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Evaluation of the repeatability of kinesiological measurements of spontaneous infant movements using OSESEC computer analysis algorithms (Q1)

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Abstract

Purpose

There is a need to create objective and reproducible tool for assessing the quality of infant movements. It's substantially important to detect movement disorders by infants as early as possible. The study aimed to evaluate the reproducibility of kinesiological measurements of spontaneous movements performed by 51 infants (aged 6 to 15 weeks) recorded three times for two consecutive days using OSESEC computer analysis algorithms by determining numerical values of parameters, i.e. speed, acceleration, direction, and movement trajectory (Q2).

Material and Methods

The study group consisted of 51 infants. The diagnostic method of Prechtl was used for qualitative assessment. The quantitative assessment was based on the use of a OSESEC system. Numerical values for all movement parameters were determined, and the data obtained in the study were used for statistical analysis.

Results

Analysis including movement parameter values on three consecutive recordings for the same infant revealed no statistically significant differences in location ($p=0.073$), range ($p=0.557$), shape ($p=0.289$), mean acceleration ($p=0.124$), and mean speed ($p=0.767$) This confirms the reproducibility of measurements of the proposed parameters of the objectification of spontaneous infant movements (Q3).

Conclusions

The interpretability and accuracy of the presented parameters were proved. All parameters estimation is fully automated. Further research and testing requires a larger study group to create an objective diagnostic device for infants.

Keywords

infants, infant development, spontaneous movements, mobility assessment, objective methods of diagnosing, computer analysis.

Introduction

Child development is a continuous and coherent process, in which the skills acquired in various spheres are correlated. It is characterized by high volatility, diversity, and variability [15, 16].

The infant makes movements within a certain range and in specific directions that are slightly different each time [14]. Variability disorders, especially in situations of minor developmental deficits, lead to diagnostic difficulties faced by doctors and physiotherapists. During the first months of life, humans develop very dynamically. In the beginning, infants are unable to make purposeful movements, and, over time, they start to move independently in their environment. This is extremely important for diagnosis, since the result of the examination, and thus the prognosis for the further development of the child can change even over the course of a week [1].

Normal motor development depends on the proper activity of the central nervous system [32]. This activity, in turn, depends on such factors as the duration of pregnancy, the course of delivery, proper care in the first days of life, or the presence of an adequate number of motor and sensory stimuli in an infant's life [22].

The emergence of new motor skills is correlated with the development of the nervous system and connections in neuronal circuits. Consequently, the potential for the evaluation of the child's motor development, based essentially on consecutive neurodevelopmental sequences that represent milestones, is the primary focus of the planned research [8].

For this potential to be practically feasible, it is necessary to have sufficiently effective and precise tools to verify neuromotor development at an early stage of a child's life. This verification is important since early detection of neuromotor development disorders contributes directly to the reduction in the prevalence of sensory disorders, coordination problems, and postural disorders in children [30].

Diagnosis of infants mainly uses subjective methods based on the knowledge and experience of the physiotherapist or physician such as observation (Prechtl's method), palpation, and manual examination (e.g. examination using Vojta or Bobath methods). There are also methods for objective assessment of infants using measurement tools such as accelerometers or a magnetic sensor system that tracks the movements of the infant's upper and lower limbs during spontaneous activity [23, 24]. However, due to the limited availability of these measuring devices, they are not widely used by diagnosticians [5](Q4).

The last decade has seen a rapid development of concepts based on the use of information technology to aid movement assessment in early childhood. More and more attention is being paid to the development of techniques based on artificial intelligence as a complement to the classical methods of assessing global movements developed by Prechtl [6, 18, 27, 28, 33].

The literature also describes studies using video images other than those performed using the analyses based on the Prechtl method. A common feature of most publications is the use of video to assess the predictability of movement as a potential symptom of cerebral palsy [20, 24].

Assessment of the infant's movements on the video using the Prechtl method is based on global visual perception (Gestalt) [31, 34]. The investigator should avoid focusing on details. His or her look should focus on the central point of the infant's body, such as the sternum. The assessment takes place without audio recording, as interference from the environment can affect the person that assesses the recording. It is important to avoid, on the recording, the presence of caregivers, siblings, a bed full of toys, or the eye-irritating colors of the blanket on which the infant lies. To an experienced observer using the Prechtl method, 1 to 3 minutes of video is enough to assess global movements (GMs). The temporal organization of fidgety movements (FMs) depends on the infant's age. At first (after 6 - 8 weeks of age), FMs occur as occasional events. Their frequency then increases at 9 to 14 weeks of age and declines again at 15 to 18 weeks.

