Quantification of the development of trunk control in healthy infants using inertial measurement units

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***Abstract*—Trunk motor control is essential for the proper functioning of the upper extremities [1] and is an important predictor of gait capacity [2] in children with delayed development. Early diagnosis and intervention can potentially increase the trunk motor capabilities in later life [3, 4]. However, current tools used to assess the level of trunk motor control are largely observation-based and lack the sensitivity to change required to accurately monitor progress and effects of therapy in children below the age of 4 [5, 6]. To the best of our knowledge, this is the first attempt to use trunk-attached inertial measurement units (IMUs) to differentiate different levels of trunk motor control in this population. We performed experiments with seven children to examine the applicability of the RMS of jerk as an outcome metric for the level of trunk motor control. This study showed that the root mean square (RMS) of jerk decreases for ages up to 24 months, is relatively independent of data segment and length, and shows results similar to a more established method: the centre of pressure (COP) velocity. These findings suggest that the RMS of jerk shows potential as a metric for the differentiation of different trunk motor control levels. However, due to the small sample size, a follow-up study is necessary to verify and validate these results.**

I. Introduction

A. Motivation

Approximately 50% of typically developing children in the Netherlands can sit independently at 9 months and will start walking at around 15.5 months [7]. These motor milestones are important indicators for later motor skill acquisition [8, 9]. However, neuromotor disorders like cerebral palsy (CP) can cause delays in such major motor milestones [10]. Trunk motor control is essential for proper upper limb function [1] and is a predictor of gait capacity [2] in these children.

Depending on the severity level, children with CP reach about 90% of their gross motor function by the age of 5 [11]. Early intervention, i.e. providing therapy at an age below 5 years old, has the potential to increase the trunk motor control abilities of affected children in later life [3, 4].

With an increasing focus on evidence-based intervention in clinical practice [12], there is also an increasing need for sensitive assessment tools that can be used to monitor progress in this population and establish the (in)effectiveness of specific protocols.

To date, all tools used to assess trunk motor control in sitting position in clinical practice are observation-based. Nine of these tools are valid for children below five and have sufficient information on clinimetric properties like reliability and validity. The type of balance assessed in these tools can be divided into three categories [5, 6]:

Static balance	The ability to remain upright without movement, i.e. quiet sitting.
Active balance	The ability to stay balanced while inclining/rotating the trunk or moving extremities.
Reactive balance	The ability to respond to perturbations.

Most tools evaluate a combination of the first two categories. Unfortunately, none of these tools can be seen as a gold standard, as they either have limited evidence on sensitivity to detect change [13]–[15] or have not been validated for children below the age of 5 [16]–[18]. Additionally, results of the existing assessment tools may vary between raters if the level of standardization is insufficient [15].

Our literature search revealed there is currently no objective quantification of trunk motor control used in clinical practice. Such an assessment may minimize subjectivity between evaluations and could potentially perceive small changes in trunk motor control [19]. It could thus adequately evaluate the effectiveness of interventions.

Therefore, the aim of the current study was to analyse the performance of an objective quantification of different levels of trunk motor control using trunk-attached inertial measurement units (IMUs), with potential applicability in monitoring children's progress and the effects of interventions.

B. Related work

In this work, trunk control is evaluated using a trunk-attached inertial measurement unit. Based on the currently available literature, this is the first study to assess sitting balance in such a young population ranging from 10 months to 3 years of age.

Most previous studies have focused on the assessment of sitting balance using metrics related to the centre of pressure (COP) [18, 20]–[25]. COP-related metrics have shown good reliability in healthy children [26] and children with or at risk of CP [20]. Comparing results between healthy and affected children ensures that the perceived results are not due to measurement artefacts [20]. While force plates have high accuracy, they are generally expensive and restrict the measurements to a single location [27]–[30].

Other types of sensors utilized in the assessment of trunk motor control in young children in sitting position are magnetic trackers [31, 32] or optical systems [19, 33]. Magnetic tracking systems are generally sensitive to magnetic interference and have a relatively small capture volume [34]. Optical systems do not have these issues, but are generally expensive and restrict measurements to a specific location [35]. IMUs are relatively cheap, easy to use and portable [36]. These sensors have been used in sitting position in adult populations [37, 38], but not yet in younger populations.

IMUs are more common in studies relating to quiet stance [39]–[41]. The jerk, i.e. the third derivative of position [42], has been used to quantify postural balance in quiet stance in both Parkinson's disease patients [43] and Huntington's disease patients [44], where it was able to distinguish between healthy and affected subjects. Furthermore, a recent study showed that the jerk in quiet stance decreased with age for subjects from five years old to adulthood [40]. This metric has thus far not been used to assess early sitting development in children.

C. Research questions

This paper aims to answer the following primary research question:

Can a trunk-attached IMU be used to differentiate between different levels of trunk motor control in typically developing children with different ages (0-4 years old)?

In order to answer the primary research question, the following secondary questions will be answered:

1) Is the root mean square (RMS) of jerk, as determined from trunk-attached IMUs, an effective outcome metric for differentiation between different levels of trunk motor control?
2) Can an IMU-based outcome metric generate similar results as a more established method like the COP velocity?
3) How well do other outcome metrics perform compared to the RMS of jerk?

II. Methods

A. Subjects

To answer the research questions of this study, eight subjects were recruited. The subject selection was based on the following two criteria:

1) The child was between six months and four years old, and,
2) He/she did not have any health problems.

