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Quantification of the Dependence of the Measurement Error on the Quantization of the A/D Converter for Center of Pressure Measurements

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Abstract: In this scientific study, the question of the influence of the quantization error on the CoP measurement is be clarified. For this purpose, the quantization error is investigated in two scenarios, first with the technical/physical reproduction of the CoP, and then with test persons. From the results, a model is derived with which a technical and economic optimum between resolution and error can be generated for an individual case. The study was carried out with 170 healthy volunteers, aged 20–30 years. The test persons stood in a bipedal position for 15 s on a Kislter force plate (type 9260AA). In the investigation, it was shown that, for the measurement of center of pressure (CoP), signals to mostly 16-bit analog/digital converters are suitable but not, per se, the most economical variant. With the introduction of a quality criterion, a reasonable design for the planned test case can be made.

Keywords: CoP; analog/digital converter; Kistler; balance board

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1. Introduction

Postural control is a basic human motor function and an elementary component for maintaining an upright posture during static and dynamic processes. The assessment of upright posture is often difficult due to the complexity and the close interaction between sensory perception and motor performance. For this reason, a variety of qualitative and quantitative methods have been developed over time to quantify postural stability, especially considering different physiologies [1]. These assessments claim to evaluate the quality of balance ability and subsequently identify persons or groups of persons at risk of falling and to provide more detailed information on postural pathomechanisms.

One of the most commonly used quantitative methods for the evaluation of postural control is the evaluation of parameters describing the CoP (center of pressure) excursion. In the upright, bipedal position, the CoP is the central starting point for all ground reaction forces in the transverse plane, the course of which is analyzed over a defined period using an objective force plate [2–5].

Due to the complexity and high biological variability of the posture control cycle, a large number of different methods and parameters have been established to describe the CoP process. In addition to the methodological conditions, such as foot position, viewing conditions, and measurement duration [6,7], the type of data collection and processing can also have a significant influence on the measurement results.

An essential parameter of the digital measurement technology used today is quantization. This describes how high the individual steps are, i.e., the resolution of a digital signal. The quantization error occurs during the sampling of the real analog signal. When planning and evaluating scientific studies in the field of CoP measurements, little or no attention has been paid to this parameter. The resolution is one of the descriptive parameters for an A/D converter. Thus, there are a few scientific publications with different procedures and varying levels of quality of the method descriptions that describe the used quantization. The consequence of these discrepancies is that the different studies are not, or only partially, comparable to each other [8–11]. A particular deficit is the lack of scientific discourse on the choice of quantification method. This may also be due to the early days of CoP measurement technology. Until the 1990s, CoP was mainly recorded with analog measuring devices (strip chart recorders, analog calculation modules, etc.) and was therefore not known to be a source of error.

Data collection using force plates is performed by force- or torque-sensitive sensors, which detect the displacement of the pressure centers of the people on them. When converting the analog signal into a digital signal, the sampling frequency and the quantization have an influence. When designing a measurement setup, it is therefore equally important to determine the quantization correctly in advance. The error resulting from a analog/digital conversion is called a quantization error. The size of this error depends on the resolution of the A/D converter (ẟ), the operating range of the A/D converter (U_{amp}), and the maximum signal amplitude (U_{sig}).

Basically, the higher the resolution (number of bits), the smaller the quantization error. However, a higher resolution is also associated with higher acquisition costs for the A/D converter. However, this is in conflict with the goal of achieving high-quality results with cost-efficient devices. For this reason, it seems reasonable to find an optimum between the parameters to guarantee an acceptable quantization error.

To determine the appropriate maximum resolution, the "resolution" of the human biological system should be considered first. For this purpose, the model of information flow in the human central nervous system during perception, movement, and consciousness selection, according to Küpfmüller 1971, should be used. From the large information offer of the sensory organs of about 107 bit/s, only about 20 bit/s are consciously perceived (narrowness of consciousness) [12]. The act of will needs much more information, which is stored in the memory after practice. The conscious control of movement performs, at most, at 50 bit/s [12]. With a pulse conduction time of 80 ms, this corresponds to a resolution of approximately 5 bit for the Aγ fibers to reach the skeletal muscles. This value can be regarded as a technically reasonable limit. However, the resolution required for the measurement of the CoP track may be greater because the entire mechanical system of the musculoskeletal system is stiff, has mass inertia, and is overlaid by the superposition of many processes in the locomotor apparatus [13].