The temporal organization of FMs can be characterized as follows:

1) Continual FMs (rated ++ in the protocol)
2) Intermittent FMs (rated + in the protocol)
3) Sporadic FMs (rated +/- in the protocol)
4) Absent FMs (rated F- in the protocol) [11, 12, 13].

Established at the Institute of Physiotherapy and Health Sciences of AWF Katowice, an OSESEC (Objective System for Evaluation and Support of Early Childhood) team of medics and engineers decided to conduct research on the use of video analysis of infants and attempted to identify parameters which, in the future, may be important for early detection of abnormalities at home and record-keeping in the outpatient settings. The study contributes to the project outlined above and takes into account the jointly developed and standardized cognitive assumptions.

Material and methods

The study was approved by the Bioethics Committee (No. 5/2018) and complied with the Declaration of Helsinki. All patients and their parents/guardians gave written informed consent to participate in the study.

Personal data and the images of patients were collected and processed in a database that complies with personal data protection regulations. The equipment used in the examinations did not pose any threat of radiation or other energy that could in any way affect the safety of the infant under observation.

The study group consisted of 51 infants between 6 and 15 weeks of age. The inclusion criteria were the parent's consent to the examination, a positive perinatal history, and an Apgar score of 8 to 10 points during delivery. The study was conducted under home conditions, at a fixed time of the day. The exclusion criteria were: failure to record the infant three times, poor psychophysical health of the infant and the infant crying during the recording, according to the diagnostic methodology recommended for Prechtl's method [12]. Of all 51 infants, 49 were included in further analysis (Fig. 1).(Q5)

The choice of study participants and numbers was guided by convenience sampling [26]. The sample size was similar to that presented in other studies and definitely provided high power for the statistical tests performed. The determined number of cases, according to the current state of knowledge and with the assumed inclusion criteria, allows a representative division of the group into FM++ and FM+[10,11,12](Q6).

