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ORIGINAL ARTICLE

# Infant posture and movement analysis using a sensor-supported gym with toys

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## Abstract

Infant posture and motor pattern development are normally analyzed by clinical assessment scales. Lately, this approach is combined with the use of sensor-supported systems, such as optical, inertial, and electromagnetic measurement systems, as well as novel assessment devices, such as CareToy. CareToy is a modular device for assessment and rehabilitation of preterm infants, comprising pressure mattresses, inertial and magnetic measurement units, and sensorized toys. Since such integrated sensor system combination is new to the field of sensor-supported infant behavior assessment and rehabilitation, dedicated methods for data analysis were developed and presented. These comprise trunk rotation, arm movement, forearm orientation, and head movement analysis, along with toy play and trunk posture stability evaluation. Methods were tested on case study data, evaluating suitability of developed algorithms for infant posture and activity analysis, regardless of behavioral responses. Obtained results demonstrate suitability of the proposed methods for successful use in studies of different motor pattern subfields. This represents an important step on the course towards objective, accurate, sensor-supported infant motor development assessment.

**Keywords** Data processing algorithms · Infant activity assessment · Pressure mattress · Inertial and magnetic measurement units · Sensorized toys

## 1 Introduction

Assessment of infant motor patterns is especially important before the first birthday, when infants set the foundations of future motor ability [1]. Motor evaluation should be complete, accurate, and performed frequently for adequate estimation of the developmental course. Surveillance approach with a combination of infant motor performance tests [13] can provide accurate positioning on the typical developmental trajectory and detection of potential developmental delays [8, 12] of gross and fine motor skills [19].

Gross motor skills analysis concentrates on acquisition of general postural information, such as trunk postural control, rolling-over motion [29], head movement ability [16], and goal-oriented reaching [30]. Mastering gross motor skills is an important developmental milestone and a pre-requirement for many activities [10–12]. Fine motor skills focus on manual interaction with the surrounding environment, advancing from spontaneous arm movements to advanced goal-oriented reach-to-grasp behavior [5]. Infants learn to perform bi- and unimanual grasps, differentiate and adapt grasp approaches in relation to object affordances, such as toy orientation, position, or form [3, 32], and acquire the ability of object manipulation of longer duration [12, 27].

Clinical-based assessment tests such as Alberta Infant Motor Scale (AIMS) and Test of Infant Motor Performance (TIMP) are recognized as valid indicators of motor development [28]. Nevertheless, remarkable technological advancements are transforming clinical motor performance evaluation towards use in combination with sensor-supported assessment systems. Researchers are designing novel methods to increase

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simplicity, accuracy, objectivity, and reliability of motor behavior evaluation [2, 14]. Camera-based systems are used for analysis of rolling maneuvers [29], arm midline-crossing reach-to-grasp behavior [24], postural control, and hand behavior relations [23], as well as head movement [16, 17]. Reach-to-grasp behavior is induced with attractive toys of different sizes and at different positions [4], followed by analyses of movement speed, hand path length, and number of movement units [3, 4]. Head movement is analyzed for lateral (LAT) and anteroposterior (ANT-POS) displacement, movement speed [16], and range-of-motion (ROM) [17]. Postural stability is assessed by center-of-pressure (COP) movement analysis either with force plates [15] or pressure mattresses [10]. The first are highly reliable and accurate, while the latter allow wider selection of outcome measures, such as infant body posture, activity, and movement behavior, obtained by application of advanced data processing algorithms on pressure imprints [11, 20]. Grasping behavior is analyzed with dedicated pressure- or force sensor-equipped toys [7]. Integration as part of a bio-mechatronic gym enables stimulation of realistic toy play [6]. Observed parameters are changes in grasping action type (uni-/bimanual grasping and midline crossing) and unimanual grasping force [27]. Sensorized toys are also used for monitoring object manipulation types (grasping, shaking, and sliding) in older infants [33].

Cecchi et al. present a measurement system with a novel combination of sensors, developed by the EU FP7 project CareToy consortium [7]. Main purposes of the dedicated playground are assessment, stimulation, and improvement of infant motor skills through intensive infant-gym interaction.

Framework of the system (see Fig. 1) comprises sidewalls with lights and speakers for stimulation of infant activity and two pressure mattresses for posture assessment [21]. Toys are positioned on the arch or on sidewalls to stimulate toy-position-dependent reaching activities [26, 27]. Circularly shaped large ring toy comprises a pressure sensor and inertial and magnetic measurement unit (IMU) for toy orientation assessment [6]. Cylindrical mouse toy comprises a pressure sensor, an IMU, and two force sensors. Video cameras are integrated for review of the performed trials. One IMU is also integrated in the CareToy gym sidewall to provide a referential orientation of the gym (see Fig. 1).

During training, infants are equipped with trunk and forearm IMUs and placed in supine, prone, or sitting position, depending on the targeted behavioral stimulation (goal of training), whereas in sitting position, a dedicated belt pillow offers additional support. IMU data are acquired synchronously with a constant sampling frequency of 100 Hz and are processed with the unscented Kalman filter (UKF), an algorithm for estimation of nonlinear systems [31]. The algorithm performs sensory fusion of angular velocity, acceleration, and magnetic field vectors to estimate IMU orientation relative to CareToy gym orientation. Estimated orientation data are further processed and improved with the estimated trunk imprint orientation on the pressure mattress, determined with in-house developed algorithms. These are a combination of contrast enhancement methods, image moments calculation, and determination of trust levels [21].

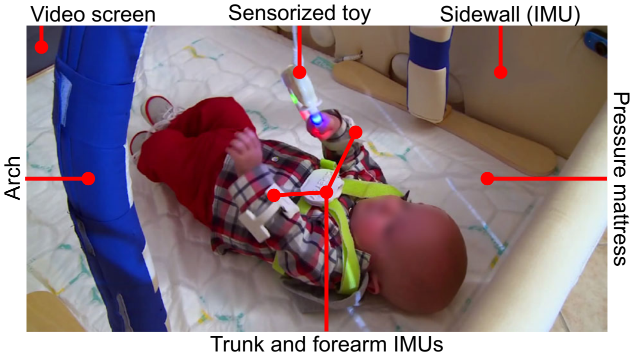


**Fig. 1** Infant performing a training scenario inside the sensor-supported CareToy gym. Hardware parts are indicated with red points and text. Sidewall includes also a referential IMU for orientation determination

Main advantages of the presented gym and proposed combination of sensors in comparison to other sensor-supported assessment approaches are the facts that the system is easy-to-use, occlusion-free, non-invasive, sufficiently accurate, transportable, and not limited to laboratory settings, providing the possibility of intensive daily use at home, directly by the infants and their caregivers. Trainings can be performed in home-based settings, remotely monitored by the rehabilitation staff. This new approach is very important to ensure relaxed, every day-like behavior, not affected by the sensor-system-based constraints. Hardware of the CareToy gym [7] cannot be used without the corresponding measurement protocol [26] and dedicated data processing algorithms that will enable further progress in the field of sensor-supported infant activity assessment.