Figure 1 shows a section of a recorded signal from a force plate (Kistler, 16 bit) during a test with a mechanical pendulum. To illustrate the effect of different quantizations, the same signal is shown with further, lower quantizations. It is easy to see how the resolutions have a significant influence on the level of the steps of the resulting signals. From the figure, it can be seen that at 10 bit (yellow curve; Figure 1), there is not much similarity with the output signal.

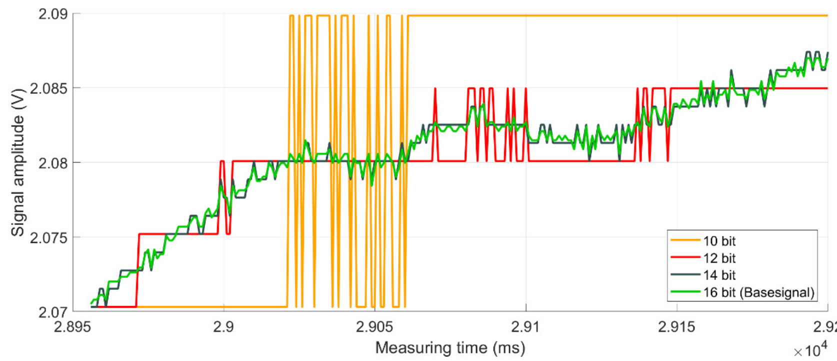

Figure 1. Representation of different resolutions of the signal with 10, 12, 14, and 16 bit.

For this reason, a scientific study can clarify the question of the influence of the quantization error on CoP measurements. For this purpose, the quantization error was investigated in two scenarios, first with the technical/physical reproduction of the CoP, and then with test persons. From the results, a model was derived, with which a technical and economic optimum between resolution and error can be generated for the individual case.

2. Materials and Methods

Data Collection

In a two-step study, the quantification error and its characteristics were analyzed when measuring the CoP. In the first stage, an analysis based on a mechanical vibration was carried out, which was to be used as a reference for further investigations with human test persons.

A Kislter force plate (type 9260AA) was used as the measuring system. As A/D wander, an NI USB 6002 with 16 bit and a sampling rate of 1 kHz was used. The software for the measurement runs was created with LabVIEW 2014.

For the reliable simulation of a one-dimensional, temporally constant reference motion, a mechanical pendulum was used. (See Figure 2. Scheme of the mechanical pendulum according to Koltermann et al., 2017 [14]). This device generates a dynamic, reproducible CoP curve over time, which was used for evaluation. The pendulum was designed as a four-legged stand with a lead ball of 25 kg attached to a steel cable suspension. Since the dimensions of the cable were many times smaller than those of the ball, the mass of the cable could be neglected in further considerations. The reference values for the assessment of the measuring accuracy could therefore be determined on the basis of the length of the pendulum, the angle of deflection, and the measuring time (see [14]). In this study, the pendulum length was 97 cm, which corresponds to a pendulum frequency of 0.5 Hz. If the measuring time was sufficiently short (15 s), the pendulum system's damping was negligible, such that it was limited to 10 s in this study [14]. The measurement was repeated 20 times in order to generate correspondingly robust results. The theoretical expected value of the oscillation distance for 10 s was 210 cm. We considered a proven deviation for the physical system of 2% as legitimate [14].

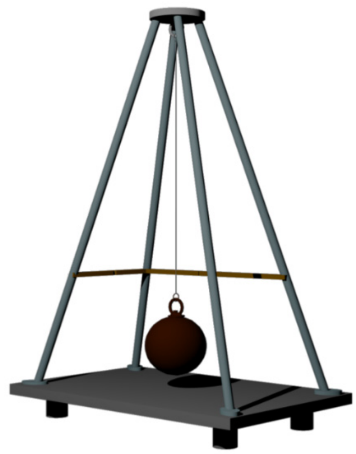

Figure 2. Scheme of the mechanical pendulum according to Koltermann et al., 2017 [14].