Table I shows an overview of the subjects, including their gender, age, and the marker used in subsequent plots. The parents of the children signed an informed consent form. The informed consent form and the experimental procedures were both approved by the Human Research Ethics Committee of the TU Delft.

Subject	**Gender**	**Age**	**Marker**
TS1	F	10 months 0 weeks	$*$
TS2	M	26 months 2 weeks	N/A
TS3	M	13 months 2 weeks	○
TS4	M	23 months 3 weeks	△
TS5	F	23 months 0 weeks	◊
TS6	M	36 months 0 weeks	+
TS7	F	13 months 1 weeks	×
TS8	M	20 months 0 weeks	□

TABLE I
OVERVIEW OF SUBJECTS, WITH THEIR TEST SUBJECT (TS) NUMBER, GENDER, AGE AND THE MARKER USED IN SUBSEQUENT PLOTS.

Subject 2 became restless when we tried to apply the instrumentation to him. To avoid agitating him, we decided to stop the experiments and exclude him from the rest of the study.

The van Wiechen scheme [45] was used as an indication of the developmental stage of each child. Most commonly, physical therapists fill in this observational scheme. However, due to the limited time and concentration of the child, the parents filled it in before the measurements. The lack of training of the parents in performing such assessments may result in a lower level of standardization of the outcomes. However, all children scored according to their expected developmental age or higher developmental stages. Subjects 1, 4, and 5 all score above their age average; subject 5 scored especially high.

B. Experimental setup

Fig. 1 presents an overview of the experimental setup. The experimental set-up consists of

- Two Xsens MTw Awinda inertial measurement units: triaxial sensors that use data from accelerometers, gyroscopes and magnetometers [46] and combine this data to obtain an orientation estimation of the sensor.
- A Qualisys optical motion capture system with 14 infrared markers: a video system that uses infrared cameras to find the position of markers in 3D space.
- Three Kistler type 9260AA6 force plates aligned next to each other: platforms that measure the ground reaction force (GRF) and determine its point of application, the centre of pressure (COP).

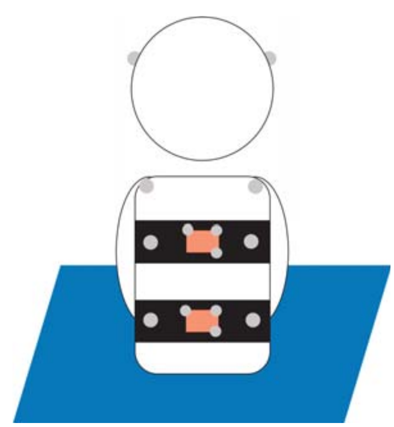

Fig. 1. Schematic overview of the experimental setup, including two IMUs, 14 infrared markers and a Kistler force plate.

The IMUs are centred on black elastic bands, with the top band right below the armpits and the bottom band at the pelvis. Three markers are placed in a triangle on each IMU to allow for comparison between the computed Xsens orientation and the QTM orientation. Appendix B presents a comparison between pitch, roll, and yaw angles using either method.

Furthermore, six markers are placed along the back and two on the temples of the subject to capture all trunk movements. We did not place any markers on the extremities to prevent possible visible distractions of the subjects. The subject is placed on top of (one of) the force plates for two conditions: directly on a force plate or on a small bench spanning two force plates.

The motion capture system provides the trigger signal to start the IMU and force plate measurement, synchronizing all three measurement methods. The motion capture system and the IMU system have a 100-Hz sample rate. The force plate has a 500-Hz sample rate.

Fig. 2 shows an overview of the relevant coordinate frames used for further analysis. The S-frame is the sensor frame, a body-fixed frame with the origin placed in the top-right corner of the sensor, corresponding with the standard sensor coordinate system [47]. The Q-frame is an inertial system with its origin aligned with the corner of the left-most force plate. The optical data and COP position are both expressed in this frame. The G-frame is the global frame of the IMU; all rotations of the IMU are with respect to this frame. The x-axis points to the local magnetic north, the z-axis aligns with the local vertical, and the y-axis is such that it forms a right-handed coordinate system with the other axes.

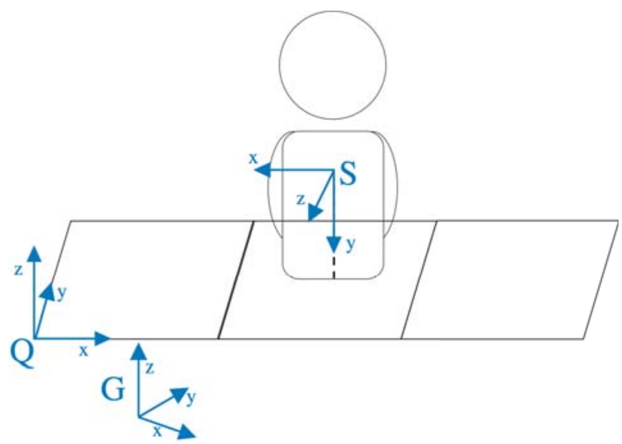

Fig. 2. An overview of the relevant coordinate frames for further analysis. The S-frame is the sensor frame, a body-fixed frame. The origin of this sensor is aligned to the top-right corner of the IMU. The Q-frame is an inertial frame used for the measurements in Qualisys and for the COP position. The G-frame is the global frame of the IMU, where the x-axis points to the local magnetic north, the z-axis is aligned with the local vertical and the y-axis is determined such that it is a right-handed coordinate frame. It should be noted that the figure does not represent the exact orientation of the G-frame, but is meant to show that the orientation of the Q- and G-frame is not the same.