This paper therefore presents a full description of the implemented methodology and corresponding results for complete infant posture and movement assessment, covering rolling, arm movement behavior, grasping, and posture stability analysis. Numerous sensor data processing algorithms are proposed and described. Methods are tested on measurement data of preterm infants and results are provided to evaluate suitability of the proposed approach for extraction of motor pattern data and activity monitoring, regardless of training goal and infant posture.

## 2 Methods

This section describes sensor data processing techniques for complete sensor-supported motor skill assessment, consecutively describing rolling motion, arm and head movement, and postural stability. Finally is given a description of infants, assessed as part of a case study. Proposed combinations of data processing algorithms and selected numerical motor pattern parameters are a result of iterative improvements, accomplished during development and optimization of the CareToy system. The applied methods are needed due to specificity of sensor data and the application itself, and represent the currently optimal approach. The selection of algorithms and parameters was determined according to good-practice approaches from other fields of human movement studies, experience of clinical partners, and characteristics of the CareToy project. Results of the technically determined parameters were also validated by taking into account clinical assessment scores, identifying high correlation of clinical and technical results [22]. Among other parameters, correlation of rolling and clinical AIMS values was statistically significant ($p < 0.01^{**}$) with Pearson correlation coefficient of 0.71, while correlation of toy grasping time for the goal with toys on midline was statistically significant ($p < 0.01^{**}$) with Pearson correlation coefficient of 0.60 [22]. Evaluation of the CareToy system itself (obtained sensor data) was performed with respect to normative data, obtained by referential optoelectronic measurement system, confirming adequacy of the proposed multi-sensor measurement system [20, 21]. Motor pattern parameter errors are under 10%, while kinematic estimation error is in range of 2 cm for a full sensor set, comprising pressure mattresses and two IMUs per arm [20, 21]. For further studies, a simplified sensor set with only 1 IMU per arm was used due to important advantages, such as simplified measurement protocol, shorter system preparation time, and lower cost, naturally at some minor expense of lower, but still acceptable accuracy of motor pattern assessment for frequent practical use.

*Rolling motion analysis* (gross motor skills) focuses on trunk rotational movements around the caudocranial axis. They are an important part of infant motor development, directly affecting infant's reachable workspace, and having strong impact on infant's interaction with the surrounding environment. When infants are presented with toys on sidewalls, they are expected to roll to the corresponding side, followed by interaction with toys. Similarly, whenever presented with rolling stimulation scenarios, they are expected to have higher rolling activity [22]. Rolling motion analysis is performed on orientation data, estimated with trunk and integrated CareToy gym IMU sensors, which are additionally corrected with pressure mattress data. A dedicated UKF algorithm [21, 31] is used in this respect, taking into account gyroscope, accelerometer, and magnetometer data, calculating orientations of each IMU sensor. Trunk orientation data is in this context defined as a rotation matrix $\mathbf{R}_T{}^{CT}$, describing the orientation of trunk IMU sensor coordinate system ($T$), relative to the integrated CareToy gym IMU sensor coordinate system ($CT$). Trunk IMU is located inside a special bracelet, mounted on the infant's trunk. Rotation matrix $\mathbf{R}_T{}^{CT}$ is obtained by pre-multiplication of transposed $\mathbf{R}_{CT}{}^{E}$ and $\mathbf{R}_T{}^{E}$ rotation matrices ($\mathbf{R}_T{}^{CT} = \mathbf{R}_E{}^{CT} \cdot \mathbf{R}_T{}^{E}$), where $\mathbf{R}_T{}^{E}$ and $\mathbf{R}_{CT}{}^{E}$ denote orientations of trunk and CareToy gym IMU sensors, relative to the Earth coordinate system ($E$), which is determined with orientations of gravity and magnetic field vectors. Assessment procedure comprises four processing steps:

1. Recalculation of improved trunk orientation data ($\mathbf{R}_T{}^{CT}$) to three-dimensional Euler angles (roll, pitch, yaw), respectively, describing rotations around caudocranial (CAU-CRA), mediolateral (MED-LAT), and anteroposterior (ANT-POS) trunk axis. Roll data for a single training session have a range of 360° and can coarsely be divided into supine and prone (see Fig. 2a, b).
2. Transformation of data by calculation of data histogram. Roll angle data are grouped into groups of 1° from − 179° to + 180° (360 groups), while each column value of the histogram denotes the occurrence frequency of the individual group.
3. Presentation of histogram values in a circular graph (see Fig. 2b). More frequent roll angles are presented with thicker dots, providing clinicians with good insight into infant's trunk posture and prevailing orientation during the measurement.
4. Calculation of numerical parameters for rolling movement interpretation:
   - *Rolling range-of-motion (ROM)* is determined as the angular distance between the 10th and 90th percentile of roll data and describes infant rolling motion ability. 10th and 90th percentile are chosen over 0th and 100th to avoid inaccuracies due to (a) potential trunk IMU movements, which are not the result of actual trunk movement, and (b) potential rolling data signal artifacts, not removed by data filtering.
   - *Average rolling speed* is calculated as the traveled path around CAU-CRA axis, normalized with respect to the session duration, and evaluates infant activity levels.