In the second stage, 170 healthy volunteers, aged 20–30 years, were examined. The anthropometric data are shown in Table 1. All subjects were informed about the study and their rights prior to the start of the study. Subsequently, all subjects signed the informed consent form.

Table 1. Anthropometric data of the volunteers, broken down by gender.

	Male (52%)	Female (48%)
Age [J.]	26.4 ± 6.6	28.54 ± 7.66
Weight [kg]	83.9 ± 13.7	66.13 ± 11.93
Size [cm]	180.9 ± 7.7	160.30 ± 34.21
BMI [kg/m²]	25.6 ± 3.8	24.2 ± 4.5
Shoe Size (EU)	42.5 ± 5.5	38.9 ± 1.5

The test persons stood in a bipedal position for 15 s on a Kislter force plate (type 9260AA). For the subject measurements, position markings for the feet were placed on the Kistler plate. In order to improve the comparability of the single-subject measurements, the subjects were placed in a fixed posture prior to performance [15,16]. This included the stipulations that the knees were not stretched to the maximum, the hands were placed on the iliac crest, the head was kept upright, and the chin was tucked in. All tests were run without shoes. In addition, an optical marker was placed at a distance of 3 meters from the test subject. The subjects were instructed to fix this with their eyes during the measurement [7]. The study nurse was instructed on how to set up and perform the test. The standardized test instructions included brief instructions on how to perform the test and an explanation of the conditions under which the test must be stopped.

Statistic

The evaluation of the collected data was performed with LabVIEW 2014 and R 3.6.3. Next, a resample of the output resolution from 16 bit to 14-, 12-, and 10 bit was performed for the collected CoP trajectories. When using resampling from a high resolution to a lower resolution, only very small signal distortions have to be calculated against the actual analog signal.

To evaluate how much the trajectories were changed by different sampling rates, a correlation to the 16 bit output signal was calculated for each calculated signal. The calculated results are given as mean values of the whole cohort.

In the next step, one power density spectrum was calculated from each signal (16, 14, 12, and 10 bits). To evaluate how the resolution affects the frequencies contained in the spectrum, the spectrum was integrated from 0.001. The resulting area has been given as an average value. The peak at 0 Hz was the same part of the signal (offset), which was not considered in the integration because it depended on the weight of the test person. To compare the individual quantization gradations with the output signal, a correlation integral was used.

The data was filtered with a Butterworth filter of the 3rd order with a cut-off frequency of 14.3 Hz. The filter was designed according to Koltermann et al., 2019 [17].

Quality Calculation

The recommendation suggests a maximum quantization step height of 1% of the signal height to be detected [18]. Since the ratio of the step height to the available resolution is exponentially decreasing, a linear quality function, which increases monotonically, was developed in the context of this work for easier representation. The developed calculation of the quality criterion for the resolution is shown in equation 1. The quality Q depends on the resolution of the A/D converter (δ), the working range of the A/D converter (U_{amp}), and the maximum signal amplitude U_{sig}. The constant 2 was introduced with the good range of Q being one, and thus equal to the dimensioning target of 1% of the step size.

$$Q = \frac{log10\frac{2^{\delta} \cdot U_{sig}}{U_{amp}}}{2} \tag{1}$$

3. Results

In the first stage, the parameters of the CoP curve generated by mechanical pedals as a function of resolution are shown in Table 2.

Table 2. Presentation of the results of CoP trajectories at different resolutions of the measurement signals.

	16 Bit	14 Bit	12 Bit	10 Bit
Mean value CoP trajectory (cm)	211.58	211.36	210.76	215.04
Standard deviation (cm)	±13.59	±13.57	±13.46	±13.24
Correlation to output 16 bit signal	1	>0.999	>0.999	>0.999

Due to the resolution, the average value of the measurement changed slightly over the individual quantization steps. In a comparison of the average mean values of 16 to 10 bit, the largest deviation can be seen; this corresponds to 3.5 cm. Looking at the correlation of the individual signals to the output signals of 16 bit, it can be seen that all correlate very well with it.