Each subject participated in a single experimental session with one of their parents. Each session included the two conditions mentioned previously:

- C1: Directly on the force plate, and
- C2: On a bench that spans two force plates.

Condition C1 corresponds most with a typical developmental timeline, where children start sitting independently on a flat surface. We included condition C2 for three reasons. Firstly, condition C2 is expected to be more challenging than condition C1 and provides a basis for comparison. Secondly, adding this condition makes future comparison with adult data sets more easily implementable, as adults have trouble sitting on the force plate directly in a comfortable, representative way. Lastly, we expect this condition to be useful for future implementation with older children with delayed development, as this position is used for interventions like adaptive seating, which can improve postural control [48].

For both conditions, four different movements were desired, following the most commonly used movements in the trunk control assessment tools that are currently in use [5, 6],

- M1: Quiet sitting;
- M2: Trunk inclination in anteroposterior (AP) direction;
- M3: Trunk inclination in mediolateral (ML) direction;
- M4: Trunk rotation.

There is currently no condition included where perturbations are applied which thus assesses reactive balance as mentioned in Subsection I-A. Reactive balance was left out at this stage because it is relatively difficult to apply perturbations in a standardized, yet safe way.

To standardize measurements as much as possible, a song was recorded, detailing the movements required of the children. The song lyrics can be found in Appendix A. The melody of a well-known Dutch children's song, "Vader Jacob", was used as a basis for this song. Each verse of the song is 20 seconds long, which results in a dataset of 120 seconds where condition M1 is repeated three times and conditions M2 through M4 are all included once. The parents were asked to sit across from their child and to try to elicit the desired response from their child using a toy. While the song was intended to be used as a tool for standardization, it was difficult to use with this age group, due to the lack of understanding of the song and the limited concentration of each child. Thus, the data segments that were eventually used for evaluation did not correspond with the original aim of a 120-second dataset. Due to the high variability in movements performed by the subjects, the focus was put on quiet sitting only.

C. Data processing

An overview of the data processing and data analysis structure can be found in Fig. 3. The steps used for data processing are presented on the left side of this figure.

1) Pre-processing: Gravity was first subtracted from the raw accelerometer data using the rotation matrices as computed by the onboard algorithm of the IMU to rotate the gravity vector from the global frame to the sensor frame. The acceleration data and the raw gyroscope data were then filtered using a second-order low-pass Butterworth filter with a cut-off frequency of 10 Hz. The cut-off frequency is determined based on pilot data of an infant, where at least 90% of the total power is found below 10 Hz. Further analysis of the other datasets showed that at least 92% of the total power was found below 10 Hz for all subjects except for subject 5 (◊). However, prior to the data selection process, the dataset of subject 5 still includes a lot of running around, which will most likely increase the power at higher frequencies.

The chosen cut-off frequency for the low-pass filter was also used for the COP data to ensure accurate comparison.

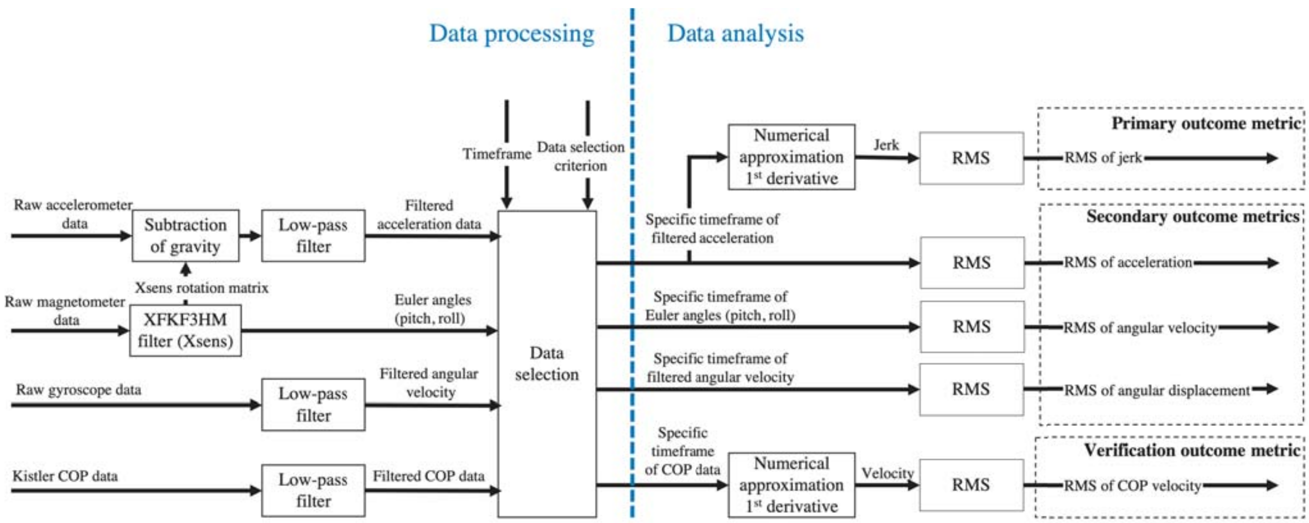

Fig. 3. Graphical overview of the data processing and analysis structure.