*Arm posture and movement assessment* (gross motor skills) are an important addition to trunk posture evaluation. They describe infant arm activity, including important well-established motor pattern parameters, such as reachable arm workspace (see Fig. 2c), arm movement smoothness, and average movement speed. IMUs positioned on infant trunk and arms can in most cases provide good substitution to large, expensive laboratory-based analysis systems, by ensuring relatively good posture and movement characterization with relatively low kinematic estimation errors. Several

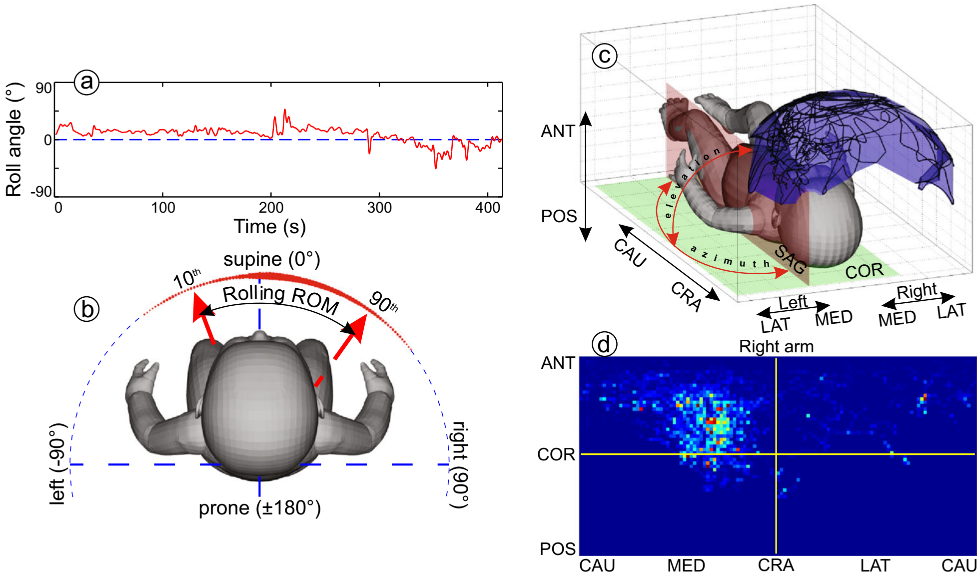


**Fig. 2** **a** Rolling motion angle data for one training session with red and blue lines showing the rolling angle and 0° line, respectively. **b** Circular presentation of rolling angle histogram, introducing 10th and 90th percentile positions and rolling ROM determination. **c**, **d** Forearm (FA) orientation map determination, where spatial (**c**) and planar (**d**) presentations of FA orientation-based movement are given. In **c**, estimated three-dimensional position of infant's right hand during a training session is presented with a black line. Concave purple hull encloses right arm workspace surface envelope. Azimuth and elevation angle are presented with red lines, positioned between infant's coronal (COR, green patch) and sagittal (SAG, red patch) planes. Infant's trunk axes are indicated with black arrows and text. In **d**, a FA orientation map for right arm movement is shown with dark blue color representing value 0, while increasing values are marked with increasing intensity from dark blue to dark red

data processing techniques are proposed and implemented, such as the alpha shapes method, optimum radius calculation, spectral-arc-length metric of hand velocity, and convex hull estimation. A simplified version of the IMU system with only 1 IMU on infant's forearm is used in the final CareToy setup, assuming that the infant's forearm is always extended. This ensures sufficient accuracy, as infants before the reaching onset period perform most of the arm movements with mainly locked elbow angle, consequently lowering the IMU setup related kinematic error [21]. Full methodology, sensor system simplification propositions, and testing exceed the main goal of this paper and are in detail described and validated in Rihar et al. [21].

*Forearm orientation analysis* (gross motor skills) is proposed to additionally describe arm activity and posture relative to infant's trunk, which can be used to study the development of goal-oriented reaching and posture. Whenever infants are presented with toys, they are expected to orient their forearms towards them, focusing on interaction with toys [22]. A novel, simplified version of assessment algorithms is suggested in the form of forearm (FA) orientation map determination. Analysis utilizes FA IMU orientation data ($\mathbf{R}_{FA}{}^{CT}$) and improved trunk orientation ($\mathbf{R}_{T}{}^{CT}$), which are both determined relative to the CareToy gym coordinate system $CT$ (estimated with an integrated IMU and a UKF algorithm [31]). Evaluation procedure consists of six consecutive processing steps:

1. Expression of FA IMU orientation data $\mathbf{R}_{FA}{}^{CT}$ (determined relative to the CareToy gym coordinate system) relative to the improved trunk coordinate system $\mathbf{R}_{T}{}^{CT}$ (determined relative to the CareToy gym coordinate system) by pre-multiplication of transposed $\mathbf{R}_{T}{}^{CT}$ and $\mathbf{R}_{FA}{}^{CT}$ rotation matrices ($\mathbf{R}_{FA}{}^{T} = \mathbf{R}_{CT}{}^{T} \cdot \mathbf{R}_{FA}{}^{CT}$) [21].
2. Recalculation of two orientation-based Euler angles from the orientation data $\mathbf{R}_{FA}{}^{T}$, where azimuth is the angle between orientation of the FA vector projection on the coronal plane and infant's sagittal plane, and elevation is the angle between the FA vector and infant's coronal plane (see Fig. 2c).
3. Reduction of large amount of data by grouping data into discretized areas of 3° × 3°.
4. Transformation of orientation data presentation from spherical to planar by plotting data onto a FA orientation map, where azimuth and elevation data are located on horizontal and vertical axis, respectively (see Fig. 2d). Azimuth data can traverse from caudal (CAU) orientation over medial (MED), cranial (CRA), and lateral (LAT) direction. Elevation data can on the other hand travel from posterior (POS) to anterior (ANT) direction, crossing the orientation, where the forearm vector is parallel to the coronal plane (COR).

5. Segmentation of FA orientation map into four quadrants and separate plotting for left and right arm, whereas planar presentation provides insight into FA activity, symmetry levels, and posture during training.
6. Calculation of numerical parameters to provide the possibility of statistical analysis:

   - *MED FA orientation intensity ($I_{MED}$)* is calculated as the percentage of session that forearm orientation is medial.
   - *MED FA orientation area ($A_{MED}$)* is determined as the area, the data are covering in the ANT-MED quadrant, divided by the entire area of the quadrant. Only data between COR and ANT direction are taken into account to increase parameter sensitivity.
   - *LAT FA orientation area ($A_{LAT}$)* is similarly calculated as the normalized area that the data are covering in the ANT-LAT quadrant.

Calculation of FA orientation areas in the POS quadrants is possible in the same manner, but not very informative, since infants do not orient their arms in the POS direction for long.

*Head imprint movement analysis* (gross motor skills) is an important segment of infant posture and movement evaluation. Several algorithms for head imprint movement analysis in supine position were proposed and developed along with calculation of appropriate corresponding statistically valuable parameters [20]. Data processing techniques comprise advanced head imprint extraction approaches, such as line-of-sight method, histogram analysis, and head movement tracking method. Statistical analysis is focused on retrieving information on potential head posture asymmetry in terms of MED-LAT head displacement, along with assessment of head activity levels by calculation of head movement rates and number of head lifts.

