 (0.71–0.88)
MOS-R (<20)	0.43 (0.23–0.66)	0.92 (0.83–0.97)	0.67 (0.43–0.84)	0.82 (0.76–0.87)	0.79 (0.69–0.87)
V2 (≥14 wks)					
FMs (absent)	0.52 (0.31–0.72)	0.99 (0.93–1.00)	0.93 (0.64–0.99)	0.87 (0.82–0.91)	0.88 (0.80–0.93)
MOS-R (<20)	0.52 (0.31–0.72)	0.95 (0.88–0.99)	0.76 (0.54–0.90)	0.87 (0.81–0.91)	0.85 (0.77–0.91)
Trajectory					
FMs (absent)	0.36 (0.17–0.59)	0.98 (0.91–1.00)	0.89 (0.51–0.98)	0.81 (0.75–0.85)	0.82 (0.72–0.89)
MOS-R (<20 and/or TC)	0.64 (0.41–0.83)	0.83 (0.71–0.92)	0.58 (0.42–0.73)	0.86 (0.78–0.92)	0.78 (0.68–0.86)

Abbreviations: ad-NDO = adverse neurodevelopmental outcome, CP=Cerebral Palsy, FMs = Fidgety Movements, HINE = Hammersmith Infant Neurological Examination, MOS-R = Motor Optimality Score-revised, NPV = negative predictive value, PPV = positive predictive value, Trajectory = infants with 2 MOS-R videos, TC = trajectory of concern (≥2 pt. decrease in MOS-R from 1st to 2nd video), V1 = timepoint 1, V2 = timepoint 2, wks = weeks, 95%CI = 95 % confidence interval.

Resources, Funding acquisition. **Robert S. Ware:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Roslyn N. Boyd:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

Prof Arend F. Bos is a tutor for the General Movements trust. All other authors have no conflicts of interest to declare.

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References

- [1] A.M. Momany, E. Jasper, K.E. Markon, M.A. Nikolas, K.K. Ryckman, Latent class analysis to characterize neonatal risk for neurodevelopmental differences, *J. Child Psychol. Psychiatry* 64 (1) (2023) 100–109.
- [2] K.M. Milner, E.F.G. Neal, G. Roberts, A.C. Steer, T. Duke, Long-term neurodevelopmental outcome in high-risk newborns in resource-limited settings: a systematic review of the literature, *Paediatr. Int. Child. Health* 35 (3) (2015) 227–242.
- [3] T. Moore, N. Arefadib, A. Deery, The First Thousand Days: An Evidence Paper, 2017 (<https://doi.org/APO-108431>).
- [4] C.R. Luke, K. Benfer, L. Mick-Ramsamy, R.S. Ware, N. Reid, A.F. Bos, et al., Early detection of Australian Aboriginal and Torres Strait Islander infants at high risk of adverse neurodevelopmental outcomes at 12 months corrected age: LEAP-CP prospective cohort study protocol, *BMJ Open* 12 (1) (2022) e053646.
- [5] P. McCalman, F. McLardie-Hore, M. Newton, H. McLachlan, D. Forster, Trust, privacy, community, and culture: important elements of maternity care for Aboriginal and Torres Strait Islander women giving birth in Victoria, *Women Birth* (2022), <https://doi.org/10.1016/j.wombi.2022.06.001>:150–60.
- [6] A. Finlay-Jones, K. Varcin, H. Leonard, A. Bosco, G. Alvares, J. Downs, Very early identification and intervention for infants at risk of neurodevelopmental disorders: a transdiagnostic approach, *Child Dev. Perspect.* 13 (2) (2019) 97–103.
- [7] A.L. Scherzer, M. Chhagan, S. Kauchali, E. Susser, Global perspective on early diagnosis and intervention for children with developmental delays and disabilities, *Dev. Med. Child Neurol.* 54 (12) (2012) 1079–1084.
- [8] M. Bosanquet, L. Copeland, R. Ware, R. Boyd, A systematic review of tests to predict cerebral palsy in young children, *Dev. Med. Child Neurol.* 55 (5) (2013) 418–426.
- [9] I. Novak, C. Morgan, L. Adde, J. Blackman, R.N. Boyd, J. Brunstrom-Hernandez, et al., Early, accurate diagnosis and early intervention in cerebral palsy: advances in diagnosis and treatment, *JAMA Pediatr.* 171 (9) (2017) 897–907.
- [10] C. Einspieler, J. Sigafos, K.D. Bartl-Pokorny, R. Landa, P.B. Marschik, S. Bölte, Highlighting the first 5 months of life: general movements in infants later diagnosed with autism spectrum disorder or Rett syndrome, *Res. Autism Spectr. Disord.* 8 (2014) 286–291.