2) Data selection: After compensating for gravity and filtering the data, an appropriate timeframe is selected. Prior to any data selection, data is excluded where

- The child is not on the force plate;
- The parent picks up or holds the child.

This is done manually, using the data from the optical motion capture system to identify these events. After exclusion of unusable data, three options can be considered for the selection of quiet sitting data,

1) Manually; the data is assessed with the Qualisys tracking manager (QTM) software to find the instances where the subject shows very little trunk movement.
2) Using the minimal RMS of acceleration; The segment of a specified timeframe is selected where the RMS of the resultant acceleration is minimal, under the assumption that this would result in the "quietest sitting". The resultant acceleration (a_{RES}) is computed as the norm of the acceleration in AP direction (a_{AP}) and in ML direction (a_{ML}),

$$a_{\mathrm{RES}} = \sqrt{a_{\mathrm{AP}}^2 + a_{\mathrm{ML}}^2} \tag{1}$$

3) Using the minimal RMS of angular velocity; Similar to the second method, the segment of a specified timeframe is selected where the RMS of resultant angular velocity is minimal. The resultant angular velocity (ω_{RES}) can be computed as,

$$\omega_{\mathrm{RES}} = \sqrt{\omega_{\mathrm{AP}}^2 + \omega_{\mathrm{ML}}^2}, \tag{2}$$

where ω_{AP} and ω_{ML} represent the angular velocity around the x- and z-axis of the sensor frame, respectively.

The second and third method are more reproducible than the first. The results of both these methods were compared to the manual method. The second method, used for 10-second intervals, corresponded with manually selected segments in 10/21 cases, while the third method corresponded with manually selected segments in 17/21 cases. Using the third method for a 30-second interval corresponded with the manually selected segments in 6 out of 7 times.

Thus, to standardize measurements as much as possible, the RMS of resultant angular velocity (second method) is used to specify the quiet sitting segments. A segment length of 30 seconds is used for further analysis, as this was expected to be a good trade-off between the accuracy of the outcome metric computation and the available useful data. Additionally, it has been found that the reliability of COP velocity is acceptable for a trial length of 30 seconds [49].

D. Data analysis: determination of outcome metrics

The right side of Fig. 3 shows an overview of the data analysis structure.

1) Primary outcome metric: RMS of Jerk: The jerk, j, is defined as the third derivative of position with respect to time, or the first derivative of acceleration [42]. Therewith, jerk is an indication of movement smoothness, with lower jerk corresponding with higher smoothness. The RMS of jerk has shown high discriminative ability in the assessment of postural control in Parkinson's disease patients [50]. Furthermore, a preliminary analysis of a pilot experiment with an infant and an adult showed a significant increase in smoothness of movement, both visually and in terms of a decrease of jerk for the adult compared to the child. To the best of our knowledge, the jerk has not been studied in this population yet. The RMS of jerk ($\mathrm{RMS}(j)$) can be computed as

$$\mathrm{RMS}(j) = \sqrt{\frac{1}{N}\sum_{i=1}^{N} j(i)^2} \tag{3}$$

with N the total number of data points and with the jerk time series j either in the AP direction,

$$j_{\mathrm{AP}} = \frac{\mathrm{d}a_{\mathrm{AP}}}{\mathrm{d}t}, \tag{4}$$

in the ML direction,

$$j_{\mathrm{ML}} = \frac{\mathrm{d}a_{\mathrm{ML}}}{\mathrm{d}t}, \tag{5}$$

or the resultant time series,

$$j_{\mathrm{RES}} = \sqrt{j_{\mathrm{AP}}^2 + j_{\mathrm{ML}}^2}. \tag{6}$$

In (4) and (5), a_{AP} and a_{ML} represent the filtered acceleration in AP and ML direction, respectively.

The derivative is approximated using the following fourth-order central-difference approximation,

$$f'(x) = \frac{-f(x+2h) + 8f(x+h) - 8f(x-h) + f(x-2h)}{12h}, \tag{7}$$

where f represents a general function of x and h corresponds with the sampling time.

2) Secondary outcome metrics: The included secondary outcomes are

- RMS of acceleration, computed as

$$\mathrm{RMS}(a) = \sqrt{\frac{1}{N}\sum_{i=1}^{N} a(i)^2}, \tag{8}$$

  where a represents the filtered acceleration data in AP or ML direction, corresponding with the z- and x-direction of the sensor frame, respectively;
- RMS of angular velocity, computed as

$$\mathrm{RMS}(\omega) = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \omega(i)^2}, \tag{9}$$

  where ω represents the filtered angular velocity data in AP or ML direction, corresponding with rotation around the x- and z-axis of the sensor frame.
- RMS of angular displacement, computed as

$$\mathrm{RMS}(\theta) = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \theta(i)^2}, \tag{10}$$

  where θ represents the roll (AP direction) or pitch (ML direction), as determined by the onboard Xsens algorithm.

3) Verification outcome metric: RMS of COP velocity: The RMS of COP velocity is used as a metric for verification of the RMS of jerk. The COP velocity is more commonly used as a metric for postural control in quiet stance [51, 52]. The RMS of COP velocity is expected to decrease with an increase in trunk motor control [51, 53].