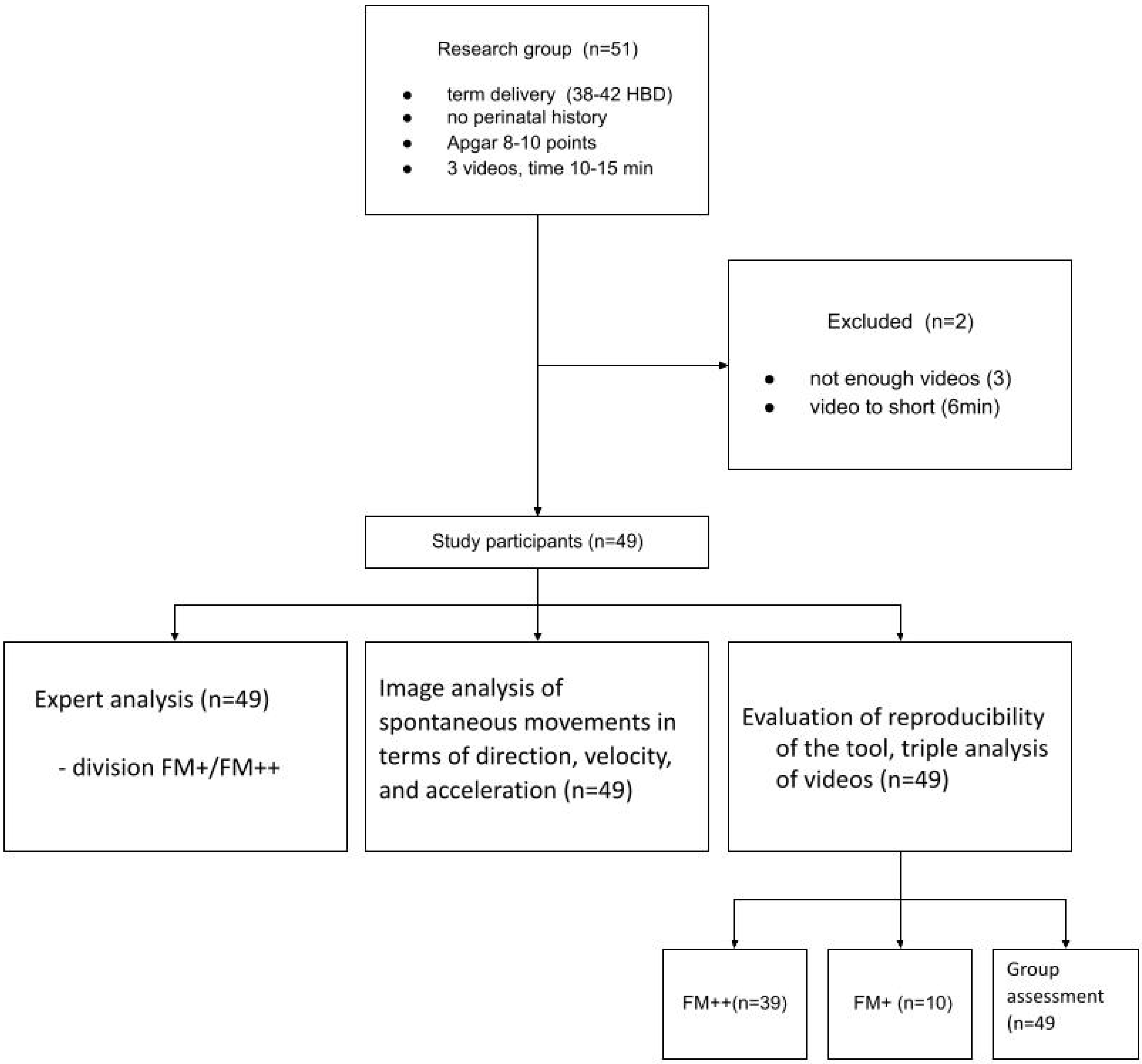

Fig 1: Flow diagram showing the choice of the group of infants whose recordings were included in the study (Q8)

Each recording was made for a maximum of 15 minutes [25] using a portable video station for recording in the patient's home as described in a previous study [7]. Videos were recorded in FullHD 1080 resolution (1920x1080, 60 fps). The position of the infant during the examination was unrestricted, lying on his or her back, without distracting people and objects. The video covered the infant's entire body. It was ensured that the infant did not cry during the examination to avoid the need to exclude material from further analysis. The examinations were performed three times according to the schedule, after sleeping and feeding.

In the group included in the study, 49 infants were video recorded in 3 separate sessions. A total of 147 videos were analyzed. The study was conducted in 3 stages.

The first examination (of a preliminary nature) involved the entire eligible group of infants. All the infants falling within the range of 6 to 15 weeks were assigned baseline values of the authors' parameters such as CMA, FMS(%), and FMA(%). The velocities ($\frac{mm}{s}$) and accelerations ($\frac{mm}{s^2}$) for upper and lower limb movements on the right and left sides of the body were evaluated.

In the next stage of the examination, the infants were divided into those with movements classified as FM+ and FM++. In the initial stage, the obtained videos were evaluated by an expert based on the Prechtl procedure by reviewing the videos and positioning each infant's movements in the FM+ to FM++ range. It was required that the expert should be a working physiotherapist with at least 10 years of experience in infant diagnosis and therapy and be certified to evaluate global movements using the Prechtl method. Spontaneous motor activity of infants was observed in the supine position. The videos were evaluated according to the methodology of observation of GMs using video recording. The first 10 minutes of each video were assessed, which is the maximum time it takes to analyze a video according to the method's guidelines [10, 11, 12, 13, 21]. Assessment of the infant's movements on the video was based on global visual perception (Gestalt).

The results of the two analyses were compared to determine whether there were differences in the expert's and the computer program's assessment of infant movements. The results were used for further research.

Based on the results obtained from previous studies, the reproducibility of the analysis using the multimodal device was evaluated. This was achieved by reading the videos in 3 sessions for the same infant. Reproducibility was essential in this context to eliminate randomness of the results. It was assumed that for the accuracy of the results, the infant would move similarly on each recording. Reproducibility of the device was additionally analysed separately on three infant's videos defined as FM+, FM++, and the whole group.

Finally, the validation of the entire tool in terms of the reproducibility of the results of the velocities and accelerations of the digital points plotted on the infant's body in the three video recordings was performed for the entire group of infants (147 videos) in infants rated FM+ (30 videos) and FM++ (117 videos).