Based on these results, a power spectral density analysis (PSD) of the signals as a function of resolution was performed. Figure 3 shows the respective frequency components as a function of power.

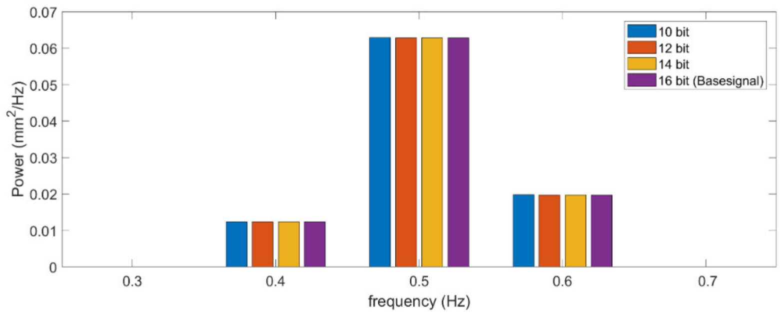

Figure 3. Representation of the mean PSD spectrum of the tests with the technical pendulum in different resolutions.

The frequency components of the 4 resolutions shown in Figure 3 show the same distribution as that predicted in Koltermann et al. [14]. In order to better quantify the very small differences, the individual spectra were integrated to calculate the area under the spectrum. The resulting areas and deviations from the 16 bit result are summarized in Table 3. Since the quantization steps were at least 100 times smaller than the signal amplitude of an oscillation, the quantization error had no significant influence on the result of the observation in the spectrum.

Table 3. Area contents of the spectra and their difference from the 16-bit signal of the pendulum investigations.

Resolution	16 Bit	14 Bit	12 Bit	10 Bit
Area (mm^2)	9.51×10^{-3}	9.50×10^{-3}	9.50×10^{-3}	9.50×10^{-3}
Difference from 16-Bit	-	8.39×10^{-5}	8.39×10^{-5}	8.39×10^{-5}

The results of Step 2 are presented in Table 4. From the results, it can be seen that it made no difference for the recorded CoP lengths whether the resolution was 16 bit or 14 bit. The recording with 12 bit showed a distortion of the signal. The average value increased here by about 10 cm. However, the signals still correlated very well compared to the output signals of 16 bit. For the signals converted to 10 bit, the results of the path and the standard deviation no longer reflected the actual results. This can also be seen when looking at the results of the correlation to the output signals which, with 0.001, showed no statistical agreement.

Table 4. Presentation of the results of CoP trajectories at different resolutions of the measurement signals in subject measurements.

	16 Bit	14 Bit	12 Bit	10 Bit
Mean value CoP trajectory (cm)	110.79	110.93	120.99	203.09
Standard deviation (cm)	57.47	57.04	55.04	196.28
Correlation to 16 bit output signal	1	0.998	0.993	>0.001

Another way to consider the influence of the quantization error is to examine the power components in the recorded signal. For this purpose, all four signals were decomposed into their power components using PSD analysis and displayed in the spectrum (Figure 4).