- [11] D.M. Romeo, F.M. Cowan, L. Haataja, D. Ricci, E. Pede, F. Gallini, et al., Hammersmith infant neurological examination in infants born at term: predicting outcomes other than cerebral palsy, *Dev. Med. Child Neurol.* 64 (7) (2022) 871–880.
- [12] C. Peyton, C. Einspieler, General movements: a behavioral biomarker of later motor and cognitive dysfunction in NICU graduates, *Pediatr. Ann.* 47 (4) (2018) e159–e64.
- [13] R. Caesar, P.B. Colditz, G. Cioni, R.N. Boyd, Clinical tools used in young infants born very preterm to predict motor and cognitive delay (not cerebral palsy): a systematic review, *Dev. Med. Child Neurol.* 63 (4) (2021) 387–395.
- [14] D.M. Romeo, D. Ricci, C. Brogna, E. Mercuri, Use of the Hammersmith Infant Neurological Examination in infants with cerebral palsy: a critical review of the literature, *Dev. Med. Child Neurol.* 58 (2016) 240–245.
- [15] D.M. Romeo, F.M. Cowan, L. Haataja, D. Ricci, E. Pede, F. Gallini, et al., Hammersmith Infant Neurological Examination for infants born preterm: predicting outcomes other than cerebral palsy, *Dev. Med. Child Neurol.* (2020), <https://doi.org/10.1111/dmcn.14768>.
- [16] K. Hay, M. Nelin, H. Carey, O. Chorna, M. Moore-Clingenpeel, N. Maitre, Hammersmith infant neurological examination asymmetry score distinguishes hemiplegic cerebral palsy from typical development, *Pediatr. Neurol.* 87 (2018) 70–74.
- [17] M.F. Frisone, E. Mercuri, S. Laroche, C. Foglia, E.F. Maalouf, L. Haataja, et al., Prognostic value of the neurologic optimality score at 9 and 18 months in preterm infants born before 31 weeks' gestation, *J. Pediatr.* 140 (1) (2002) 57–60.
- [18] A.K.L. Kwong, L.W. Doyle, J.E. Olsen, A.L. Eeles, K.J. Lee, J.L.Y. Cheong, et al., Early motor repertoire and neurodevelopment at 2 years in infants born extremely preterm or extremely-low-birthweight, *Dev. Med. Child Neurol.* 64 (7) (2022) 855–862.
- [19] A. De Roubaix, D. Van de Velde, H. Roeyers, H. Van Waelvelde, Standardized motor assessments before the age of five predicting school-aged motor outcome including DCD: a systematic review, *Eur. J. Paediatr. Neurol.* 30 (2021) 29–57.
- [20] C. Einspieler, A.F. Bos, M. Kriebler-Tomantschger, E. Alvarado, V.M. Barbosa, N. Bertoncelli, et al., Cerebral palsy: early markers of clinical phenotype and functional outcome, *J. Clin. Med.* 8 (10) (2019).
- [21] C. Crowle, M. Jackman, C. Morgan, The general movements motor optimality score in high-risk infants: a systematic scoping review, *Pediatr. Phys. Ther.* 35 (1) (2022) 2–26.
- [22] A.K. Kwong, R.N. Boyd, M.D. Chatfield, R.S. Ware, P.B. Colditz, J.M. George, Early motor repertoire of very preterm infants and relationships with 2-year neurodevelopment, *J. Clin. Med.* 11 (7) (2022).
- [23] D.M. Romeo, A. Guzzetta, M. Scoto, M. Cioni, P. Patusi, D. Mazzone, et al., Early neurologic assessment in preterm-infants: integration of traditional neurologic examination and observation of general movements, *Eur. J. Paediatr. Neurol.* 12 (3) (2008) 183–189.
- [24] D. Dicanio, G. Spoto, A. Alibrandi, R. Minutoli, A.G. Nicotera, G. Di Rosa, Long-term predictivity of early neurological assessment and developmental trajectories in low-risk preterm infants, *Front. Neurol.* 13 (2022).
- [25] A.K.L. Kwong, L.W. Doyle, J.E. Olsen, A.L. Eeles, D. Zannino, R.M. Mainzer, et al., Parent-recorded videos of infant spontaneous movement: comparisons at 3–4 months and relationships with 2-year developmental outcomes in extremely preterm, extremely low birthweight and term-born infants, *Paediatr. Perinat. Epidemiol.* 36 (5) (2022) 673–682.
- [26] M. Örtqvist, C. Einspieler, P.B. Marschik, U. Ådén, Movements and posture in infants born extremely preterm in comparison to term-born controls, *Early Hum. Dev.* 154 (10) (2020) 5304.
- [27] L. Haataja, E. Mercuri, R. Regev, F. Cowan, M. Rutherford, V. Dubowitz, et al., Optimality score for the neurologic examination of the infant at 12 and 18 months of age, *J. Pediatr.* 135 (2) (1999) 153–161.
- [28] StataCorp, Stata Statistical Software: Release 17, StataCorp LLC, College Station, TX, 2021.
- [29] S. Salavati, A.F. Bos, L.W. Doyle, P.J. Anderson, A.J. Spittle, Very preterm early motor repertoire and neurodevelopmental outcomes at 8 years, *Pediatrics* 148 (3) (2021).
- [30] M. Örtqvist, C. Einspieler, U. Ådén, Early prediction of neurodevelopmental outcomes at 12 years in children born extremely preterm, *Pediatr. Res.* 91 (6) (2022) 1522–1529.
- [31] C. Crowle, M. Jackman, A. Webb, C. Morgan, Use of the Motor Optimality Score-Revised (MOS-R) to predict neurodevelopmental outcomes in infants with congenital anomalies, *Early Hum. Dev.* 187 (2023) 105876.