*Grasping and interaction activity analysis* (fine motor skills) is of great importance for infant's toy grasping and manipulation ability evaluation. It is expected that grasping toys of circular form is easier for infants in comparison to grasping toys of cylindrical shape, as the latter demands adjustments to forearm orientation [22]. This implies higher grasping activity, but practically unchanged interaction activity. Whenever infants are presented with toys on sidewalls, they are expected to have lower grasping activity, as such toy position requires additional rolling manoeuvers [22]. The procedure utilizes toy sensor signals (pressure, force, and IMU). Grasping activity analysis consists of the following steps:

1. Low-pass filtering of toy pressure sensor signal $P$ (see Fig. 3a) to reduce presence of high-frequency noise.
2. Application of signal trend removal method, needed to remove signal drifting character, which can be a consequence of pressure chamber air temperature changes and other effects. Such intervals are extracted by calculation of slope and signal variability information.
3. Adjustment of pre-processed signal and comparison to pre-determined threshold to eliminate atmospheric pressure level and retain pressure activity of actual grasps (see Fig. 3c).
4. Application of data connectivity method for extraction of pressure-based grasping activity intervals and removal of extremely short intervals.
5. Low-pass filtering and application of threshold comparison method to the force sensor signal of mouse toy, which is less prone to drift and artifacts.
6. Identification of mouse toy force-based grasping activity intervals using a data connectivity method.
7. *Grasp percentage* parameter calculation as the ratio between grasping time and session duration, characterizing infant grasping ability.

*Mean and max grasp pressure* parameter determination as mean and maximum value of processed toy pressure signal, providing insight into characteristics of power grasp intensity.

Less skilled infants are often unable to perform advanced grasping manoeuvers for longer periods of time and restrain their toy interaction to touching activity. Analysis thus comprises the following steps:

1. Low-pass filtering of three-dimensional angular velocity data ($\omega_{X,Y,Z}$) and transformation to the gym coordinate system by taking into account toy IMU orientation.
2. Application of multi-level one-dimensional wavelet decomposition method [18] on each axis of angular velocity data $\omega_{X,Y,Z}$ (see Fig. 3b).
3. Reconstruction of signals at the 4th level using each axis wavelet decomposition values.
4. Low-pass filtering of absolute values and comparison to a pre-set empirically determined threshold. Parts of the resulting signal above the selected threshold directly determine intervals of toy movement, similar to free sinusoidal toy oscillations. These are identified as toy movement without interaction.
5. Calculation of angular velocity signal energy and comparison to a pre-set threshold to determine the intervals without toy movement.
6. Extraction of toy movement intervals from the toy IMU gyroscope signal by removing toy oscillation intervals and intervals without toy movement (see Fig. 3d).
7. At this point, two options for further analysis are possible as follows (see Fig. 3e):

   a. Grasping intervals can be added to the resulting signal of toy movement intervals without free oscillations

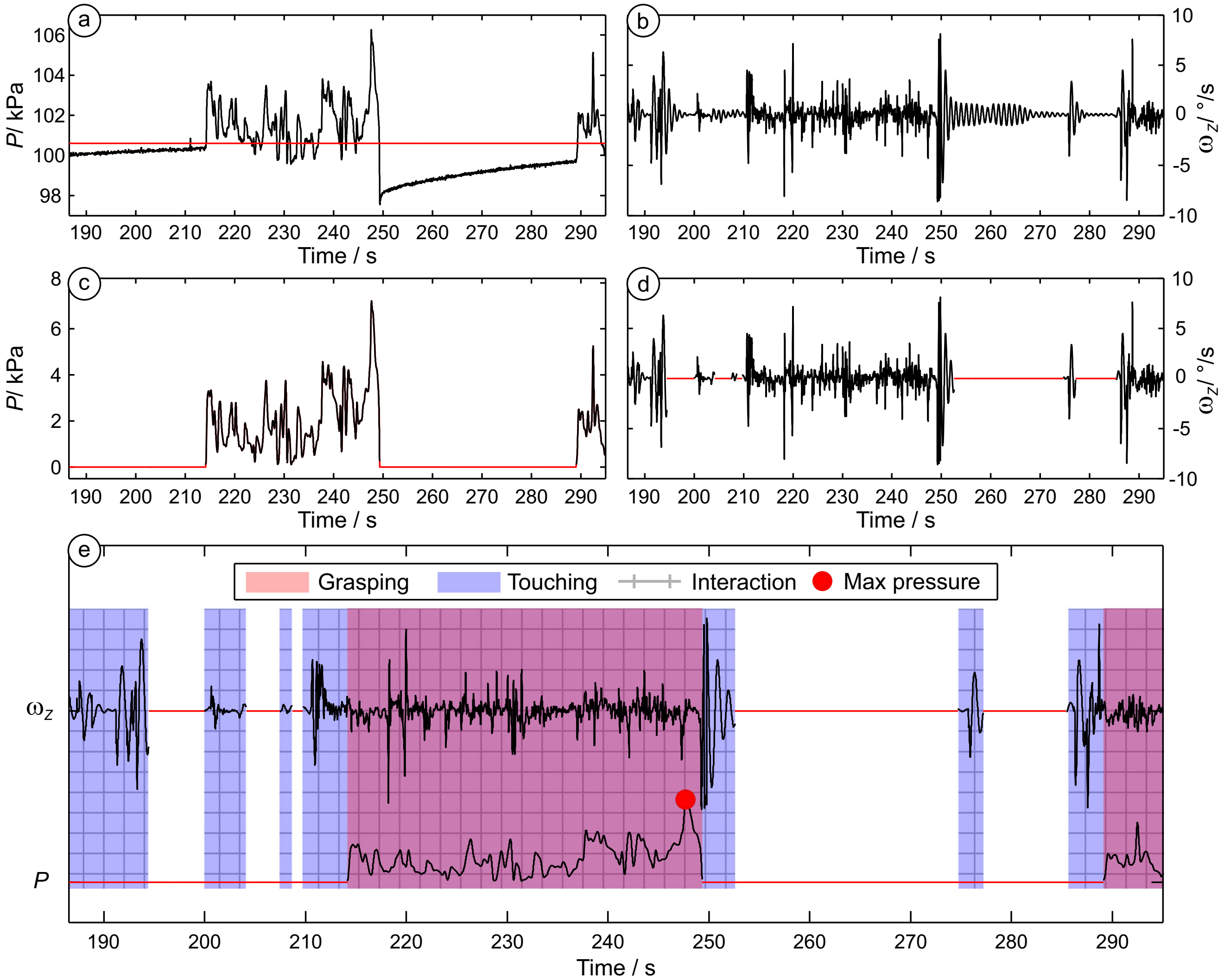


**Fig. 3** Extraction of grasping, touching, and interaction intervals. Raw signal values of toy pressure and gyroscope sensors, namely pressure $P$ (**a**) and $Z$-axis of angular velocity $\omega_Z$ (**b**) are presented with black lines. The red line in **a** indicates the original threshold level at the value of atmospheric pressure. **c**, **d** Signal processing results, including toy pressure signal trend removal and thresholding, along with toy angular velocity thresholding and free oscillation intervals removal. **e** Final results of toy data processing, namely extraction of grasping (red patches), touching (blue patches), and interaction (hatched blue and red patches) intervals, along with the determined max pressure value (red circle)