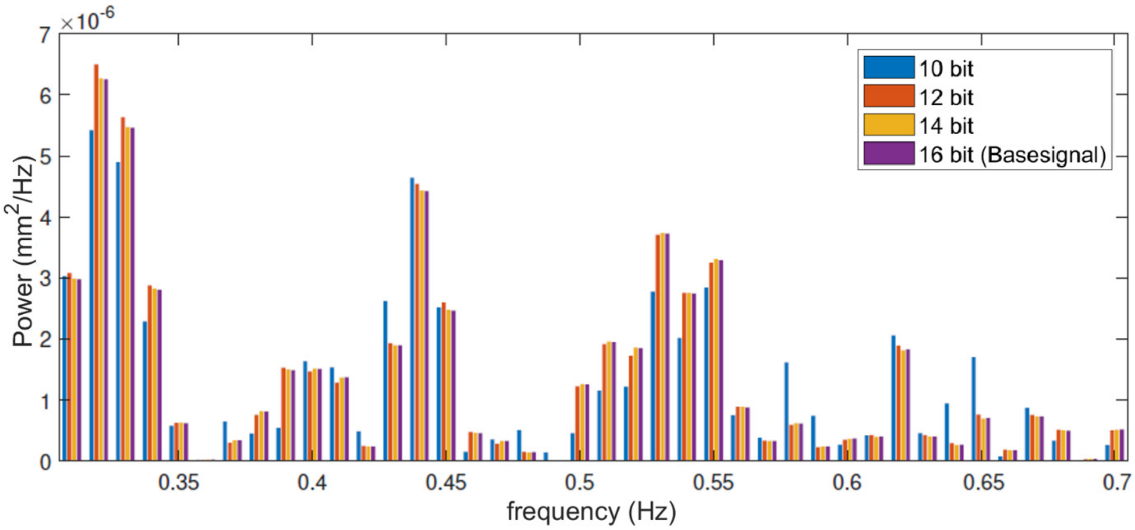

Figure 4. Representation of the mean PSD spectrum of the tests with test persons in different resolutions.

The signals of the 12 bit, 14 bit, and 16 bit resolutions show an equal distribution of the spectral components here. The 10 bit signal (blue) shows a deviation from the other signals in many places. In order to quantify the difference, each spectrum was integrated, and the area covering the spectrum was calculated for each signal. To evaluate the change, the deviations from the 16 bit signal were calculated and are shown in Table 5. The results show that the 10 bit signal has a deviation 100 times greater than the 14-bit signal.

Table 5. Area contents of the spectra and their difference to the 16-bit signal.

Resolution	16 Bit	14 Bit	12 Bit	10 Bit
Area (mm^2)	29.50×10^{-5}	29.51×10^{-5}	29.90×10^{-5}	34.53×10^{-5}
Difference from 16 bit	-	-1.53×10^{-7}	-4.003×10^{-6}	5.03×10^{-5}

The following quality parameters resulted from the example calculated above (see Table 6).

Table 6. Presentation of the results of different resolutions and their calculated quality according to equation 1 for the measurement with test persons and the technical pendulum in comparison to the technical pendulum.

Test Persons				
Resolution (Bit)	16	14	12	10
Working range (V)	20	20	20	20
Average signal amplitude (V)	0.3	0.3	0.3	0.3
Quality criterion	1.5	1.2	0.9	0.6
Pendulum				
Resolution (Bit)	16	14	12	10
Working range (V)	20	20	20	20
Average signal amplitude (V)	0.8	0.8	0.8	0.8
Quality criterion	1.7	1.4	1.2	0.8

At a small signal amplitude (corresponding to an average signal amplitude of the test-person measurements shown here), a quality value of greater than 1 was only obtained for 16 bit and 14 bit. We found that 12 bit quantization was sufficient when a larger signal amplitude of 0.8 V was considered.

For a better classification of the evaluation of the results from the quality calculation, a characteristic curve field for quality class 1 (in Figure 5) was developed.