Research methodology

The videos and the assessment protocol prepared by the physiotherapist were submitted to the Faculty of Biomedical Engineering at the Silesian University of Technology in Gliwice. The team of engineers involved in the project performed computer-aided image processing.

Infant movements recorded with a video camera in the frontal plane were analyzed. Based on the parameters obtained from the calibration using a checkerboard pattern, distortions caused by the camera's optics were removed from each recording. The data from the videos were used to determine characteristic points on the infant's body. OpenPose software was employed to detect them automatically [3]. The software allows tracking the position of points on the wrists, elbows, shoulders, ankles, knees, hips, neck, and facial points.The results were subjected to additional processing to reduce incorrect readings and to filter noise [29]. A similar approach has been used in previous studies on the analysis of infant recordings in the context of diagnostic support [4, 17, 28].

Due to the different recording times, the initial 10 minutes of each recording were analyzed.

Based on the locations of each body point, numerical values of movement indicators were determined. Two groups of indices were determined for wrists and ankles:

. Kinematic quantities calculated based on the variability of the position over time, expressed in statistical measures.

− Estimation of actual velocity and acceleration (expressed as $\frac{mm}{s}$ and $\frac{mm}{s^2}$, respectively) required determining the actual pixel size on the recording, at a distance corresponding to the position of the infant. For this purpose, the known actual spacing of the supports of the test stand was used.

− for the left and right wrists and left and right ankles, velocity and acceleration curves over time were determined. Statistical measures were then computed to obtain values that characterize the movement over the entire analyzed part of the video.

b. Dimensionless relative numerical factors were developed by a project team of physiotherapists and engineers.

− the proposed factors are based on the parameterization of the movement trajectory formed from the location of the analyzed point at successive time points. The basis for the parameterization is to describe the ellipse on the trajectory with known algorithms used in the principal component analysis. The center of the ellipse was determined by calculating the mean value for each coordinate of the point's trajectory. The principal component analysis method yielded the location of the center of the ellipse and the lengths of the long and short axes (expressed in pixels).

− to reduce the effect of the infant's position in relation to the camera and the change in its position during the recording, the obtained locations were transformed by translation and rotation. All the points in the subsequent frames were shifted so that the point defining the position of the neck remained fixed. All locations were then subjected to rotation relative to this point by such an angle that the body axis (the line between the point of the neck and the point between the hips) was aligned parallel to the image axis throughout the recording.

− the indices range from 0 to 1 due to normalization against the estimated limb length in the image. The correctness of the proposed method for determining the limb length from the frames of a recording requires that, at any time of the analyzed segment, the limb be parallel to the image plane. Manual verification of the results demonstrated that this condition was met in all cases.

− based on the parameters of the ellipse, the author's dimensionless quantitative factors describing the extent, location, and nature of the movement were proposed:

1) FMS (factor of movement shape) - the ratio of the length of the short axis of the ellipse to the length of the long axis. This factor defines the shape of the surface in which the movement takes place. The shape of the movement area forms an ellipse or circle. A value close to 1 means that the shape of the area trajectory is close to a circle, and, the more the FMS is close to 0, the more elongated the shape of the resulting ellipse (Fig. 2)

2) FMA (factor of movement area) - the quotient of the area of the ellipse circumscribed around the trajectory to the area of a circle with a radius equal to the length of the analyzed limb (defined as the maximum range of motion of the limb) (Fig. 3)

3) CMA (center of movement area) - position of the center of the ellipse circumscribed on the trajectory in the coordinate system associated with the corresponding shoulder for the upper limbs and hip for the lower limbs. The unit in the above-described coordinate system is the automatically determined length of the analyzed limb (Fig. 4). CMA contains two components: vertical (CMA-v) and horizontal (CMA-h).

CMA-v indicates the direction of up-down movement. A value of 0 determines the shoulder (upper limbs) and hip (lower limbs). Values above 0 indicate upward movement of the arms or legs, and a value of 1 is the maximum value of elevation of the upper or lower limbs. Values below 0 indicate downward movement of the arms or legs, and a value of - 1 is the maximum value of lowering the upper or lower limbs.

CMA-h indicates the horizontal direction of the movement. A value of 0 refers to the shoulder (upper limbs) and hip (lower limbs). The higher the value of CMA-h, the more “outwards" the infant's movements. On the other hand, the closer the value is to zero, the more "inwards” the movements. Negative CMA values may be indicative of the movement of a limb very close to the body or even on the opposite side [7].