and the acquired signal intervals would represent hand-toy interaction intervals. *Interaction percentage* can be calculated as the ratio between assessed interaction time and session duration.

b. Grasping intervals can be removed from hand-toy interaction intervals and the newly determined signal intervals would represent toy touch intervals. *Touch percentage* is obtained as the ratio between touching time and training session duration.

*COP movement assessment* (gross motor skills) is important for providing insight into postural stability and activity, focusing on evaluating infant's responses to the changes in the surrounding environment. Presenting infants with toys is expected to affect their postural stability and increase their activity [22]. Evaluation is performed by processing pressure distribution data of the pressure mattresses. The assessment is conducted as follows:

1. Determination of pressure mattress bias (see Fig. 4a) and application of a bias removal method. Pressure mattress data are subject to temperature dependent bias, which can reach up to 10% of pressure data output (see Fig. 4b, e). Bias removal is performed by subtraction of the pre-assessed bias matrix from the pressure data.
2. Removal of superposed noise, which is initially partly removed by comparison to a pre-set threshold. Afterwards, data connectivity algorithm is applied to

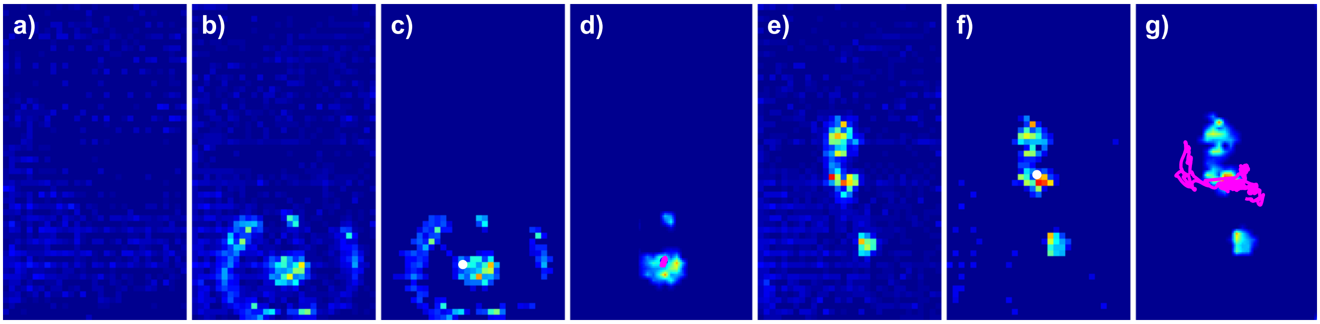


**Fig. 4** Center-of-pressure (COP) movement determination. Examples of pressure mattress data processing steps are given in subplots **a**–**g**. **a** The unloaded pressure matrix, indicating initial data offset. Data analysis procedures for scenarios with infants in sitting and supine position are given in subplots **b**–**d** and **e**–**g**, respectively. **b**, **e** Loaded pressure mattress data values, where dark blue color represents value 0, while increasing load is marked with color of increasing intensity from dark blue over bright yellow to dark red. **c**, **f** Pressure matrix values after bias removal, threshold comparison, and superposed noise removal, while superposed white circle indicates the current COP position. **d**, **e** Final processing results, produced with additional interpolation, small patch removal, and when necessary belt pillow removal (**d**). Pink lines demonstrate assessed COP movement during the training session

group the connected imprints, and differences between the maximum and minimum pressure value of each imprint are calculated. Imprints with low difference values (contrast) and small area are removed from further processing (see Fig. 4c).

3. Interpolation of pressure data with a linear interpolation method and calculation of COP position, taking into account pressure mattress pixel load and position values.

   In training scenarios with infant in supine, this procedure provides body COP results of sufficient accuracy for the entire training session (see Fig. 4g). In case infant is in sitting position, additional processing is required, due to the belt pillow, which is used for additional support.
4. Calculation of initial COP position and the *full load value* of pressure mattress data. Whenever infants are in a stable sitting position, COP position should be within or at least near the buttocks pressure imprint polygon area, which should be positioned near the center of short edge of the pressure mattress.
5. Application of data connectivity algorithm on pressure mattress data and removal of imprint objects that are either far away from COP position or positioned laterally.
6. Identification of buttocks and feet imprints as pressure imprints, positioned near the center of pressure data.
7. Calculation of updated COP position for each pressure frame, along with determination of the *partial pressure load* of buttocks and feet.
8. Further statistical analysis of presumably stable sitting data by selection of frame indices, where partial pressure load values are either higher than a minimum pre-set load threshold or higher than a relevant portion of the full load.
9. Interpolation and low-pass filtering of selected COP data, followed by calculation of well-established analytical postural stability parameters [9], such as:

   - *Root-mean-square displacement (RMSd)*,
   - *ANT-POS and MED-LAT range-of-motion*, and
   - *area of a best-fitting circle*, enclosing 95% of COP data.

Statistical relevance of data correlation among COP movement and rolling angle data of infants in supine position was assessed by calculation of Pearson correlation coefficients.

## 2.1 Subjects

Suitability of proposed assessment algorithms was evaluated on measurement data of two infants, enrolled as part of a randomized clinical trial (RCT) [22, 25, 26] of CareToy project. Infants #1 and #2 were born preterm and at the start of training trials had a corrected age of 20 weeks and 5 days, and 21 weeks, respectively. Infants had different motor skills, as before the onset of trials their AIMS total scores were 18 and 13. During measurements, infants were presented with different training sequences [27] to induce different behavior responses (rolling, toy play, head movement) [22]. Signed informed consent was obtained from infant parents before the start of assessment, while the measurements were performed in compliance with Helsinki Declaration. Suitability of the measurement protocol was approved by Tuscan Region Pediatric Ethics Committee and Italian Ministry of Health (DGDFSC 0066613-P-17/09/2013).