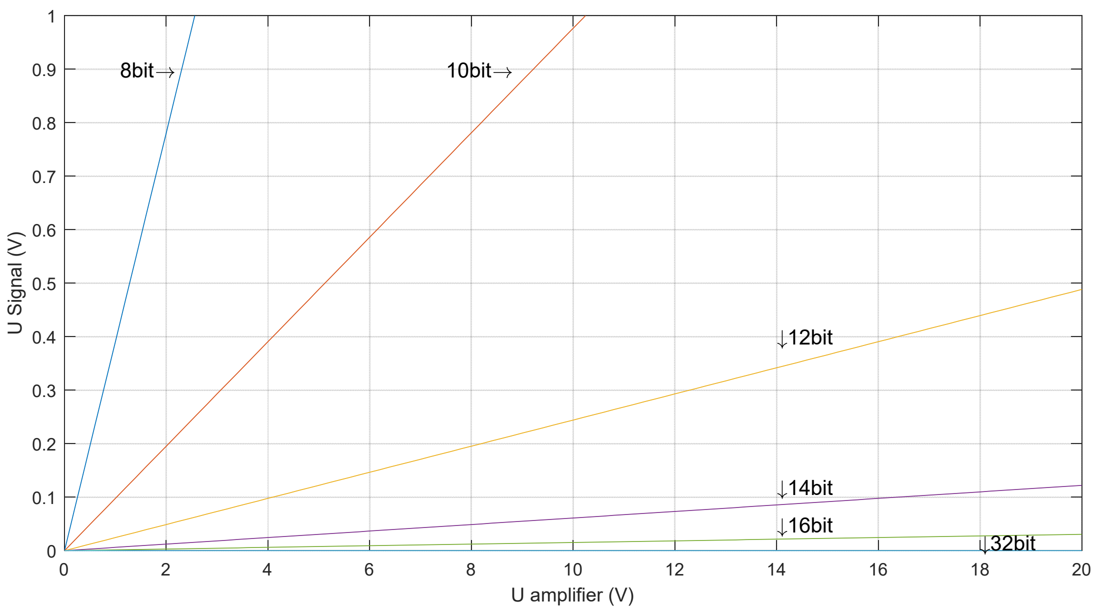

Figure 5. Representation of a characteristic diagram for the quality Q = 1 for different resolutions depending on the working range of the A/D converter and the signal amplitude U_{sig}. The area to the left of the cutoff line describes a Q >1 to the right of the line Q <1.

4. Discussion

The results of the first stage of this investigation were that, for simple tasks, the here technically simulated CoP track can be investigated with low resolutions. For the investigation of devices with the technical pendulum, a sampling rate of 10 bit was suitable, as was 16 bit. However, this statement cannot be directly transferred to measurements with test persons since the deflections to be measured over the plate would be smaller in that case. This means that the electrical levels of the sensors must also be lower. This means that, for diagnostic applications or investigations of the success of interventions with test persons, these results are not applicable.

Step 2 clearly showed that it is crucial to choose the correct quantification, especially when considering the measurement of test persons. To determine how strongly different quantizations would affect CoP trajectories measured with test persons, the courses of 170 test persons were examined. For this purpose, the signals measured with 16 bit were subsequently converted to the respective resolutions using a calculation algorithm. The used A/D converter has a working range of −10–10 V, and the average signal amplitude is 200 mV. To evaluate how similar the curves of the signals with lower resolution would be to the 16 bit signal, a cross-correlation between the two signals was calculated. This means that, if both signals are the same, the calculation will result in 1. Here, slight differences in the quality of the signal and in the spectrum can be seen, even with the 14- and 12 bit signals. On the other hand, the 10 bit did not give acceptable results. The correlation of the 14 and 12 bit signals to the original was still very good. However, there are no other criteria to evaluate the differences. Therefore, a model would need be developed which outputs a quality criterion. The calculation of the quality criterion was developed from the dimensioning recommendation for A/D converters.

The characteristic curves field shows the working range of the A/D converter over the signal level (U_{sig}). The straight-line indicators show the criterion at 1 at the respective resolution. This means that, if the working point lies on the line, it corresponds to $Q = 1$. If the working point shifts such that it lies above the line, it corresponds to $Q < 1$ to the resolution, or $Q > 1$ to the line above it. If the working point moves within an area between two resolutions, the most economical choice is an A/D converter with the resolution of the lower straight line. Technically, there is nothing to be said against using A/D converters with higher resolutions, but from a procurement point of view, this is associated with a multiplication of the costs (approximately EUR/bit 25–50).

The results shown were recorded with a sampling frequency of 1 kHz. Especially for the quality analysis, a check should be made when using multiples of the sampling frequency used here. From our point of view, it can be assumed that the results presented here retain their validity, up to a minimum of 10 kHz, with correspondingly high-performance hardware.

5. Conclusions

In the investigation, it could be shown that, for the measurement of CoP signals, most A/D converters are suitable but not, per se, the most economical variants. With the introduction of a quality criterion, a reasonable design for a planned test case can be made.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

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