The RMS of COP velocity can be computed as,

$$\mathrm{RMS}(v_{\mathrm{COP}}) = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_{COP}^2(i)}, \tag{11}$$

where v_{COP} represents the COP velocity, as computed using (7) to numerically approximate the derivative of the COP position.

III. Results

A. Primary outcome metric: RMS of jerk

1) Condition C1 (directly on the force plate) versus C2 (on a bench): Fig. 4 provides an overview of the RMS of jerk for the resultant, AP, and ML directions for both conditions C1 and C2 for 30 seconds of quiet sitting. The RMS of the resultant jerk shows a downward trend for the ages of 10 months up to 24 months for condition C1. Furthermore, subjects 3 (○) and 7 (×) show results of comparable magnitude for this condition. For condition C2, the downward trend is not as clear, specifically due to the larger difference between subjects 3 (○) and 7 (×). Also, subject 5 (◊) and 6 (+) have a significantly higher magnitude than their younger counterparts. For condition C1, subject 6 (+) also has a higher magnitude than the younger subjects. Generally, the same results are found in the AP and ML direction. The magnitude of the RMS of jerk is higher for condition C2 for all subjects except subject 1 (∗) and 7 (×).

There is no data available for subject 4 (△) and subject 5 (◊) for condition C2 and C1, respectively. Subject 4 became too restless after condition C1 to continue. Subject 5 did not remain seated on the force plate for the required timeframe for condition C1.

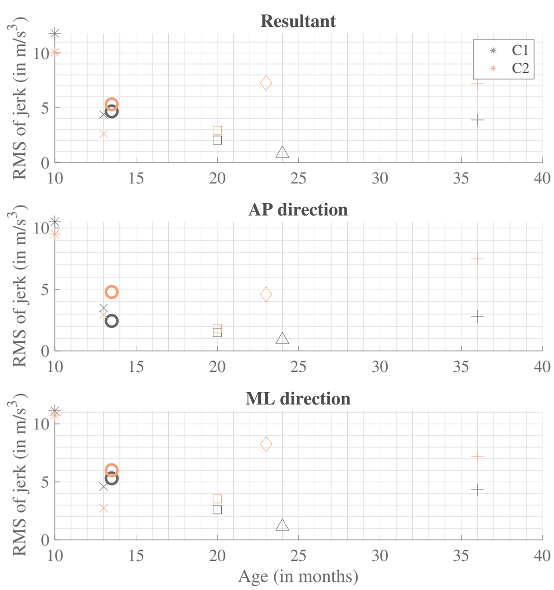

Fig. 4. RMS of jerk for condition C1 (directly on the force plate) and condition C2 (on a bench on the force plate) for 30 seconds of quiet sitting data.

2) Different data lengths: Fig. 5 provides an overview of the variability of the RMS of resultant jerk for data lengths from 5-35 seconds with 1-s intervals. The limit of 35 seconds was set because a valid interval can be found for 6 out of 7 children for this interval. The only exception is subject 5 (◊), for this subject the longest valid data length is 28 seconds. The blue dots in the figure show the 30-second data point for each subject. The overall trend of the boxplots follows the same trend as these data points. The 30-second data points have magnitudes on the higher end of the spectrum. There is a large overlap for the subjects with age 13 months (subject 7, $\times$) and 13.5 months (subject 3, $\bigcirc$). The variability of the 23-month-old subject (subject 5, $\Diamond$) is largest, with its interquartile range spanning a total of approximately 2 m/s^3. Also striking is that the 24-month-old subject (subject 4, $\triangle$) shows very little variability.

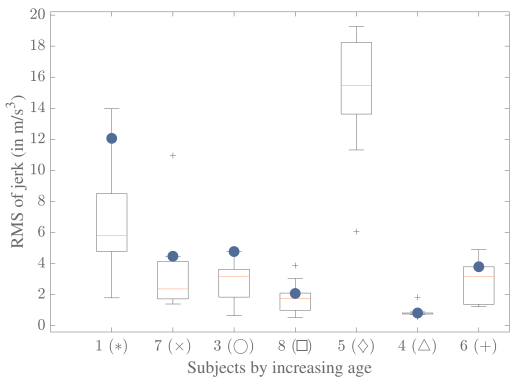

Fig. 5. Boxplot of the RMS jerk for varying data lengths, 5-35 seconds with 1-second intervals, for the resultant time series for condition C1 (directly on the force plate) in movement M1 (quiet sitting).

3) Different data segments: Fig. 6 shows the RMS of jerk for three different data segments of 30 seconds each, and thus provides an overview of the sensitivity to the chosen data segment. It should be noted that for subject 7 ($\times$), only two data segments are included, because there was not enough useful data available. In almost all cases, the magnitude of RMS of jerk increases for higher minimal RMS of velocity. The difference between data segments is most pronounced for the segment with third-lowest RMS velocity for subject 8 ($\square$).