The proposed factors were determined for each frame of the recording independently, leading to variability in their values over time. Therefore, as in the case of kinematic quantities, statistical measures were determined for each of the characteristics which were further analyzed such as mean value, standard deviation, median, first and third quartiles, and coefficient of variation.

Fig 2. Visualization of the short axis and the long axis of the ellipse describing the movement of the left upper limb. The FMS value was obtained by dividing the length of the short axis of the ellipse by the length of the long axis.

Fig 3. The maximum range of movement for the left upper limb (blue circle) and the ellipse circumscribed about the example trajectory (orange). The FMA value was obtained by dividing the area of the ellipse circumscribing the trajectory by the area of the circle defining the maximum range of motion of the upper limb.

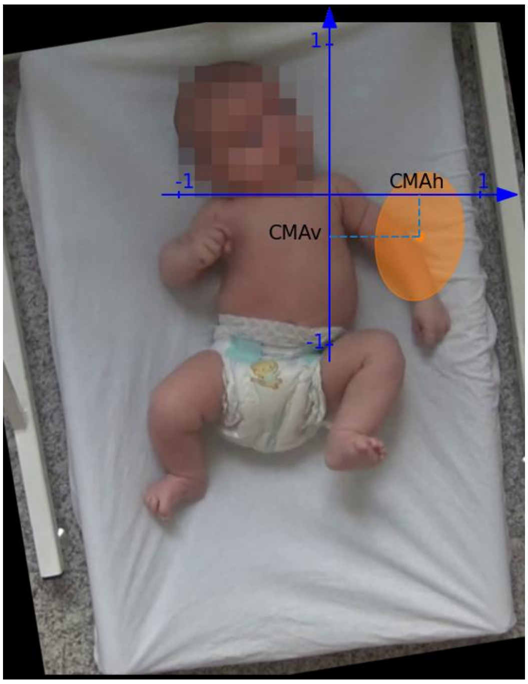

Fig 4. Visualization of the position of the center of the ellipse in a coordinate system related to the position of the shoulder normalized to the length of the limb. The CMA coefficient contains two components that determine the position relative to the shoulder: vertical (v) and horizontal (h).

Statistical analysis was carried out using the software R ver. 4.1.2 language in the RStudio environment ver. 01.04.1106. The following packages were used: car, icesTAF, grDevices, rstatix, rcompanion, stats, and e1071. The statistical significance for all analyses was set at 0.05 and used two-tailed tests.

Descriptive statistics for qualitative variables included the number and percentage of instances of each category. For continuous variables, descriptive statistics included the number of non-empty observations, mean with standard deviation (SD), median with interquartile range (IQR), and minimum-maximum range.

The significance of differences in the results obtained from recordings 1, 2, and 3 for individual parameters determining movements was tested using the repeated measures ANOVA. The test allows for the comparison of means between groups while taking into account the effects of repeated measurements for the same individual. Therefore, it is used, among other things, to compare the variability between measurements at different time intervals. The Friedman test was used if the assumptions of normal distribution of the variables, statistical equality of variances (Brown-Forsythe test), and statistical equality of sample sizes (chi-squared test) were not met. This test is a non-parametric alternative to repeated measures ANOVA(Q7).

Results

The results were compared for the assessment of individual parameters between recordings 1, 2, and 3 in the entire group and in subgroups of infants rated FM+ and FM++ on the Prechtl scale.

For the entire group included in the analysis and the FM++ subgroup, no significant differences in parameters were found between recordings 1, 2, and 3. For the FM+ subgroup, the results for the FMA parameters for the right wrist and mean accelerations for the left ankle were significantly different. For other parameters, the differences were not statistically significant. For FMA for the right wrist in the FM+ subgroup, its value was highest for recording 3 and lowest for recording 1, while for the mean acceleration for the left ankle in the FM+ subgroup, the parameter was highest for recording 3 and lowest for recording 3 (Tab.1.).