# 3 Results

This section consecutively presents sensor data processing results for rolling activity, FA orientation behavior, interaction and grasping activity, and COP movement assessment with the aim of evaluating applicability of proposed algorithms.

With the exception of rolling activity analysis, where results are shown for both infants, results are mostly provided only for infant #1 to keep the focus on methods. This infant was selected, because of specific stimuli-related behavior, being appropriate for demonstrating ability of the proposed algorithms for behavior distinction. Results of infant #2 were added to the rolling-related results to show that the algorithms are able of detecting differences in rolling responses.

Rolling activity results are presented for both infants as circular graphs for four training goals (see Fig. 5), including data of 3 weeks of training, whereas data in the same week are grouped and presented together. Rolling data of infant #1 are evenly spread around the graph for goals of grasping toys on midline and rolling stimulation. For the goal of grasping toys on right sidewall, dots are thicker on the right half, but high data spread persists. Infant was not trained to roll towards the left sidewall, due to good rolling ability (see Fig. 5). Data of infant #2 are available for all four aforementioned training goals. In the case of grasping toys on midline goal, trunk orientation data are concentrated mostly in the supine part, while for the rolling stimulation goal data dots are spread evenly. In the case of grasping toys on sidewalls goals, data are concentrated near the corresponding sidewall side.

Additionally, rolling activity analysis results are presented as numerical values of parameters for both infants and for all four goals (see Table 1). Numerical values were obtained by calculating median values of determined numerical parameters (median roll data angle, rolling ROM and average rolling speed) for individual sessions of each week (week #1, week #2, and week #3).

Results for FA movement behavior are presented as FA orientation maps for left and right arm for the following training goals: grasping toys on midline (see Fig. 6a), maintaining posture in midline without toys (see Fig. 6b), and grasping toys on right sidewall (see Fig. 6c). Parameter values are provided for MED FA intensity, MED, and LAT FA area. In case of grasping toys on midline goal (see Fig. 6 a), FA orientation values are concentrated in the ANT-MED quadrant, being practically symmetrical for left and right arm. In the case of second goal (see Fig. 6b), data are mostly concentrated in the ANT-LAT quadrant with occasional excursions towards the POS-LAT and ANT-MED quadrants. FA orientation maps are again relatively symmetrical for both arms. As regards the third goal (see Fig. 6c), data are practically evenly spread among ANT-LAT and ANT-MED quadrants for both arms with additional distinct orientation of left arm towards POS-LAT quadrant. Data patterns are not symmetrical, when comparing both arms.

Toy play activity results are provided as line graphs with indicated signal intervals of grasping, interaction, and touching activities (see Fig. 7) to show toy shape and position related behavioral differences. Interaction and grasp percentage values are for goals of grasping large ring toy on midline 95% and 43% (see Fig. 7a), grasping mouse toy on midline 79% and 5% (see Fig. 7b), and grasping large ring toy on the right sidewall 45% and 24% (see Fig. 7c), respectively.

COP movement assessment data are first presented for trials with and without toys in sitting position (see Fig. 8a, b). When toys are present, COP data have higher spread with no distinct prevailing direction. Parameter values for selected trials are for RMSd 1.4 cm and 0.6 cm, for the circle area 14.9 cm$^2$ and 3.1 cm$^2$, for the MED-LAT range 4.4 cm and 0.8 cm, and for the ANT-POS range 3.8 cm and 3.0 cm, respectively. Results for training trials in supine position are given for goals of grasping toys on midline (see Fig. 8c), rolling stimulation (see Fig. 8d), and grasping toys on right

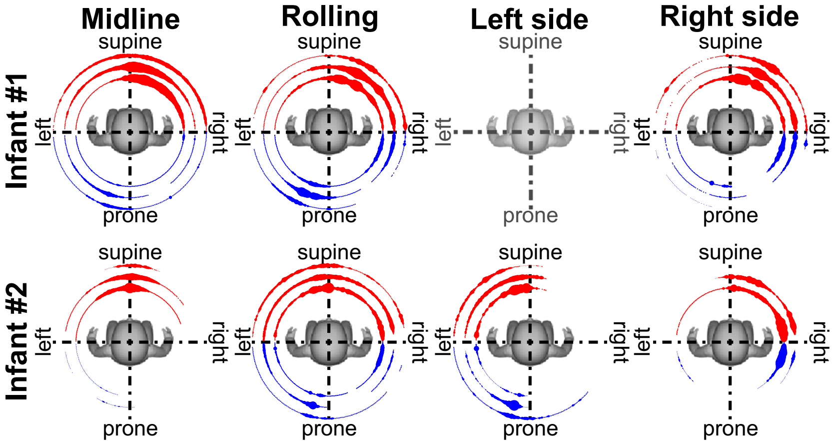


**Fig. 5** Rolling activity analysis results for infant #1 (first row) and infant #2 (second row) for four different goals, namely grasping toys on arch midline (midline), rolling stimulation (rolling), and grasping toys on left (left side) and right (right side) sidewall. Red and blue colored lines indicate trunk rolling activity in supine and prone position, respectively. Rolling angle histogram results are given for all sessions of 3-week training as circular graphs, whereas values from first to last week are presented with circles of increasing radius. If infant was not presented with training scenarios for a certain goal in 1 week, corresponding circle is empty