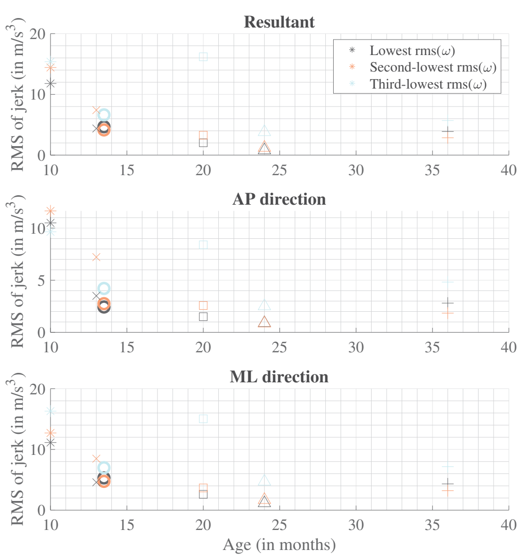

Fig. 6. RMS of jerk for quiet sitting of condition C1 at three 30-second intervals.

B. *RMS of jerk versus RMS of COP velocity*

Fig. 7 shows a comparison of the RMS of jerk of the IMU with the COP velocity. Both metrics show very similar trends, with subject 7 ($\times$) the main exception, with a significantly higher relative magnitude compared to the other data points.

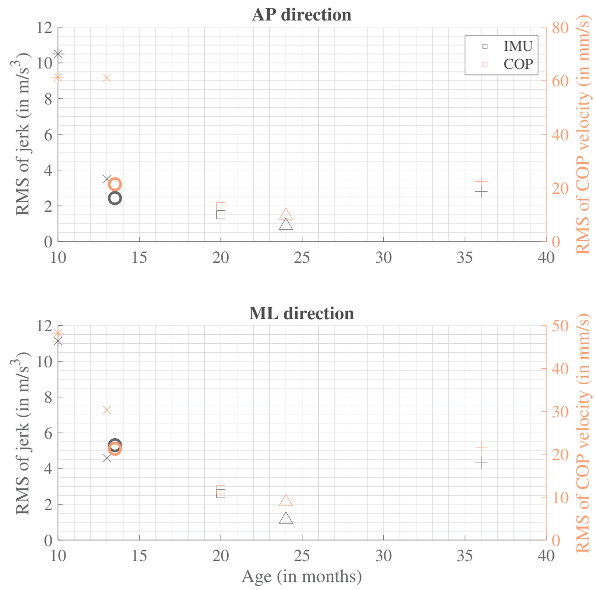

Fig. 7. RMS of jerk as determined with the IMU data, compared to COP velocity in both AP and ML direction.

C. *Secondary outcome metrics*

A combination of the primary and secondary outcome metrics can be found in Fig. 8. For the AP direction, both the RMS of jerk and the RMS of acceleration show a clear downward trend from 10-24 months. The RMS of displacement and the RMS of velocity in the AP direction both show a higher magnitude for 13-month-old subject 7 ($\times$) compared to 10-month-old subject 1 ($*$). The RMS of angular velocity shows a similar trend from this subject onward, but there is no apparent trend for the RMS of angular displacement for the AP direction.

For the ML direction, the RMS of jerk and the RMS of acceleration show approximately the same trend. The RMS of angular velocity and the RMS of angular displacement show a similar trend up to 20 months, after which both show an increase in magnitude. Subjects 3 ($\bigcirc$) and 7 ($\times$) are very close in magnitude, similar to subjects 4 ($\triangle$) and 8 ($\square$).

IV. Discussion

A. *Performance of the RMS of jerk as a metric for trunk motor level differentiation*

1) Condition C1 (directly on the force plate) versus C2 (on a bench): For both movement conditions, the RMS of jerk is expected to decrease with increased motor control, as movement smoothness is expected to increase. This downward