Tab. 1. Comparison of assessment of movements using a OSESEC system for image analysis between the three recordings in the entire study group, in the subgroup of infants assessed as FM+, and in the subgroup of infants assessed as FM++

Parameter	**The whole group n = 49**	**FM+ n = 10**	**FM++ n = 39**
	p-value for comparison of the results of recordings 1, 2, and		
CMA-h: left ankle	0.287 [1]	0.984 [1]	0.260 [1]
CMA-h: right ankle	0.696 [1]	0.090 [1]	0.971 [1]
CMA-h: left wrist	0.824 [2]	0.640 [1]	0.414 [2]

Parameter	The whole group n = 49	FM+ n = 10	FM++ n = 39
	p-value for comparison of the results of recordings 1, 2, and		
CMA-h: right wrist	0.073 [1]	0.195 [1]	0.095 [1]
CMA-v: left ankle	0.775 [2]	0.602 [1]	0.373 [2]
CMA-v: right ankle	0.145 [2]	0.500 [2]	0.261 [2]
CMA-v: left wrist	0.183 [1]	0.489 [1]	0.076 [1]
CMA-v: right wrist	0.486 [1]	0.630 [1]	0.497 [1]
FMA: left ankle	0.557 [2]	0.751 [1]	0.299 [2]
FMA: right ankle	0.691 [2]	0.732 [1]	0.766 [2]
FMA: left wrist	0.670 [2]	0.787 [1]	0.505 [2]
FMA: right wrist	0.711 [2]	**0.008 [2]**	0.310 [2]
FMS: left ankle	0.579 [1]	0.159 [1]	0.780 [1]
FMS: right ankle	0.369 [1]	0.338 [1]	0.104 [2]
FMS: left wrist	0.289 [1]	0.312 [1]	0.545 [1]
FMS: right wrist	0.561 [1]	0.927 [1]	0.588 [1]
Mean acceleration: left ankle	0.342 [2]	**0.027 [1]**	0.760 [2]
Mean acceleration: right ankle	0.124 [2]	0.092 [2]	0.491 [2]
Mean acceleration: left wrist	0.520 [2]	0.741 [2]	0.321 [2]
Mean acceleration: right wrist	0.480 [2]	0.614 [2]	0.586 [2]
Mean velocity: left ankle	0.767 [2]	0.670 [2]	0.584 [2]
Mean velocity: right ankle	0.922 [2]	0.566 [1]	0.735 [2]

Parameter	The whole group n = 49	FM+ n = 10	FM++ n = 39
	p-value for comparison of the results of recordings 1, 2, and		
Mean velocity: left wrist	1.000 [2]	0.907 [1]	0.902 [2]
Mean velocity: right wrist	0.832 [2]	0.628 [1]	0.926 [2]

[1] - ANOVA for repeated measures; [2] - Friedman test

Discussion

The results of the present study show that the computer-aided video analysis of spontaneous movements of infants helps evaluate the velocity and accelerations of specific points on the infant's body. The results are repetitive and allow for linking particular sequences of movements with normal or abnormal motor development of the infant. The standard condition was defined based on a series of averaged data on the velocities and accelerations of the limbs in healthy infants. It was possible to determine the mean values of velocities and accelerations for the upper and lower limbs. Numerical values were determined for parameters such as CMA-h (center of movement area: horizontal direction), CMA-v (center of movement area: vertical direction), FMA (factor of movement area), FMS (factor of movement shape) for the right and left upper and lower limbs. The results presented here represent values computed for full-term infants, with positive perinatal history and with a high APGAR score (minimum 8 points). In most cases, the analysis of spontaneous movements of the right and left sides of the body showed similar or even the same values, indicating that the device provides objective and reproducible results.

Assigning numerical values to spontaneous movements provides an opportunity to describe the movements objectively and unambiguously. The essential selection criteria have been defined precisely to exclude arbitrariness. If, at the time of the interview, patients met the inclusion criteria, they were offered participation. Although the study concerns infants, it is primarily validating in nature. The study group was characterized by a specific age range of 6 to 15 weeks due to the presence of FM movements during this period of life. These movements occur only at this age, are easy to observe by the diagnostician (including the analysis of video images), and are a good predictor for detecting movement disorders in children. In Prechtl's method, the assessment is performed so that the infant remains in a supine position. During the assessment, it is essential to be attentive to the infant's psychophysical status, as it should be remembered that the FMs are only present when the infant is awake and disappear when the infant becomes restless or cries or when the infant is drowsy or asleep [11,12,13](Q10). The numerical data of movements in healthy infants allow for the creation of a map of movement behaviors that can support diagnosis in the future. This will lead to the objectification of the neurological diagnosis of infants and allow for access to a more common and accessible diagnostic device.