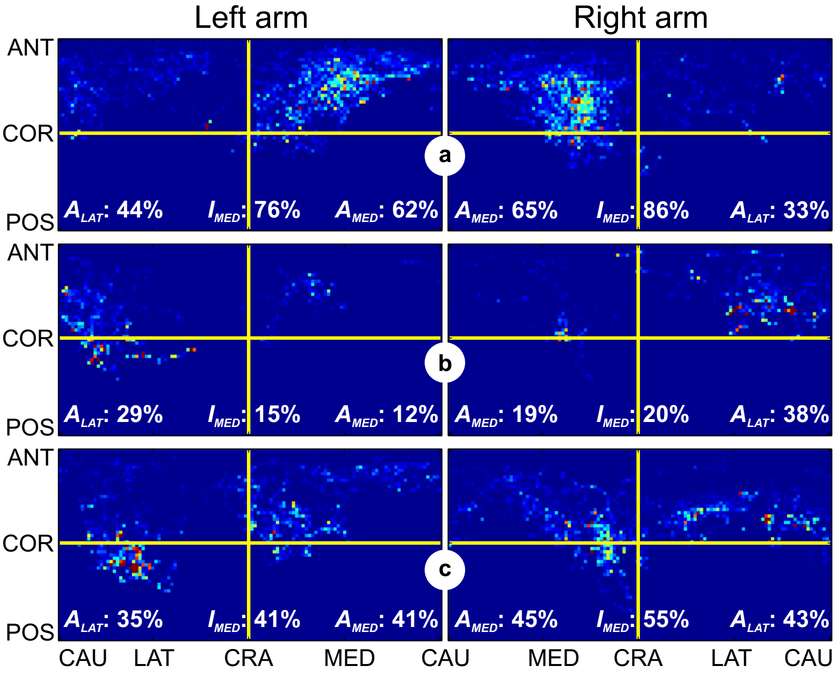
**Table 1** Rolling activity analysis results for four different goals, namely grasping toys on arch midline (midline), rolling stimulation (rolling), and grasping toys on left (left side) and right (right side) sidewall. Bold #1 and #2 denote infants #1 and #2, respectively. Presented median (median roll data angle), rolling ROM, and average rolling speed parameters were determined as median values of the corresponding parameters, calculated for sessions of each week, where w #1, w #2, and w #3 indicate the week of training. When an infant was not presented with training scenarios for a certain goal in 1 week, this is indicated with o

| | | Midline | | Rolling | | Left side | | Right side | |
|---|---|---|---|---|---|---|---|---|---|
| | | #1 | #2 | #1 | #2 | #1 | #2 | #1 | #2 |
| Median / ° | w #1 | 29.8 | − 0.8 | 29.4 | 17.2 | o | − 17.6 | 29.4 | 76.1 |
| | w #2 | 2.4 | 0.9 | 17.8 | − 4.1 | o | − 88.2 | 50.0 | 28.1 |
| | w #3 | 21.9 | 2.8 | 23.1 | − 27.7 | o | − 54.2 | 30.2 | o |
| Rolling ROM / ° | w #1 | 53.9 | 17.2 | 143.9 | 107.3 | o | 67.3 | 105.5 | 88.7 |
| | w #2 | 104.1 | 36.1 | 82.5 | 83.7 | o | 84.9 | 55.2 | 71.4 |
| | w #3 | 178.0 | 20.7 | 173.9 | 129.0 | o | 156.4 | 107.3 | o |
| Aver. roll. speed / °/s | w #1 | 4.8 | 4.0 | 6.0 | 4.0 | o | 2.4 | 5.7 | 5.7 |
| | w #2 | 5.9 | 4.6 | 4.6 | 5.2 | o | 5.2 | 4.8 | 6.0 |
| | w #3 | 7.1 | 2.7 | 5.5 | 6.2 | o | 6.2 | 4.7 | o |

sidewall (see Fig. 8e). Rolling angle data are provided additionally as vertical line graphs. For the first goal, COP data are focused around the center with a small spread and a single excursion in MED-LAT direction, while roll angle data are concentrated around 0° with a single excursion towards 90° (see Fig. 8c). For the second goal, COP data have several excursions in the MED-LAT direction, while trunk orientation data continuously change from − 90° to 90° (see Fig. 8d). COP data for the goal of grasping toys on right sidewall have two distinct parts, where one is concentrated with a relatively small spread, while the second has larger spread mainly in the longitudinal trunk direction. Roll angle data are concentrated mainly between 45° and 90° and are only occasionally near 0° (see Fig. 8e). Parameter values are for selected trials of aforementioned goals respectively for RMSd 2.0 cm, 6.3 cm, and 4.8 cm, circle area 36.7 cm$^2$, 421.2 cm$^2$, and 196.4 cm$^2$, MED-LAT range 11.9 cm, 29.3 cm, and 16.2 cm, and ANT-POS range 6.3 cm, 15.8 cm, and 19.0 cm. Rolling ROM values are 21°, 87°, and 57°, while average rolling speed values are 2.3°/s, 5.7°/s, and 5.1°/s.

Correlation among the MED-LAT direction of COP and corresponding roll angle data was assessed by using data of

**Fig. 6** Forearm (FA) orientation map results for training sessions for goals with toys on midline (a), without toys on midline (b), and with toys on right sidewall (c). Left and right column present results for left and right arm, respectively. Values of calculated parameters (MED FA intensity, LAT, and MED FA areas) are given with white text for each FA orientation map



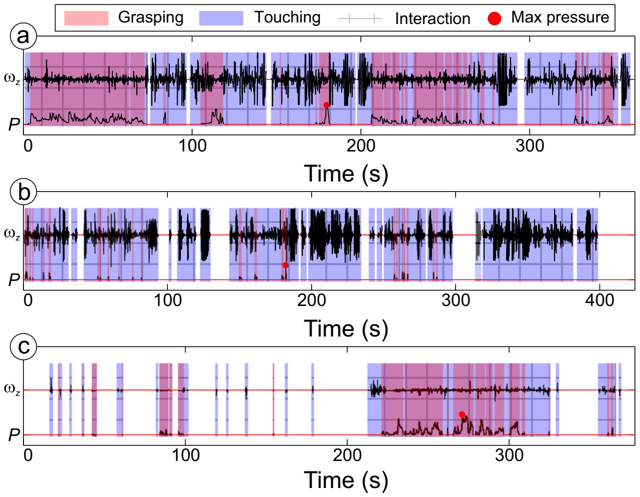


**Fig. 7** **a**, **b**, **c** Toy play analysis results for training scenarios with large ring toy on midline, mouse toy on midline, and large ring toy on right sidewall, respectively. Processed toy pressure *P* and angular velocity $\omega_Z$ signals are presented, including indication of max grasp pressure (red circle), interaction (hashed red and blue patches), touching (blue patches), and grasping (red patches) intervals. Force sensor of mouse toy was not touched during the training trial, thus force signal is not presented

infant #1 for the three mentioned training goals, intended for supine position. Obtained Pearson correlation coefficients for the goal of grasping toys on midline (11 trials), the goal of rolling stimulation (15 trials), and the goal of grasping toys on right sidewall (6 trials) are 0.58, 0.78, and 0.77, respectively.

## 4 Discussion

This section provides discussion of acquired results, seeking to evaluate suitability of the proposed data processing algorithms for complete assessment of gross and fine motor skills.