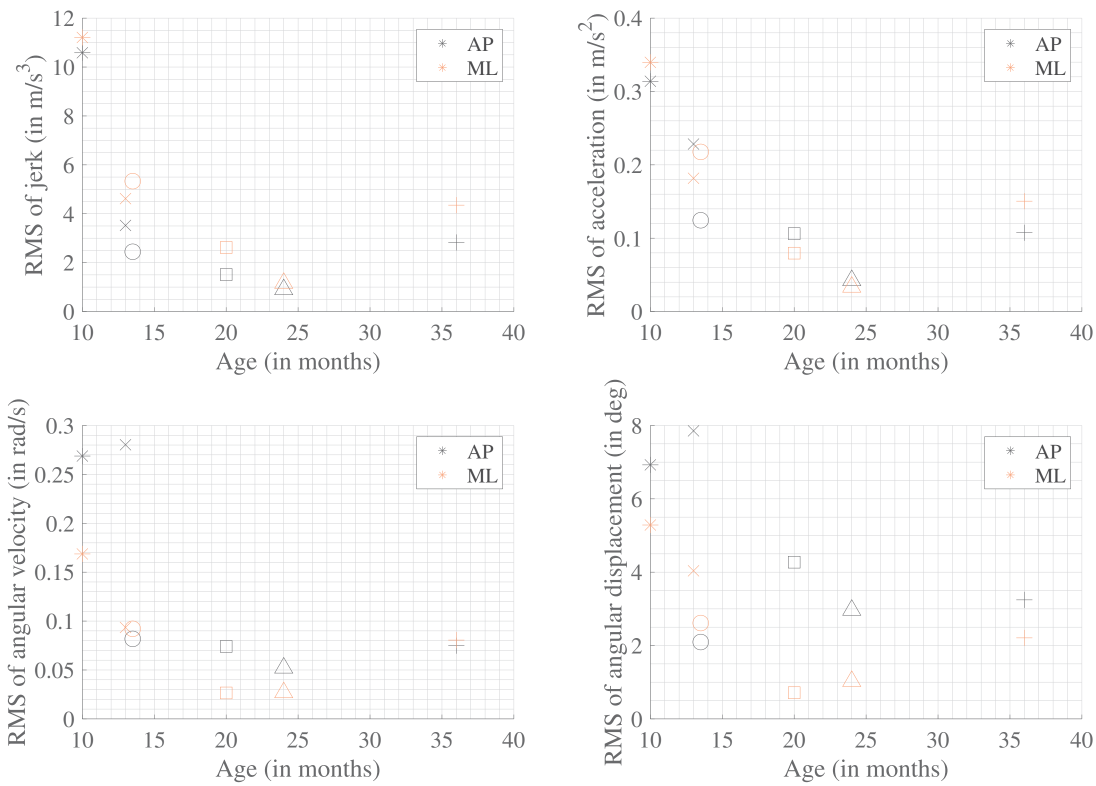

Fig. 8. Secondary outcome metrics in AP and ML direction: RMS of jerk, RMS of acceleration, RMS of angular velocity, RMS of angular displacement.

trend is clearly visible in Fig. 4 for ages 10 months to 24 months for condition C1. Furthermore, following the expectation that children with approximately the same age have the same developmental level, the similarity in magnitude for subjects 3 (○) and 7 (×) is very promising, as these subjects are only two weeks apart in age. The developmental age as indicated by the van Wiechen scheme was approximately equal to the actual age for both subjects, further validating this result.

For the same condition, the RMS of jerk increases for the oldest subject (subject 6, +), which is an unexpected outcome. This may be related to the age of this child. As children grow older, their movement ability is increased and the tasks may become (too) easy for them. If they become distracted or impatient, they may start to fidget, resulting in an increased RMS of jerk that is not directly related to the level of trunk motor control that they have. Thus, because of the increase in movement ability, the effect of behaviour will become more apparent for older children.

The same effect is visible for condition C2, where this increase is apparent for subject 5 (◊) and subject 6 (+). Subject 5, specifically, moved around during the majority of the measurements. This is also the reason that no data is included for this child for condition C1, as there was no segment of 30 consecutive seconds in these datasets during which the child remained seated. Interestingly, subject 5 had a very high score on the van Wiechen scheme, with a score corresponding with a four-year-old child. This further reinforces the idea that the subject may become distracted more easily if their movement ability increases and a task is too easy for them.

For condition C2, the magnitude of the RMS of jerk for subjects 3 (○) and 7 (×) is further apart than for the first condition. This may be due to the (expected) increased difficulty for movement condition C2 compared to C1. This increase in difficulty is reflected for subjects 3 (○), 8 (□) and 6 (+), but it is not visible for the youngest two subjects, subject 1 (∗) and subject 7 (×).

To conclude, condition C1 seems to show more promising results, with a clear decreasing trend from 10 months to 24 months and very similar magnitudes for the subjects that are close in age. Thus, further analysis was focused on this condition.

2) Different data lengths: As results may be influenced by the chosen data length, the effect of data length is evaluated in Fig. 5, where the primary outcome metric is computed for data lengths varying from 5 to 35 seconds. As the same trend remains visible, the data length does not seem to significantly influence the validity of the results. However, the 30-second data points are all higher than the median, which would indicate that the RMS of jerk does increase with increasing data length. Be that as it may, a longer data length may also provide a more general overview of the quality of sitting, in contrast with a "snapshot" of only 5 seconds. It is not surprising that both the variability and the magnitude of the RMS of jerk for subject 5 (◊) is highest, as this subject was moving during the majority of the measurements. The similarity between the results for subjects 3 (○) and 7 (×) is also not surprising, due to their similar age and developmental level.

The low variability of the 24-month-old subject, subject 4 (△), was also apparent in the recordings made with the optical motion tracking system, where it was clear that the subject sat quietly for extended periods of time, resulting in very low variability with dataset length.

3) Different data segments: Following Fig. 6, the RMS of jerk seems to be relatively independent of the chosen data segment, which is promising. Furthermore, the segment where the child is sitting "least still" according to the data selection criterion has the highest magnitude of RMS of jerk for all children, which is as expected. This difference in magnitude is most pronounced for subject 8 (□). This is surprising, as the minimal RMS velocity for the consecutive sections is only approximately 5% apart. This could be an indication that the data selection criterion is imperfect and/or not fully descriptive of quiet sitting.

In conclusion, the RMS of jerk shows promise as an outcome metric for differentiating between different levels of trunk motor control for ages up to 24 months. The results are relatively independent of data length and chosen data segment.

B. Comparison of the RMS of jerk with the COP velocity

Both the RMS of jerk and the RMS of COP velocity are expected to decrease with increasing trunk motor control and thus with increasing age. Fig. 7 shows the same trend for the both metrics, with subject 7 (×). For this subject, the RMS of COP velocity is closer in magnitude to that of subject 1 (∗), specifically in the AP direction. After review of the relevant data segment in QTM, it became apparent that the subject slid forward with a rocking motion. This most likely resulted in the increase in RMS of COP velocity. As this behaviour is not an indication of poorer trunk control, this suggests that the RMS of jerk is a more accurate indicator of trunk motor control for this child. This is further affirmed by the similarities viewed between the two subjects who are two weeks apart in age, i.e. subject 3 (○) and 7 (×).