Our study confirms that computer-aided video analysis applied to standardized GM recordings in infants can provide objective information about the quality of movements, repeatability of the analyzed movements, and the presence of FM (+/++).

It is likely that with the further development of technology and extensive systems of validation research in the future, diagnosing infants using only computer systems will be fully feasible. This will undoubtedly reduce costs and ensure universality, even in the form of screening. Standardization in terms of the effectiveness of IT methods will allow statistically earlier treatment and improve its efficiency.

However, with the current state of knowledge on the performance of automated infant movement diagnosis technologies, both the effectiveness of the method and its cost-effectiveness need to be confirmed by further research [19].

The conclusions of the research results support the scientific need indicated above. Based on the study, it is very likely that disseminated methods of examinations based on a OSESEC system for image analysis or other similar tools will prove more effective for early identification and referral to early intervention programs. At the same time, globally, such examinations will be more cost-effective and less time-consuming.

Therefore, an effective, accurate, and universal method of assessing infant motor development is required [9]. For these infants, early diagnosis leading to the diagnosis of disorders in psychomotor development is a key step in achieving the best possible quality of life and functioning. Consequently, any available tools to accelerate the recognition of existing and potentially future disorders are an extremely valuable addition to the diagnostician's competencies. Early identification of infants with a negative perinatal history is a prerequisite for specialized diagnosis, early intervention, and possible further therapeutic interventions [2]. The search for computerized methods can potentially contribute to a breakthrough in the objective assessment of infant movements made in the context of possible developmental disorders. An undoubted advantage of the method used is its non-invasiveness and ease of use, and, therefore, greater availability of the method and the possibility of its use by diagnosticians in any conditions, not just in laboratory settingsQ(11).

However, so far, the findings in this context are only an inspiration for further research and development of computer-aided movement analysis technology. Further research is needed to validate the technologies that have been developed to date. Future technologies that combine 3D motion analysis with markerless techniques (e.g., KinectTM) are likely to provide greater specificity and sensitivity compared to 2D video technologies and will help avoid the inconvenience and cost of marker technologies. Furthermore, future research should include larger samples of high-risk populations to train classifiers and create neonatology specific to various underlying pathologies.

The present analysis is a stage of the project in which the main objective is to design a tool and a system. Furthermore, the system will be able to support the work of the professionals responsible for the functional assessment of infants Q(9).

The device presented here seems to help assess and quantify the infants' movements. It offers opportunities not only for the digital description of motor skills in terms of the area and range of movement performed, but also can numerically evaluate the ranges, trajectories, velocities, and accelerations of a given movement. The objective operation of the device is evidenced by the reproducibility of the results. The values of limb movements, both upper and lower, are very similar to each other. Therefore, the program "sees" and reads them in the same way. The reproducibility of the results in the three recordings is somewhat indicative of the precision of the device. In three independent tests, it read the infant's movement parameters at the same level. The program also identified FM movements correctly. Identification of FM movements may help develop a computer-aided and therefore objectified method of assessing the movements of infants.

It should be emphasized that the study group was a pilot group and was limited here to only a few dozen infants. Consequently, the deviation of the results on movements is small, with a potential and assumed trend beyond the spectrum found in the study. Achieving the goals of the OSESEC research implies the need to repeat the research with a higher number of infants and to diversify the study group in terms of perinatal history. Such research is currently being planned.

Conclusion

- the OSESEC system, tool for image analysis presented in the paper allowed for the assessment of spontaneous movements of the upper and lower limbs in terms of the direction of movement (CMA-h, CMA-v), range (FMS, FMA), velocity, and acceleration based on the digital points plotted on the infant's body
- the reproducibility of the results of the tool was demonstrated for the assessment of the spontaneous movements of infants; the values of the analyzed parameters were not statistically significantly different between the videos

– the study indicated that the proposed tool provides a basis for further research on the analysis of selected parameters that determine infant movements; undoubtedly, it is important to perform observations also for infants without positive perinatal history and diagnosis.

– in further research, the analysis of points plotted by a computer on the infant's body should include the parameters of the torso or head position

– The attempt to assess the reliability of the tool may suggest its clinical usefulness, but clinical research should be used to verify whether the tool is actually useful. This could provide an additional objectified source of knowledge for physicians and physiotherapists on infant movement behavior(Q12).

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