Rolling activity results (see Fig. 5 and Table 1) indicate high activity (average rolling speed values mostly near or above 5°/s) and good rolling ability (rolling ROM values mostly above 100°) of infant #1, which were expected due to his typical behavior. Moreover, the rolling activity was not the main goal of his training. Additional results of infant #2 demonstrate that (a) infant apparently successfully responded to the presented goal-specific scenarios with expected rolling-related behavior and (b) use of proposed data processing algorithms on the trunk IMU data was suitable to determine the side of performed movements and locations of prevailing orientation. Median roll angle data parameters were near 0° for midline, negative for left side, and positive for right side goals, while rolling ROM values were below 40° for midline and above 80° for the rolling stimulation goal.

FA orientation results comply with the expected FA movement behavior (see Fig. 6) and demonstrate increased arm activity ($I_{MED}$ over 75%), prevailing MED orientation ($A_{MED}$ over 60%), and symmetrical behavior for the trial with toys in midline, as well as lower activity ($I_{MED}$ under 25%) and LAT orientation ($A_{MED}$ under 20%), when toys are not present (see Fig. 6a, b). Presenting infants with a toy on sidewall induces evenly

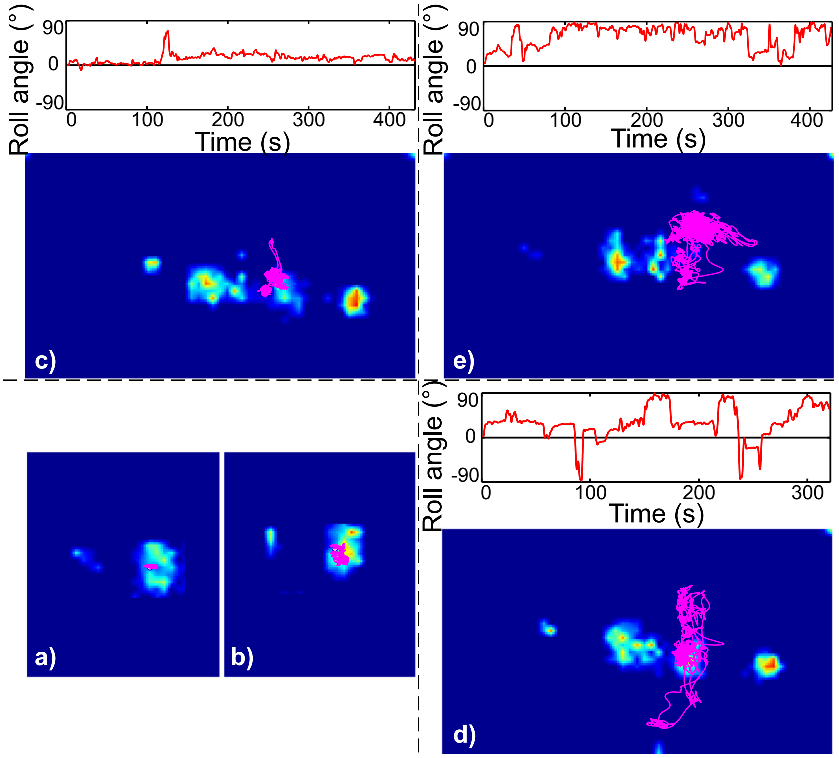


**Fig. 8** Centre-of-pressure (COP) movement assessment results of buttocks pressure imprints are presented with pink lines for training scenarios without (**a**) and with (**b**) toys in sitting position. **c**, **d**, **e** COP movement path (pink line) examples for goals of grasping toys on midline, rolling stimulation, and grasping toys on right sidewall, respectively. Vertically are shown roll angle signals (red lines) for corresponding training sessions

spread FA orientation with average activity ($I_{MED}$ around 50% and $A_{MED}$ around 40%).

Grasping and interaction activity results demonstrate high activity levels for both toys (interaction percentage above 75%), as well as low grasping percentage (5%) for the mouse toy, which is due to the need for appropriate FA orientation more difficult to grasp. When toy is positioned on the sidewall and thus placed away from the central focus of infant's workspace, lower interaction (under 50%) and grasping (under 25%) activity are expected and determined.

COP movement assessment results indicate that presenting infant with the toy in sitting actually increases infant activity by stimulating toy play and movement, resulting in higher dispersion and higher parameter values, due to increased interest in the surrounding environment. On the other hand, presenting infant with a video on the video screen actually draws attention and stimulates focus on postural stability. In supine position, stable posture while grasping toys on midline is verified with MED-LAT range under 12 cm and ANT-POS range of 7 cm. For the goal of rolling stimulation, larger COP data dispersion and higher rolling activity are expected and identified with MED-LAT range, rolling ROM, and average rolling speed values over 29 cm, 85°, and 5°/s.

Results demonstrate strong correlation among rolling activity and shifting of COP position in the MED-LAT direction, as for goals with relevant rolling activity Pearson coefficient values were almost 0.8. Besides the presented inter-subfield relations, the system could offer important insight into several currently perhaps not fully revealed inter-motor pattern subfield relations.

## 5 Conclusion

Presented results demonstrate suitability of the proposed data processing algorithms for gross and fine motor skill analysis, regardless of the behavioral responses. Results are promising and the proposed methods were already implemented in all the CareToy systems. Algorithms are universal enough to be implemented and applied to other systems with similar data outputs. Therefore, the proposed approach presents an important step towards intensive, objective daily home-based assessment of infant motor patterns, providing great assistance to clinician-guided evaluation. The non-invasive, easy-to-use, and transportable character of the sensor-supported system is also an important benefit and advantage. The combination of CareToy system with toys and proposed algorithms thus has strong potential for the future of sensor-supported infant posture, movement, and motor pattern assessment and training.

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## Compliance with ethical standards

Signed informed consent was obtained from infant parents before the start of assessment, while the measurements were performed in compliance with Helsinki Declaration. Suitability of the measurement protocol was approved by Tuscan Region Pediatric Ethics Committee and Italian Ministry of Health (DGDFSC 0066613-P-17/09/2013).

**Conflict of interest** The authors declare that they have no conflict of interest.

**Abbreviations** AIMS, Alberta Infant Motor Scale; ANT, anterior; CAU, caudal; COP, center-of-pressure; COR, coronal plane; CRA, cranial; EMG, electromyography; FA, forearm; IMU, wireless magneto-inertial measurement unit; LAT, lateral; MED, medial; POS, posterior; RCT, randomized clinical trial; RMSd, root-mean-square displacement; ROM, range-of-motion; TIMP, test of infant motor performance; UKF, unscented Kalman filter

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