Generally, the RMS of jerk shows a trend that closely resembles the COP velocity. This indicates that the RMS of jerk can provide similar results as the more well established COP velocity.

C. Performance of secondary outcome metrics

The RMS of jerk shows very similar results to the RMS of acceleration (see Fig. 8), which is as expected as both metrics are closely related. Assuming that all metrics are an indication of the level of trunk motor control, we would expect all outcomes to show similar results. The same trend is visible for the ML direction for both the RMS of angular velocity and the RMS of angular displacement. This trend is not apparent for the AP direction of the latter two metrics. A recent study showed that sitting performance correlated better with COP movement in ML direction than in AP direction [54], which matches our results.

Interestingly, the RMS of displacement and the RMS of velocity show the same relatively high magnitude for subject 7 (×) as was shown in Fig. 7 for the RMS of COP velocity. This further validates the idea that this increase is caused by the child sliding forward, as both the angular displacement and angular velocity are increased for this movement.

Generally, secondary outcome metrics perform comparably well to the RMS of jerk, but the clear trend and the proximity of the values for the subjects close in age show most promise for the RMS of jerk as an outcome metric.

D. Study limitations

The main limitations of this work are related to the sample size and sample characteristics. Due to the small sample size of seven subjects, it is difficult to generalize the results to a larger population. Furthermore, the subjects' ages are too far apart, making it difficult to distinguish age-related changes. Additionally, the effect of subject behaviour likely increases with age. As the movement ability of a child increases, a task may become (too) easy for them. This can result in them becoming impatient and starting to fidget or move around, which influences the perceived results. Also, the song used to standardize measurements did not have the desired effects, as it is more distracting than useful for the younger children that do not understand the instructions yet.

Moreover, the elastic bands used to apply the IMUs were not sufficiently comfortable for the wearer. Having to wear the bands even made subject 2 so uneasy that we had to stop the experiment of this subject without being able to perform any measurements. Multiple other subjects also became uncomfortable and started to pull on the bands. It is also unclear how sensitive the metrics are to exact sensor placement. The elastic bands made it difficult to accurately place the IMUs in the same position for each subject.

Furthermore, we assume that the developmental age of each subject corresponds with their actual age when interpreting the results. To check the validity of this assumption, the van Wiechen scheme is used as an indication of developmental age. However, this scheme is filled in by the parents, while it is normally an observation-based tool for physical therapists. This can result in an over- or underestimation of the developmental age of a child and is thus not conclusive enough to determine the actual developmental age.

Lastly, the segment with the minimal RMS of resultant angular velocity was used to determine which data segment corresponded with quiet sitting. While initial analysis suggested that the resulting segments were valid, this is not a widely used method and may be an oversimplification.

E. Recommendations for future work

The first and main recommendation is to perform a longitudinal follow-up study. Firstly, this study should focus on ages from 6 months to approximately 1.5 years old. The downward trend was clearly visible for this age group, but its validity should be proven using longitudinal measurements to eliminate inter-subject variability. Furthermore, most children will be able to walk by the age of 1.5 years, due to which the subject's behaviour instead of the level of trunk motor control could become dominant in the results. Secondly, an alternative way to attach the IMU sensors should be found. As the elastic bands felt intrusive and unnatural for multiple subjects, something resembling a t-shirt or vest might be more comfortable. A customized placement method like a vest may also help to place the IMUs in the same location for each subject. Thirdly, either only quiet sitting should be included, or a more natural way of performing trunk movements should be examined. With the current method, a lot of variability was observed between subjects for different movement conditions. Finally, this study should include an accurate evaluation of overall developmental level, performed by a therapist or other trained personnel. While the van Wiechen scheme provides an indication of the developmental level, a more elaborate evaluation is necessary to accurately correlate outcome metrics with developmental level. Ideally, the assessment is performed by the same physical therapist for each child, to overcome the (potential) bias of parents filling in the observation and the potential inter-rater bias caused by using multiple therapists.

Beside performing a follow-up study, more information can also be extracted through further analysis of the existing datasets. For example, the focus of the data analysis in this paper was on segments of quiet sitting, while movements were included in the measurements. It would be interesting to examine the effect of including these movements in further analysis. We expect that the RMS of jerk, out of the examined metrics, will be most successful in distinguishing trunk motor control levels for movement conditions. Furthermore, the secondary outcome metrics could be examined further, focusing on the variability for different data lengths and segments. Out of the secondary outcome metrics, the RMS of acceleration is expected to be most interesting, as the results are closely related to the RMS of jerk, but require less processing. Also, the sensitivity of the metrics to sensor placement should be examined and, if necessary, a normalization procedure should be attempted to negate this effect. Lastly, other metrics like correlation dimension and approximate entropy may be included to potentially find features of the datasets that are not included in the current analysis.

V. Conclusion

This study is the first to use outcome metrics computed from trunk-attached IMUs as an objective tool for the assessment of trunk motor control in children between 0 and 4 years old. While further study is still required, the preliminary results for the RMS of jerk as an outcome metric are promising for ages of 10 to 24 months, where a downward trend is visible. The metric is relatively independent of chosen data length and data segment and compares well to the RMS of COP velocity, an established method.

However, with a sample size of only seven subjects, these results are preliminary. A follow-up longitudinal study is advised to further examine the effectiveness of the RMS of jerk as an outcome metric for the differentiation of trunk motor control levels.

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